



# A novel AAO-SBSPR process based on phosphorus mass balance for nutrient removal and phosphorus recovery from municipal wastewater

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## ABSTRACT

A novel AAO-SBSPR (Anaerobic-Anoxic-Oxic/Sequencing Batch Sidestream Phosphorus Recovery) process was developed for phosphorus (P) recovery and nutrient removal from municipal wastewater. Meanwhile, an operational strategy based on the P mass balance for the process was proposed, where P recovery rate was coupled with sludge retention time (SRT) so as to reduce the impact of P recovery on P content in activated sludge and maintain a stable operation of the process. The results show that the proposed operational strategy is helpful for the stable operation of the AAO-SBSPR process and up to 65% of the influent P was recovered with the phosphate removal efficiency of 99.1%. Both P recovery and extended SRT had limited influence on the P release and uptake rates of polyphosphate accumulating organisms (PAOs). The results of high-throughput sequencing analysis indicated that the relative abundance of *Accumulibacter* increased while SRT was extended under high P recovery rate. Moreover, significant promotion of simultaneous nitrogen removal and P uptake was observed, where the ratio of anoxic P uptake to the total P uptake of the whole process increased from 41.7% in the AAO process to 77.5% in the AAO-SBSPR process, combined with the increase of total nitrogen (TN) removal efficiency from 71.9% to 80.4%. The P recovery process is also beneficial for the reduction of sludge production and nitrification process as SRT was extended for high P recovery rate. Overall, the AAO-SBSPR process together with the operational strategy proposed in this study provides a promising and practical alternative for P recovery from municipal wastewater.

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## 1. Introduction

Phosphorus (P) is a nonmetal of the nitrogen group, which is essential to all life on the earth. It is widely used as a raw material in many areas including household applications and agricultural applications (accounting for 95% of the global phosphate production) such as fertilizer industry to increase the crop yield, phosphorus-based pesticide and animal feed supplements (Cisse and Mrabet, 2004; Desmidt et al., 2015). However, it was reported that the economically available phosphate mineral reserves can only be maintained for 30 years, after which the global demand for

phosphate will exceed supply and lead to global P scarcity (Cordell et al., 2009). On the other hand, the presence of P in natural water bodies has a great impact on aquatic ecosystems. Excessive P can lead to eutrophication of water bodies, resulting in a sharp drop in biodiversity in the water and contamination of drinking water sources. Therefore, to protect the water bodies from P induced pollution, techniques such as chemical precipitation and enhanced biological phosphorus removal (EBPR) have been used in wastewater treatment plant (WWTP) to remove P.

Meanwhile, approximately 10–20% of the total global P demand could be satisfied if the P was recovered from municipal wastewater (Yuan et al., 2012). Basically, there are two ways to recover P from the municipal WWTPs with nutrient removal. One way focuses on recovering P from the sludge line after the anaerobic digestion and the other way recovers P from the wastewater treatment line. In general, as approximately 90–95% of the influent

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P load is finally incorporated into the sludge, the potential of P recovery from sludge or sewage sludge ash is higher than that from water line whose maximum P recovery potential ranged in 50–70% (Levlin and Hultman, 2003; Cordell et al., 2009; Petzet and Cornel, 2011). However, the methods for recovering P from sludge line have some disadvantages such as the uncontrolled precipitation of struvite inside the anaerobic digester. Besides, the presence of calcium and/or magnesium ions as well as the silicate hinder the transition of P from the solid phase to the liquid phase (Wild et al., 1996). These problems result in a large variation of P recovery rate (0–75%) from the sludge line (Strickland, 1999; Petzet and Cornel, 2011), whereas the P recovery rate from the wastewater treatment line is stable, which is around 60%–70% according to Levlin and Hultman. (2003). Furthermore, the cost of recovering P from water line is almost half of that from the sludge line (Strickland, 1999; Balmer, 2004; Cordell et al., 2009). Therefore, recovering P from water line is considered to be a more economical strategy, and it could be easily implemented in the municipal WWTP if well designed.

One option to recover P from the water line is to generate P-rich supernatant using sidestream treatment. The sidestream treatment often affiliates to EBPR process in municipal WWTPs. The main mechanism of EBPR process is to enrich P into the biomass as polyphosphate (poly-P) by polyphosphate accumulating organisms (PAOs), where the P content in activated sludge could reach up to 5–7% in a full-scale WWTP (Metcalf, Eddy, Tchobanoglous, Burton, & Stensel, 2003). The P concentrated solution can be acquired by sidestream treatment where an anaerobic condition is usually provided to release P from biomass to the liquid phase. In recent years, many of such recovery processes have been reported (Levlin & Hultman, 2003; Cordell et al., 2009; Desmidt et al., 2015). These processes may include the conventional EBPR processes such as University of Capetown (UCT) and Anaerobic-Anoxic-Oxic (AAO) as the mainstream process to enrich P in biomass and the P-rich supernatant is generated either by sidestream treatment or directly diverged from the anaerobic tank of the mainstream processes (Levlin and Hultman, 2003). However, regardless of various configurations of the P recovery processes, many researchers had found that there is a negative correlation between P recovery rate and the P content in activated sludge (Xia et al., 2014; Lv et al., 2014; Acevedo et al., 2015), which is contrary to the stable operation of the mainstream EBPR systems. Excessive extraction of P may lead to the depletion of the poly-P in biomass, which is an important energy source for PAOs and an indicator of the performance of EBPR systems (Henze et al., 2008). Consequently, deterioration of the EBPR systems may occur due to the proliferation of glycogen accumulating organisms (GAOs) (Lv et al., 2014). Moreover, as reported by Barat and van Loosdrecht. (2006), excessive extraction of P may also be detrimental to the nitrification process in the mainstream system. Therefore, a balance between P recovery rate and the stable operation of the mainstream EBPR process should be explored.

