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# Enhanced biological nutrient removal in modified carbon source division anaerobic anoxic oxic process with return activated sludge pre-concentration☆

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ABSTRACT

A pilot-scale modified carbon source division anaerobic anoxic oxic (AAO) process with pre-concentration of returned activated sludge (RAS) was proposed in this study for the enhanced biological nutrient removal (BNR) of municipal wastewater with limited carbon source. The influent carbon source was fed in step while a novel RAS pre-concentration tank was adopted to improve BNR efficiency, and the effects of an influent carbon source distribution ratio and a RAS pre-concentration ratio were investigated. The results show that the removal efficiency of TN is mainly influenced by the carbon source distribution ratio while the TP removal relies on the RAS pre-concentration ratio. The optimum carbon source distribution ratio and RAS pre-concentration ratio are 60% and 50%, respectively, with an inner recycling ratio of 100% under the optimum steady operation of pilot test, reaching an average effluent TN concentration of 9.8 $mg \cdot L^{-1}$ with a removal efficiency of 63% and an average TP removal efficiency of 94%. The mechanism of nutrient removal is discussed and the kinetics is analyzed. The results reveal that the optimal carbon source distribution ratio provides sufficient denitrifying carbon source to each anoxic phase, reducing nitrate accumulation while the RAS pre-concentration ratio improves the condition of anaerobic zone to ensure the phosphorus release due to less nitrate in the returned sludge. Therefore, nitrifying bacteria, denitrifying bacteria and phosphorus accumulation organisms play an important role under the optimum condition, enhancing the performance of nutrient removal in this test.


## 1. Introduction

To prevent the eutrophication in enclosed water system and meet increasingly stringent effluent discharge standards, the upgrade of existing wastewater treatment plants (WWTPs) with biological nitrogen and phosphorus removal has been extensively investigated and developed [1–3]. For the nutrient removal of municipal wastewater, especially with low carbon source available in most of southern China, it is significant to select the optimal BNR process and optimize the influent carbon source. The two points are the research focus and some modified BNR processes based on the conventional activated sludge process have been developed, including anaerobic/anoxic/oxic (AAO) and oxidation ditch. The results show that deep nitrogen removal and optimal phosphorus removal are achieved [4–7].

Due to extensive use of AAO process in municipal wastewater treatment, more researches have been carried out to obtain simultaneous nitrogen and phosphorus removal [8–10]. Two strategies are usually employed in the modified AAO process: using the carbon source to a better extent and improving the situation to mitigate the competition of available organic substrates between denitrifiers and phosphorus accumulation organisms (PAOs). The optimal utilization of carbon source and advanced nitrogen removal has been achieved with step feeding in two, three and four stages [10–12]. Wang *et al.* have indicated that the modified step-feeding anaerobic/anoxic/oxic nutrient removal system ($SFA^2/O$) is a technically feasible and economically favorable process for simultaneous nitrogen and phosphorus removal from municipal wastewater without external carbon source [13]. In this process, the optimization of feeding ratio is a key issue to make use of available organic substrate for nitrogen and phosphorus removal. Moreover, it is well known that the remaining $NO_3^-$-N brought by the returned activated sludge (RAS) can change the anaerobic zone to an anoxic zone, inhibiting the biological phosphorus removal process [14,15]. The remaining nitrate in the anaerobic zone leads to a competition for available carbon source between denitrifiers and PAOs, deteriorating

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significantly the anaerobic phosphorus release and reducing the phosphorus removal in the enhanced biological phosphorus removal system [16–18]. Chang and Hao [19] observed that phosphorus removal efficiency increased with the reduction of nitrate content in effluent. Kazmi *et al.* [20] modeled the remaining $NO_3^-$-N shock on phosphorus removal and demonstrated that the phosphorus release was low in the anaerobic zone and TP content was higher in the effluent with the increase of the remaining $NO_3^-$-N concentration. Zou *et al.* [21] found that anaerobic phosphorus release rate declined as soon as $NO_3^-$-N was added to the anaerobic zone, resulting in low phosphorus removal efficiency. Peng *et al.* [22] showed that TP removal efficiency of 80% could be achieved when the content of remaining $NO_3^-$-N was below 6 $mg \cdot L^{-1}$. These researches indicate that the remaining $NO_3^-$-N in the RAS will deteriorate biological phosphorus removal. However, some studies have verified that in the absence of exogenous carbon sources in the anaerobic zone, phosphorus removal may occur in the presence of nitrate [23–26]. In addition, anoxic denitrifying phosphorus removal technology, depending on the denitrifying phosphate-accumulating organisms, can potentially save external carbon source and energy and achieve better phosphorus removal [18,27–29]. Denitrifying phosphorus removal has been verified to be beneficial to enhance simultaneous nitrogen and phosphorus removal in $SFA^2$/O system [30].

Some novel and modified step feeding processes have been developed to enhance nitrogen or phosphorus removal capability and meet satisfactory effluent quality [31,32]. However, previous studies on the step feeding process are mainly conducted with synthetic wastewater and focus on nitrogen removal performance. Although $SFA^2$/O system has been employed in a pilot scale for nitrogen and phosphorus removal, stable nutrient removal and real-time control need to be strengthened, especially when applied to full-scale municipal WWTPs.

