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Comparison of Nitrogen and Phosphorus Removal between Two Typical Processes under Low Temperature in a Full-Scale Municipal Wastewater Treatment Plant

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Abstract: Given its strict discharge standards for wastewater treatment plants (WWTPs), China focuses on improving the removal effect of nitrogen and phosphorus in biological treatment processes under low temperatures. The variations in nitrogen and phosphorus during the anaerobic–anoxic-oxic (AAO) and AAO-sequencing batch reactor (SBR) processes in a full-scale WWTP were compared by sampling. Results showed that the removal efficiencies of total nitrogen (TN) and total phosphorus (TP) in both processes exceeded 85% and 91%, respectively, when the water temperature was lower than 15 °C. The wastewater treatment potential capacity of the AAO process was larger than that of AAO-SBR, indicating that the AAO process could realize the subjective demand of nitrogen or phosphorus removal by adjusting its operation mode. The anaerobic phosphorus release of the AAO process was affected when part of the internal reflux entered the anaerobic tank. Thus, the biological phosphorus removal of the AAO process was worse than that of the AAO-SBR process. Since the nitrification and denitrification rates of the AAO process were all higher than that of the AAO-SBR process, the TN removal efficiency of AAO was higher than that of AAO-SBR. These results could provide some advice for the upgrade, operation optimization, and process selection of both processes in the future.

Keywords: nitrogen and phosphorus removal; low temperature; AAO process; AAO-SBR process

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1. Introduction

According to the statistics of the China Urban Water Yearbook (2020), China had 4140 municipal WWTPs with a capacity of 2.14×10^8 m^3/d at the end of 2019; in comparison, only 3340 WWTPs with a capacity of 1.42×10^8 m^3/d were counted in 2012 [1]. The effluent of most WWTPs (77.0% in amount and 87.6% in treatment capacity) enforces Class 1A of the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18918-2002), and an increasing number of provinces and cities have enforced strict discharge standards [2]. For example, the effluent in some WWTPs in Beijing, Tianjin, and Jiangsu Province enforces “Quasi Class IV”, or nearly “Class III” of the Environmental Quality Standards for Surface Water (GB 3838-2002). The annual reduction in COD, BOD_5, TN, and TP by these WWTPs reached 1536.85, 675.11, 158.82, and 23.52 tons, respectively. These reductions played a considerable role in upgrading the surface water quality in China from a polluted situation [3] to an improved status [4].

At present, China's WWTPs have no problem with COD removal, but some difficulties exist in nutrient removal, particularly TN removal [1]. Therefore, the treatment processes adopted by WWTPs in China, such as anaerobic-anoxic-oxic (AAO), oxidation ditch, and sequencing batch reactor (SBR) [5], can simultaneously remove nitrogen and phosphorus. For instance, the AAO process accounted for 43.52% of large-scale WWTPs, whereas the SBR process accounted for 17.19% of the total number of WWTPs [1]. The AAO and SBR processes have been widely used worldwide; thus, current research on both processes mainly focus on adding specific treatment installations [6–8], process improvement [9,10], and the effect of some influencing factors, such as DO [11,12], temperature [13,14], carbon source [15], pH [16], and Fe^{3+} [17], etc. These findings provide good technical guidance for the operation and optimization of the AAO and SBR processes; however, most of them were based on laboratory- or pilot-scale [6–8], thereby limiting the application of the AAO and SBR processes in practical WWTPs to a certain extent.

Given China's strict discharge standards for WWTPs and the overall requirements for carbon emission reduction, WWTPs in China face urgent needs for upgrade and operation optimization in view of the poor operating performance and the sustainable development demands [2]. Therefore, the operation status and nitrogen and phosphorus removal potential capacity of the existing WWTPs must be understood because of the urgent nutrient removal requirements in China. As mentioned, the AAO and SBR processes, which are widely used in WWTPs in China, represent the typical processes of continuous flow and batch flow, respectively. The two typical processes have obvious differences in terms of operation modes and treatment effects. In the present study, the operation parameters and treatment effects of the AAO and AAO-SBR operation processes in a full-scale WWTP, particularly their nitrogen and phosphorus removal under low water temperature, were compared to provide some advice for the upgrade, operation optimization and process selection in the future.

