



# Effects of side-stream, low temperature phosphorus recovery on the performance of anaerobic/anoxic/oxic systems integrated with sludge pretreatment

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## HIGHLIGHTS

- Sustainable removal of P and controlling the excess sludge production.
- Reduction of sludge production (28%) can be obtained.
- No significant accumulation of inorganic substances was observed.

## ARTICLE INFO

### Article history:

Received 5 February 2013

Received in revised form 15 April 2013

Accepted 16 April 2013

Available online 29 April 2013

### Keywords:

Selective P removal

Anaerobic/anoxic/oxic reactor

Biological nutrient removal

Sludge reduction

Sustainable nutrient removal

## ABSTRACT

Introduction of sludge reduction practices in enhanced biological phosphate removal (EBPR) often leads to a decrease in phosphorous (P) removal efficiency. In this study, an attempt has been made to develop sustainable P removal in an anaerobic/anoxic/oxic (AAO) system integrated with sludge reduction by incorporating side-stream P recovery. Two AAO reactors, one acting as a control (CAAO) and the other as an experimental system (EAAO), were used in our experiment. The average P solubilisation efficiency and its recovery from thermally pre-treated sludge were found to be 28% and 99%, respectively. The P recovery process prevented the biomass in the EAAO system from reaching its threshold level and resulted in sustainable P removal throughout the study period. Thermochemical pre-treatment, at a rate of 1.5% Q in the EAAO reactor, was responsible for a 28% reduction in the amount of sludge produced. The yield observed ( $Y_{obs}$ ) values for the system with and without pre-treatment were found to be 0.28 and 0.22 kg MLSS/kg COD, respectively. An initial 50 days of reactor operation was utilised to stabilise the systems (Phase 1). The total nitrogen removal during Phase 2 (51–225 days) was slightly higher than that in Phase 1 (76–80% and 68–75%, respectively). The MLSS/MLVSS ratios of both systems were identical and were between 78% and 83% for both the CAAO and EAAO. The effluent COD concentration was not significantly affected by the proposed method of treatment. From the results of the present study, it is concluded that the proposed mode of treatment was capable of both sustainable removal of P and control of excess sludge production.

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## 1. Introduction

The most commonly used process for nutrient removal is a single-sludge suspended-growth system incorporating anaerobic, anoxic and aerobic stages (AAO) in sequence (Ma et al., 2005; Vaipoulou and Aivasidis, 2008). AAO systems favour the growth of phosphorous-accumulating organisms (PAO) and are responsible for phosphorous (P) removal. PAOs absorb phosphorous, resulting in P removal from the AAO system. The P concentration in normal

activated sludge systems ranges from 2–3%, whereas it ranges from 10–12% in enhanced biological phosphorus removal (EBPR) systems (Metcalf and Eddy, 2003). Thus, P removal in EBPR processes is achieved by PAO uptake of P and the wasting of P-rich biomass (Mulkerrins et al., 2004). Integration of sludge pre-treatment with aerobic biological treatment systems is an interesting approach for controlling excess sludge production. Pre-treatment of sludge enhances its biodegradability and subsequent biodegradation, which requires more energy per volume of sludge treated. By integrating these two steps into a single system, biodegradation occurs with less energy use, saving a considerable amount of energy (Young et al., 2007). The integration of sludge reduction methods also

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reduces the amount of wasted sludge (Yoon and Kim, 2004). The major disadvantage of the integrated method is that it reduces the amount of P wasted through excess sludge removal, which leads to a decrease in the P removal efficiency of the system. This problem can be overcome by side-stream removal of P. It requires the solubilisation of biomass-bound P into soluble P, and can be achieved by various methods. However, these methods typically convert polyphosphate (poly P) into inorganic phosphate, and the recovery of inorganic P is difficult. In addition, extreme pre-treatment processes also generate soluble organics, which hinder the selective removal of P. It has been reported that the negative aspects of P recovery can be overcome by precipitating phosphorous in the presence of poly P (Kuroda et al., 2002; Banu et al., 2012).

Among the various disintegration techniques used, thermochemical hydrolysis using sodium hydroxide has been found to be the most efficient at inducing cell lysis (Uma Rani et al., 2012a). When compared with other pre-treatment methods, alkaline treatment proved to be efficient because of the use of a simple device, convenient operation, and high efficiency (Kim et al., 2003; Uma Rani et al., 2012b). During alkaline treatment, floc structures and cell walls are destroyed by hydroxyl anions. Due to the extremely high pH, the proteins lose their natural shape, and saponification of lipids and hydrolysis of RNA takes place. Chemical degradation and ionisation of the hydroxyl groups lead to extensive swelling and subsequent solubilisation of gels in the sludge (Neyens et al., 2003). After the destruction of extracellular polymer substances (EPS), the cell walls are exposed to a high pH. Because the cells are unable to withstand the resulting turgor pressure, they collapse and intracellular substances are released (Apples et al., 2010). Thermal pre-treatment was studied using a wide range of temperatures (60–270 °C). Temperatures over 200 °C have been found to be responsible for formation of refractory compounds (Muller, 2000). The most common treatment temperatures are reported to be between 60 °C and 180 °C. Treatments applied at temperatures below 100 °C are considered low-temperature thermal treatments (Gavala et al., 2003).