In this study, a novel AAO-SBSPR (Anaerobic-anoxic-oxic/sequencing batch sidestream phosphorus recovery) process was proposed, in which a conventional AAO mainstream line was coupled with a sidestream P recovery line. The sidestream P recovery process was operated in a batch mode. The AAO-SBSPR process was designed based on P mass balance strategy with consideration of P recovery rate, SRT and the P content in activated sludge. At high P recovery rate, in order to alleviate the conflict between the P extraction and P content in sludge, the SRT of the P recovery process was extended to reduce the loss of P from the system. Several operation modes were applied to evaluate the feasibility of the proposed operational strategy and the P mass balance equation was validated by the experimental data acquired

from those operation modes. The performance of the P recovery and nutrient removal for each operation mode, as well as the microbial community, were also investigated. The aim of this research is to demonstrate the applicability of the novel AAO-SBSPR process based on the proposed operational strategy at a laboratory scale and to provide a new perspective on the transition of municipal WWTP from traditional biological nutrient removal process into a nutrient recovery process.

## 2. Materials and methods

### 2.1. Wastewater

The composition of the synthetic municipal wastewater fed to the AAO and AAO-SBSPR processes were as follows: 150 mg/L sodium acetate (117 mgCOD/L), 50 mg/L glucose (53 mgCOD/L), 150 mg/L peptone (approximately provide 170 mgCOD/L and 25 mgN/L), 90 mg/L  $\text{NH}_4\text{Cl}$  (23 mgN/L), 31 mg/L  $\text{KH}_2\text{PO}_4$  (7 mgP/L), 123 mg/L  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ , 125 mg/L  $\text{CaCl}_2$  and 1.0 mL mineral medium solution. The details of the medium can be found in Smolders et al. (1994). The synthetic wastewater was maintained between pH 7–8 by adding  $\text{NaHCO}_3$ . Influent COD, TN, TP and  $\text{NH}_4^+-\text{N}$  concentrations are presented in Table 1.

### 2.2. Operation of the AAO and AAO-SBSPR processes

Fig. 1 shows the configuration of the AAO-SBSPR process. The process consisted of two parts: the mainstream AAO reactor for nutrient removal and sidestream sequencing batch reactors (SBR) for P recovery. During the operation of the process, part of the sludge in the secondary clarifier was pumped into the sidestream P release reactor (PRR), and in the meantime, part of the influent was also diverged into the PRR to provide the carbon source for P release under anaerobic conditions. After P was released to the liquid phase, the sludge was allowed to settle to obtain the P enriched supernatant, which was then pumped to the chemical precipitation reactor where P was recovered by adding  $\text{Ca}(\text{OH})_2$ . The settled sludge was recycled back to the anoxic tank of the AAO reactor. The supernatant of the chemical precipitation reactor after P recovery was pumped back to the influent of the AAO reactor to further remove the residual COD, nitrogen (N) and other contaminants.

Three lab-scale parallel AAO-SBSPR systems were set up in this study. The working volume of the AAO reactor was 10 L. The volume ratio of the anaerobic, anoxic and aerobic tanks was 1:1:3. The volume of the secondary clarifier was 4 L. The total volume of PRR was 5 L. PRR was operated in sequencing batch mode with a 24-h cycle per day: sludge filling period 2.5 h; wastewater filling period 0.5 h (providing COD for P release); anaerobic reaction period (with stirring) 3 h; settling period 3 h; supernatant decanting period 0.5 h; sludge recycling period 2.5 h; idle period 12 h. The total influent flowrate to either the AAO or the AAO-SBSPR process was kept at 20 L/d, with the hydraulic retention time (HRT) of 12 h for the AAO reactor. The internal recycle rate and sludge recycle rate of the AAO system were 300% and 80% of the influent flowrate, respectively. The DO concentration in the aerobic tank of the AAO reactor ranged from 1.5 to 2.5 mg/L. The three parallel systems were first operated in conventional AAO configuration without sidestream P recovery module. The seed activated sludge was obtained from a full-scale municipal WWTP in Shanghai. When the stable performance of N and P removal was achieved, the P recovery sidestream module was integrated into the AAO mainstream line and the system was operated as the AAO-SBSPR configuration mode. The excess sludge was discharged from the systems by discarding a certain amount of mixed liquor from the aerobic tank either in the AAO process or in the AAO-SBSPR process. For the

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