2. Materials and Methods

2.1. Introduction of the Investigated WWTP

The investigated WWTP is located in Jiangsu Province. Its design scale is 1.8×10^5 m^3/d. The design concentrations of influent and effluent are shown in Table 1. In this WWTP, two treatment processes were adopted: AAO-SBR and AAO. The design scale of the AAO-SBR process is 1.2×10^5 m^3/d; this process has four groups in parallel operations. In comparison, the design scale of the AAO process is 6×10^4 m^3/d; this process has two groups in parallel operations. In particular, the design scale of each group is 3×10^4 m^3/d. The influent of both processes comes from the grit chamber. The coarse grid and fine grid were placed before this chamber. The effluent of both processes was treated by coagulation sedimentation for phosphorus removal, which was followed by sand filtration and disinfection in turn. The design hydraulic retention time (HRT) and reflux ratio are shown in Table 2. The wastewater flow direction of the AAO and AAO-SBR processes is shown in Figure 1. In particular, the AAO-SBR process can realize continuous inflow and outflow, which is different from traditional SBR: SBR1 and SBR2 are alternately used as aeration or sedimentation tanks, and when one SBR is converted from an aeration tank to a sedimentation tank, there is a transition period of 0.5 h. At this time, neither tank is aerated, but the wastewater still flows into the anaerobic tank, and the supernatant from the original sedimentation tank is discharged through a decanter.

Table 1. Design concentrations of influent and effluent in the investigated WWTP.

Item	COD (mg/L)	BOD_5 (mg/L)	SS (mg/L)	NH_3-N (mg/L)	TN (mg/L)	TP (mg/L)
Influent	360	180	250	35	50	4.0
Effluent	50	10	10	5(8)	15	0.5

Table 2. Design HRT and reflux ratio of the AAO and AAO-SBR processes in the investigated WWTP.

Process	AAO	AAO-SBR
Anaerobic tank (AnaT)	2.4 h	1.45 h
Anoxic tank (AnT)	6.1 h	4.1 h
Oxic tank (OT)	9.6 h	3.35 h

Table 2. *Cont.*

Process	AAO	AAO-SBR
Horizontal sedimentation tank (HST)	3.55 h	/
Sequencing Batch Reactor (SBR1 + SBR2)	/	6.67 h + 6.67 h
Internal reflux (IR)	160–200%	340–400%
Sludge reflux (SR)	60–80%	120–140%