The previous study of our research team shows that pre-concentration of RAS will significantly improve the phosphorus removal efficiency, where the ratio of returned flow of a pre-concentration tank and a RAS flow of secondary clarifier ($\eta$) plays an important role [33]. In this study, a pre-anoxic tank is introduced before the anaerobic tank, followed by two stages of anoxic/oxidation (A/O) for part nitrogen removal and elimination of the effect of $NO_3^-$-N in returned liquid to the following anaerobic zone for a strict anaerobic condition. Besides, a pre-concentration tank is introduced to concentrate the RAS before it returns to the pre-anoxic tank to reduce the dilution effect of influent carbon source and mainly mitigate the competition of denitrifying bacteria with PAOs for available organic carbon substrate for better phosphorus release. Moreover, the RAS pre-concentration tank will enhance the $NO_3^-$-N removal efficiency in the pre-anoxic zone. The objective of this study is to examine the technical feasibility of simultaneous nitrogen and phosphorus removal at different carbon source distribution ratios ($\lambda$) and RAS pre-concentration ratios ($\eta$) with a modified AAO process in a pilot scale. The effects of carbon source distribution and RAS pre-concentration on nitrogen and phosphorus removal efficiency are studied, and their optimum values are determined. Furthermore, the mechanism of nitrogen and phosphorus removal is discussed. The removal rates of nitrogen and phosphorus are determined under the optimal operation condition. Finally, some fundamental data are provided to the design of full-scale WWTPs to enhance BNR with this modified AAO system.

## 2. Materials and Methods

### 2.1. Experimental set-up and operational conditions

Fig. 1 shows a pilot-scale modified AAO system, which consist of a pre-anoxic zone (1.1 $m^3$) and an anaerobic zone (3.0 $m^3$) followed by two identical pairs of anoxic [1.6 $m^3 \cdot (1.6\ m^3)^{-1}$] and aerobic zones [3.2 $m^3 \cdot (2.1\ m^3)^{-1}$] in series. A secondary clarifier was arranged at the end of the process and a pre-concentration tank was for concentrating RAS. The influent of 2 $m^3 \cdot h^{-1}$ was pumped into the anaerobic zone with hydraulic retention time (HRT) of 0.5 and 1.5 h. The effluent of anaerobic zone was divided into two parts: one part flowing into the first anoxic chamber and the rest by-passing to the secondary anoxic chamber directly with a ratio defined as distribution ratio ($\lambda$) in this study. The following two stages of anoxic/aerobic (A/O) were with HRT of 1.5, 3.0, 1.5 and 2.0 h in sequence followed by the secondary clarifier with HRT of 2.5 h. The RAS from the secondary clarifier was pumped back to the pre-thickener for sludge pre-thickening. Then the pre-thickened RAS was pumped into the pre-anoxic zone for eliminating $NO_3$-N by endogenous denitrification, while the supernatant generated in the pre-concentration zone flowed back to the second stage of aerobic zone by gravity, as the returned thickened sludge from pre-thickener is less than the RAS from secondary clarifier. Mixed liquid was pumped from the secondary aerobic zone to the first anoxic zone as the internal recycle. Several mechanical stirrers were equipped in pre-anoxic, anaerobic and anoxic zones separately to ensure complete mixing of sludge and wastewater. Two sets of fine bubble air diffusers were installed at the bottom of two aerobic zones to supply oxygen. DO probe was placed in the aerobic zones and DO concentrations were controlled automatically at the preselected set point (~1.5 $mg \cdot L^{-1}$). The sludge retention time was maintained at 15 d by controlling sludge wastage. The resulting mixed liquor suspended solid (MLSS) concentration was in the range of 3700–4000 $mg \cdot L^{-1}$. The sludge recycle ratio was constantly set at 0.75. DO, pH, ORP, MLSS and flow rate were all measured on-line. A RAS pump and a pre-concentrated RAS pump were controlled by PLC. The experiment was carried out from February 2011 to August 2011 (182 d). All the experiments were conducted at temperature 19–25 °C. Each run lasted for at least 30 days.

### 2.2. Sludge and wastewater characteristics

The pilot-scale reactor was installed in Longwangzui WWTP (150000 $m^3 \cdot d^{-1}$) with AAO process in Wuhan, China. The reactor was operated for about one year. The seed sludge was taken from the aerobic tank of a full-scale WWTP. After one month of acclimation periods, the process was stable and experiments were carried out.

The influent fed to the reactor was fetched from the grid removal tank of WWTP by influent pump. The MLSS in the pilot reactor were controlled to (3500 ± 500) $mg \cdot L^{-1}$. The major characteristics of the influent with limited carbon source are shown in Table 1.

### 2.3. Batch tests

To evaluate the sludge performance of nitrification, denitrification, phosphorous release and uptake, batch tests were carried out. For nitrification, the activated sludge of aerobic phase of pilot system was transferred to a 12 L Sequencing Batch Reactor (SBR) reactor. $NH_4Cl$ was fed to maintain the initial $NH_4$-$N^+$ concentration at 30 $mg \cdot L^{-1}$. Air was supplied to keep the DO of mixed liquid at 2–3 $mg \cdot L^{-1}$ and samples were taken to analyze $NO_2^-$-N and $NO_3^-$-N at 10 min interval. For denitrification, anoxic sludge was transferred to a 12 L SBR reactor, then NaAc and $KNO_3$ was fed to obtain initial COD and $NO_3^-$-N concentrations of 250 and 30 $mg \cdot L^{-1}$, respectively. DO was controlled under 0.2 $mg \cdot L^{-1}$ and samples were taken with 10 min interval. For endogenous denitrification, the sludge of pre-concentration tank was transferred to a 12 L SBR reactor and $KNO_3$ was fed to obtain the initial $NO_3^-$-N concentrations of 30 $mg \cdot L^{-1}$. DO was controlled under 0.2 $mg \cdot L^{-1}$ and samples were taken with 20 min interval.

To investigate phosphorous release and uptake, the anaerobic sludge of pilot system was transferred to a 12 L SBR reactor. NaAc and $K_2HPO_4$ were fed to obtain the initial COD and $PO_4^{3-}$-P concentrations of 100 and 4 $mg \cdot L^{-1}$, respectively. The mixed liquid was