In the present study, a new, advanced wastewater treatment process is developed for sustainable nutrient removal and sludge reduction in mainstream AAO reactors by integrating the reactors with a side-stream sludge treatment process. Three steps are involved in the process. Step I aims to release P in the form of condensed P to aid subsequent selective P recovery and to maintain sustainable P uptake in mainstream reactor. During step II, lime is used to recover the released P. Lime is preferred over other coagulants because it can act as a buffering agent in the nitrification tank (Banu et al., 2009) and induce disintegration (Banu et al., 2011a). In step III, the sludge is pretreated thermochemically to enable disintegration. The disintegrated sludge is amenable to biodegradation and is recycled back into the reactor for sludge reduction. The experimental data obtained during 225 days of reactor operation were used to evaluate and compare the performance of this integrated system with a control system operating under the same conditions.

## 2. Methods

### 2.1. Reactors

The experimental system consisted of two AAO reactors with a total working volume of 10 L each. One was designated the control reactor and the other was designated the experimental reactor. Simulated domestic wastewater was used as the feed and was pumped into the system at a flow rate ( $Q$ ) of 21.6 L day<sup>-1</sup> using a peristaltic pump. The hydraulic retention times (HRTs) of the anaerobic, anoxic and aerobic basins were 1.6, 4.2, and 5.3 h,

respectively. To facilitate nitrogen removal, the reactor was provided with an internal recycle (IR) between the aerobic and anoxic basins (IR1 = 300%  $Q$ ). The second internal recycle (IR2) between the anaerobic and anoxic basins was maintained at 100%  $Q$ . Low-speed mixers were placed in the anaerobic and anoxic basins to keep the mixed liquid-suspended solids in suspension. The dissolved oxygen (DO) concentration in the aerobic basin was maintained in the range of 2.0–4.0 mg L<sup>-1</sup>. The systems were operated for 225 days, of which 50 days were utilised for system stabilisation (Phase 1).

### 2.2. Thermal treatment and recovery of P

The mixed liquor was withdrawn from the aerobic basin of the EAAO reactor at the rate of 4%  $Q$  and subjected to thermal treatment once every 10 days. This was done by removing 864 mL day<sup>-1</sup> of mixed liquor (4%  $Q$ ) and then pooling 10 days of refrigerated (4 °C) sludge (8.6 L). The pooled 8.6 L of sludge was placed in a 10 L beaker and immersed in a water bath (60 °C) for 3 h. The mixed liquor in the beaker was kept in suspension by using a slow-speed stirrer (Digital Overhead IKA RW 20). After thermal treatment, the contents were allowed to settle to allow for solid/liquid separation. The settled sludge represented 20% (1.72 L) of the total volume and was separated by careful withdrawal of the supernatant, which represents the remaining 80% (6.88 L) of the total volume. Selective P removal was carried out on the supernatant (6.88 L) using lime as a coagulant at a mole ratio of 1.2. After P removal, 50% (4.3 L) of the slightly alkaline (pH 7.8) supernatant solution was recycled to the aerobic tank at the rate of 0.43 L day<sup>-1</sup> and the remaining 30% (2.58 L) slightly alkaline solution was sent into sludge disintegration tank. Out of the 20% (1.72 L) settled solids, 12.5% (1.07 L) was returned to anoxic tank at the rate of 0.107 L day<sup>-1</sup>, and the remaining 7.5% (0.65 L) was disintegrated.

### 2.3. Thermochemical sludge disintegration

Thermochemical sludge disintegration was carried out by mixing 0.65 L of settled sludge and 2.58 L of supernatant in a 5 L beaker. The total volume of mixed liquor subjected to thermochemical pre-treatment was 3.23 L (0.65 + 2.58 L) and it accounted for 1.5%  $Q$ . The mixed liquor was placed in a 5 L batch reactor and its pH was adjusted to 11 using sodium hydroxide (1 N). Sodium hydroxide was chosen based on earlier studies which indicated that sodium hydroxide was more efficient than other alkaline agents in solubilising the sludge (Kim et al., 2003; Lin et al., 2007). After adjustment of the pH, the batch reactor was submerged in a thermostatic bath at 60 °C for 3 h. During thermochemical pre-treatment, the reactor was covered with aluminium foil to avoid water evaporation. The mixed liquor in the reactor was kept in suspension by a slow-speed stirrer (Digital Overhead IKA RW 20) to ensure temperature homogeneity.

### 2.4. Domestic wastewater

Synthetic domestic wastewater was used for this study. The wastewater consisted of a mixed carbon source, macronutrients (N and P), an alkalinity control (NaHCO<sub>3</sub>) and a microelement solution (Banu et al., 2008). The synthetic wastewater composition contained (L<sup>-1</sup>) 350 mg of glucose, 200 mg of NH<sub>4</sub>Cl, 220 mg of NaHCO<sub>3</sub>, 22–34 mg of KH<sub>2</sub>PO<sub>4</sub>, microelement solution (0.19 mg of MnCl<sub>2</sub> 4H<sub>2</sub>O, 0.0018 mg of ZnCl<sub>2</sub> 2H<sub>2</sub>O, 0.022 mg of CuCl<sub>2</sub> 2H<sub>2</sub>O, 5.6 mg of MgSO<sub>4</sub> 7H<sub>2</sub>O, 0.88 mg of FeCl<sub>3</sub> 6H<sub>2</sub>O, 1.3 mg of CaCl<sub>2</sub> 2H<sub>2</sub>O). The synthetic wastewater was prepared three times a week, and had COD, TN and TP concentrations of 420 ± 5 mg L<sup>-1</sup>, 40 ± 1 mg L<sup>-1</sup> and 5.0 ± 0.1 mg L<sup>-1</sup>, respectively.

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