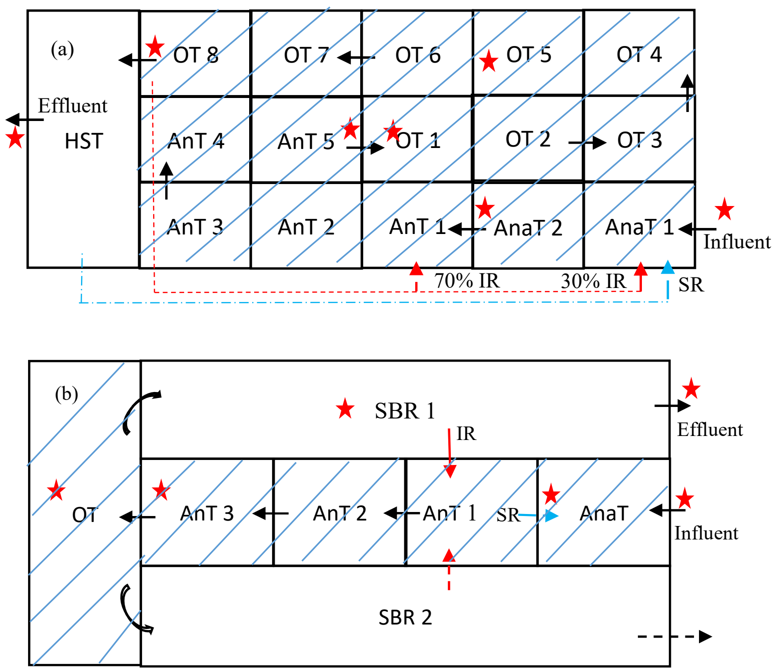

Figure 1. Layouts of the AAO (**a**) and AAO-SBR (**b**) processes in the investigated WWTP. (Note: Shaded area is the odour collection cover; ★ shows the location of the sampling point).

2.2. Sampling and Analysis

The AAO and AAO-SBR processes have 7 and 6 sampling points, respectively, as shown in the star shape in Figure 1. The samples were taken from each group of the AAO and AAO-SBR processes. Some samples were directly determined on-site, whereas the others were analyzed after filtration. The details are shown in Table 3.

Table 3. Sampling points and measured index of the AAO and AAO-SBR processes.

Sample	Index	Note
Influent	COD, SCOD (0.45 μm filtered), BOD_5, NH_4^+-N, NO_3^--N, TN, TP, SS, PO_4^{3-}-P, pH, T	Influent was identical to AAO and AAO-SBR process
End of AnaT	PO_4^{3-}-P, pH, ORP, T	Samples were filtered with 0.45 μm microfiber filter in site to determine NO_3^--N, PO_4^{3-}-P and NH_4^+-N
End of AnT	NO_3^--N, PO_4^{3-}-P, NH_4^+-N, pH, ORP, T	
Front of OT	pH, DO, T	
Middle of OT	NH_4^+-N, PO_4^{3-}-P, pH, DO, T, MLSS, MLVSS	
End of OT #	NH_4^+-N, PO_4^{3-}-P, pH, DO, T	
Effluent *	COD, SCOD (0.45 μm filtered), BOD_5, NO_3^--N, TN, TP, SS	Samples were taken alternately every week from AAO and AAO-SBR process

Note: # Samples were taken from SBR1 after aeration for 1.5 h in the AAO-SBR process; * Samples were taken from SBR1 after precipitating for 1.0 h in the AAO-SBR process.

The whole test, which started on 20 December and ended on 7 March, was conducted for 12 weeks. During this period, the samples were taken every Thursday morning. ORP, pH, T, and DO were determined with a handheld multiparameter meter (YSI

Professional Plus, Yellow Springs, OH, America) at the site. COD and SCOD were determined according to the standard methods of HJ 828-2017; BOD_5 and SS were determined by HJ 505-2009 and GB/T11901-1989; TN, NH_4^+-N, and NO_3^--N were determined by HJ 636-2012, HJ 535-2009, and HJ/T 346-2007, respectively; TP and PO_4^{3-}-P were determined by GB/T11893-89; MLSS and MLVSS were determined by CJ/T221-2005.

3. Results and Discussion

3.1. Overview of the Operating Parameters

The major operating parameters, including temperature, pH, DO, ORP, MLSS, and MLVSS, were monitored during the sampling period. The end temperature of the oxic tank was 1 °C higher than that of the influent in both processes. Moreover, the end temperature of AAO was slightly higher than that of AAO-SBR (Figure 2). These phenomena occurred because of (1) the combined effect of the high-temperature gas from the fine-bubble air-diffusion system and the heat production through biological oxidation, and (2) the role of the covers at the top of the biological tank collects the odour in thermal insulation. Given that the top of the SBR1 and SBR2 tanks had no odour collection covers (Figure 1), the end temperature of the AAO-SBR process, which was lower than that of the AAO process, proved the heat preservation effect of these two processes. The gradual decrease in pH during the process resulted from the influence of the nitrification process and sludge reflux and internal reflux. Moreover, the final pH was lower than that of the influent by approximately 1 unit. The final pH of AAO was lower than that of AAO-SBR because the former had a high nitrification rate (see the variation in N for details). The final pH was higher than 6.5; thus, no inhibitory effect of pH existed at the full-scale municipal WWTP [16].

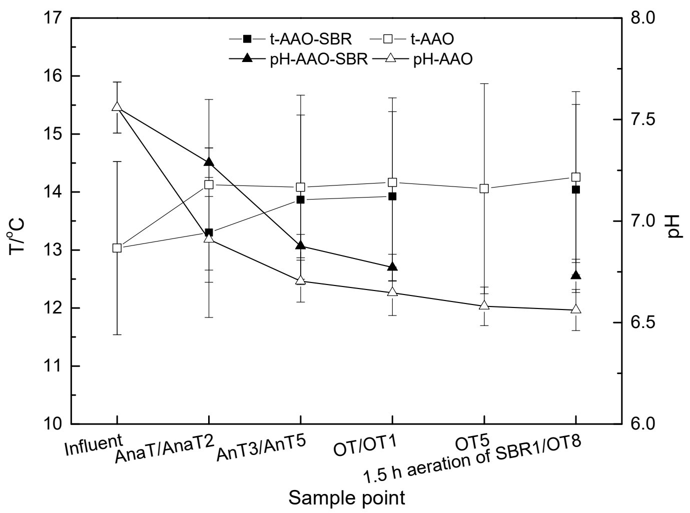

Figure 2. Variations in temperature and pH during the AAO-SBR and AAO operation processes.

The mean ORPs of the anaerobic and anoxic tanks in AAO-SBR were −39.7 mv and −17 mv, respectively, whereas those of the anaerobic and anoxic tanks in AAO were −10 mv and −6.8 mv, respectively (Figure 3). The initial DO of the oxic tank in AAO-SBR and AAO was 1.72 ± 1.22 mg/L (OT) and 2.37 ± 1.26 mg/L (OT1), respectively. These values increased to 3.19 ± 2.37 mg/L (1.5 h aeration of SBR1) and decreased obviously to 0.63 ± 0.28 mg/L (OT8) in the end. Controlling the final DO in the AAO process prevented the influence of internal reflux on the denitrification in the anaerobic tank.

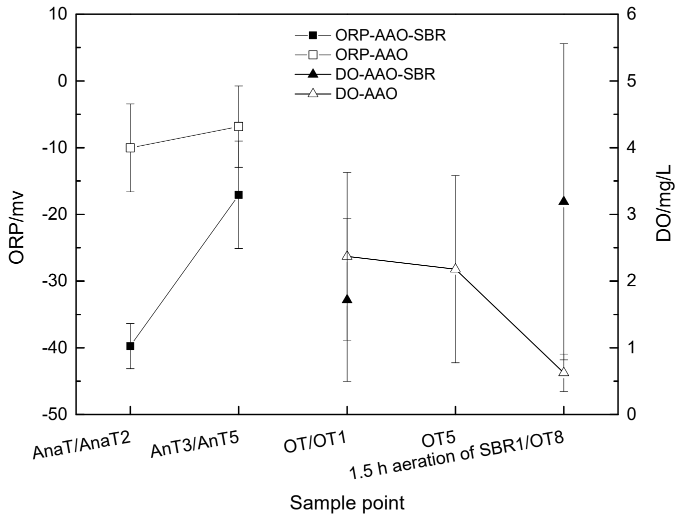

Figure 3. Variations in ORP and DO during the AAO-SBR and AAO operation processes.

The MLSS and MLVSS concentrations of both processes were kept relatively high (Table 4) during the sampling period to maintain the treatment effect of WWTP when the water temperature was lower than 15 °C. The MLSS and MLVSS of the AAO-SBR process were considerably higher than those of the AAO process because the sludge return ratio of the former was larger than that of the latter. Nevertheless, the MLVSS/MLSS ratios of both processes, 0.67 ± 0.03 and 0.65 ± 0.04, respectively, were nearly the same, indicating that the ratio of MLVSS/MLSS was mainly related to the influent characteristics and had little correlation with the treatment process [14].

Table 4. MLSS and MLVSS of the middle of the oxic tank in the AAO-SBR and AAO processes.

Process	MLSS (mg/L)	MLVSS (mg/L)	MLVSS/MLSS
AAO-SBR	7848.2 ± 1534.2	5222.9 ± 1013.1	0.67 ± 0.03
AAO	4806.7 ± 664.1	3116.7 ± 378.1	0.65 ± 0.04

3.2. Overall Treatment Effect of WWTP

During the sampling period, the specific group's average wastewater treatment capacity of the AAO and AAO-SBR processes were 3.75 ± 0.20 × 10^4 m^3/d and 2.72 ± 0.26 × 10^4 m^3/d, respectively. The former exceeded 25% of its design capacity, whereas the latter was lower than 9.3% of its design capacity.

The influent COD, BOD_5, TN, TP, and SS were all higher than the design value; however, the effluent of both processes met the discharge standard, except for the effluent TP of the AAO process (Figure 4). Moreover, the removal efficiencies of influent COD, BOD_5, TN, TP, and SS were more than 94%, 97%, 85%, 91%, and 96%, respectively. Henze [18] indicated that the actual COD/N ratio should be 5.0–10.0 gCOD/gN if high nitrogen removal efficiency is needed, while Carrera et al. [19] found that the optimum influent COD/P ratio was between 41 and 48 for simultaneous nitrogen and phosphorus removal. The influent ratios of COD/TN and COD/TP in this investigated WWTP were 8.5 and 71.9, which were higher than 5.0 and 41, respectively; therefore, high removal efficiencies of TN and TP could be achieved simultaneously. The treatment effects of both processes on COD and TN removal could be compared by calculating the sludge loads of COD and TN as 0.24 and 0.12 kgCOD/(kgMLVSS•d) and 0.027 and 0.013 kgTN/(kgMLVSS•d), respectively, based on the following. (1) The MLVSS concentration in the anaerobic and anoxic tanks in the respective processes is equal to that in oxic tanks (the actual detection results showed that the MLVSS concentration was equal, mainly because of the influence of sludge reflux and internal reflux). (2) The actual HRT of the oxic tank in the AAO-SBR process was calculated as 3.55 + 6.67 h. The sludge load of the AAO process was higher than that of

AAO-SBR. However, the effluent of COD and TN was better, indicating that the AAO process had a large potential treatment capacity. In comparison, the removal effect of AAO-SBR on TP during the sampling test was better than that of AAO. Different TP removal rates might result from the different ORPs in the anaerobic tank (Figure 3) and the influence of IR on the anaerobic tank in AAO (Figure 1). The influent SCOD/COD and BOD_5/COD were approximately 0.45 and 0.53, but the effluent of SCOD/COD and BOD_5/COD were more than 0.80 and lower than 0.26, respectively. This finding indicates that the easily biodegradable substances in the influent were completely degraded by both processes.

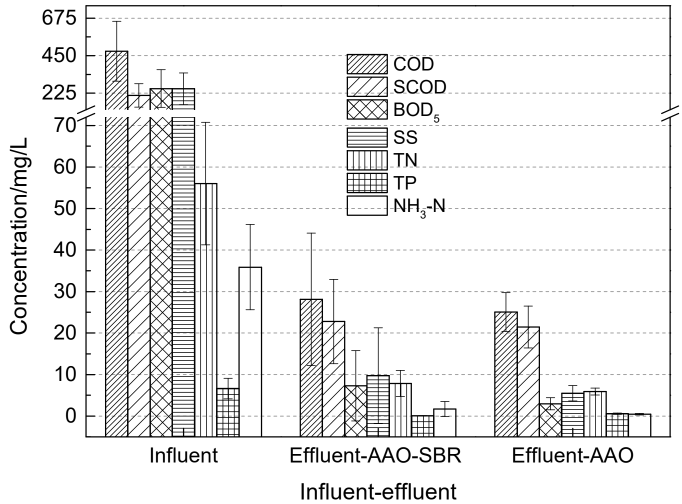

Figure 4. Treatment effects of AAO and AAO-SBR during the sampling test.

3.3. Variation in N and P during the Operation Process

As shown in Figure 5, the NH_3-N concentration gradually decreased during the operation processes because of the influence of degradation and sludge reflux and internal reflux. In the AAO process, the nitrification of NH_3-N was nearly realized in the middle section of the oxic tank (OT5). Moreover, the NH_3-N concentration was only 1.05 ± 1.02 mg/L, and finally reduced to 0.41 ± 0.19 mg/L in the end (OT8). However, the NH_3-N concentration of 1.72 ± 1.98 mg/L remained after 1.5 h aeration of SBR1. A larger standard deviation implied obvious fluctuation. The nitrification effect of the AAO-SBR process was worse than that of the AAO process because of the difference in their nitrification rates, which were 0.59 and 1.48 mgNH_3-N/(gVSS•h), respectively. Although the internal reflux ratio of AAO-SBR was higher than that of AAO (Table 2), the denitrification rate of AAO-SBR at 1.31 mgNO_3^--N/(gVSS•h) was also lower than that of AAO at 2.15 mgNO_3^--N/(gVSS•h). According to the above results, the nitrification and denitrification capacities of AAO-SBR must be strengthened by prolonging the HRT of oxic and anoxic tanks or increasing the aeration intensity in the oxic tank to enhance the TN removal efficiency. In addition, the ratio of the sum of NH_3-N and NO_3^--N to TN effluent was approximately 90%, illustrating that the dominant component of TN in the effluent was NO_3^--N, which was followed by NH_3-N. These results showed that although the water temperature was lower than 15 °C, the nitrification and denitrification effects of both processes were not greatly affected; this finding was confirmed by Komorowska–Kaufman et al. [20]. However, the nitrification rates of both processes were lower than that reported in the literature [13], which might result from the high influent COD/N. This finding was confirmed by Payraudeau et al. [21], who observed that temperature-induced reductions of nitrification capacity occurred at the temperature below 14 °C only when the nitrifying was subject to high C/N loads.

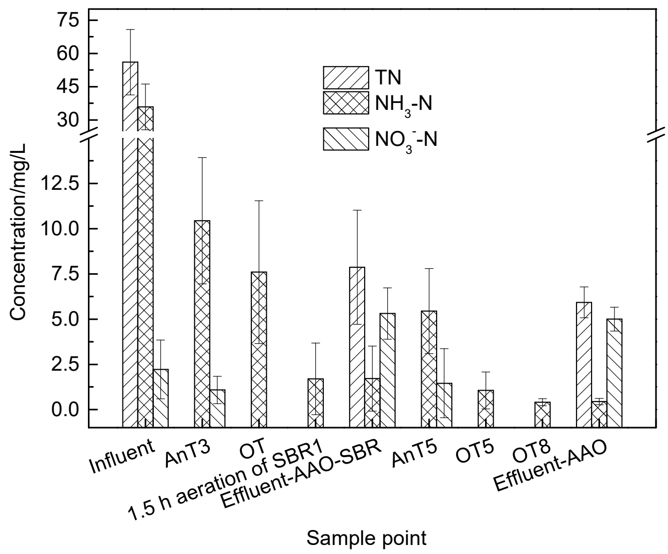

Figure 5. Variations in N during the AAO and AAO-SBR processes in the sampling test.

Unlike the variation in NH_3-N, the concentration of PO_4^{3-}-P increased substantially in the anaerobic tank in the AAO-SBR process and then decreased gradually (Figure 6), indicating that the anaerobic phosphorus release in the AAO-SBR process was apparent. In the AAO process, the PO_4^{3-}-P concentration gradually decreased during the operation process. Moreover, a light phosphorus release occurred in the anaerobic tank due to the influence of higher nitrate concentration from the internal reflux [11], resulting in insufficient phosphorus absorption capacity in the subsequent aerobic tank. Therefore, the final effluent TP of AAO was higher than that of AAO-SBR. Nevertheless, the phosphorus removal efficiency of AAO reached 91%. In comparison, the phosphorus removal efficiency of AAO-SBR reached 96%, which was higher than that of the AAO-SBSPR process [8] and close to that of STH-SBR [9]. A balance between nitrogen and phosphorus removal during the operation of both processes and the variation in N must be determined. In particular, the removal of nitrogen or phosphorus should be selectively strengthened according to the characteristics of the subsequent advanced treatment process. For example, if the AAO process follows a chemical phosphorus removal process, we can return part of the mixed liquid to an anaerobic tank to enhance the denitrification, as in the case of the investigated AAO process in the present study, to improve the biological nitrogen removal.

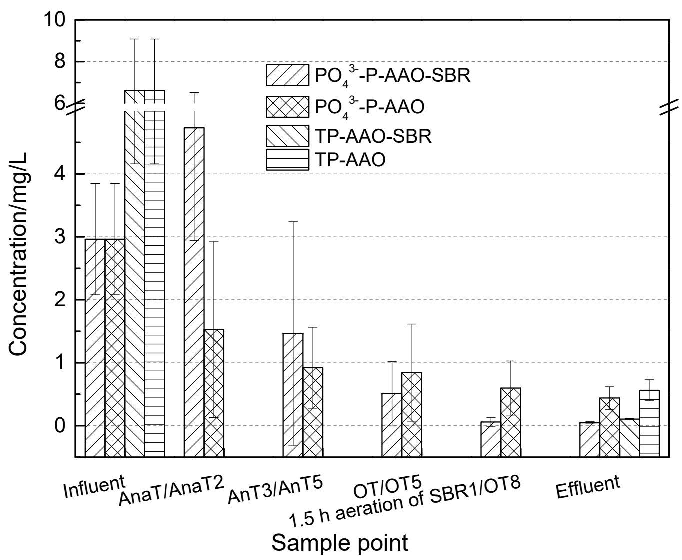

Figure 6. Variations in P during the AAO and AAO-SBR processes in the sampling test.

4. Conclusions

The AAO-SBR and AAO processes could still obtain a good treatment effect when the water temperature was lower than 15 °C. Moreover, the removal efficiencies of COD, BOD_5, TN, and TP were more than 94%, 97%, 85%, and 91%, respectively. However, the AAO process had a large potential treatment capacity. The anaerobic phosphorus release of the AAO process was affected when part of the internal reflux entered the anaerobic tank, thereby resulting in poor biological phosphorus removal. Nevertheless, the AAO process had a high TN removal of 89.4%, indicating that the AAO process could meet the requirements of nitrogen or phosphorus removal by adjusting the operation mode. The nitrification and denitrification rates of the AAO-SBR process were lower than those of the AAO process. According to these results, suggestions for enhancing the nutrient removal performance for both processes could be given as follows.

(1) In the AAO process, the proportion of the internal reflux entering the anaerobic tank should be reduced or stopped the internal reflux, in order to improve the phosphorus release in the anaerobic tank; submerged propeller mixers might be used instead of aerators at the oxic end to control DO at about 0.5 mg/L, so as to further reduce the impact of internal reflux on the anaerobic tank and anoxic tank.

(2) The HRT of the oxic tank should be prolonged to about 6.0 h, or high aeration intensity of the oxic tank and SBR tank is needed to strengthen its nitrification ability; meanwhile, a long HRT of the anoxic tank might be needed too to strengthen its denitrification ability in the AAO-SBR process.

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