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Enhancing phosphorus release from waste activated sludge by combining high-voltage pulsed discharge pretreatment with anaerobic fermentation

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ABSTRACT

The effect of high-voltage pulsed discharge (HVPD) pretreatment on waste activated sludge (WAS) for phosphorus (P) release enhancement via anaerobic fermentation (AF) was studied. Batch tests were performed to investigate the P release via HVPD pretreatment and AF. The P release could be enhanced by a 26.7% soluble ortho-P [$SOP_{(L)}$] concentration increase via HVPD + AF compared with the control sample (AF of WAS without pretreatment). The HVPD and AF contributed 42.2% and 57.8% to the total $SOP_{(L)}$ increase, respectively. The P speciation analyzed using the Standards, Measurements, and Testing extraction protocol indicates that the decrease of non-apatite inorganic P (NAIP) in the solid phase is consistent with the increase of $SOP_{(L)}$ in the liquid phase and the release of poly-P from WAS could be enhanced due to the destruction of sludge flocs by HVPD. In addition, removal rates of 23.8% of total suspended solids (TSS) and 34.3% of volatile suspended solids (VSS) were calculated for the HVPD-pretreated solid phase, which suggests that the soluble organics production and WAS reduction were also enhanced via HVPD + AF. The results reveal that HVPD pretreatment is a promising method for the recovery of P from WAS and WAS reduction.

1. Introduction

Phosphorus (P) is an essential and irreplaceable nutrient for living organisms (Karl, 2000). Existing rock phosphate might be exhausted in the future 50–100 years because of the significant demand and overexploitation (Cordell et al., 2009). At the same time, the one-way process of P migration from minerals to water bodies induces severe eutrophication and complicates P recycling (Cordell et al., 2011; Dawson and Hilton, 2011). Thus, it is urgent to protect P resources and enhance the P recovery from P-rich waste (Mayer et al., 2016).

Waste activated sludge (WAS), produced from wastewater treatment plants (WWTPs), always contains different amounts of P depending on the wastewater treatment processes (Tyagi and Lo, 2013). The P content in WAS produced from enhanced biological phosphorus removal (EBPR) can reach up to 7%–10% of the total solids (TS), which is mainly due to polyphosphate (poly-P) storage by polyphosphate-accumulating organisms (PAOs) (Marti et al., 2008). Therefore, WAS is a great potential resource for P recovery.

For P recovery from WAS, P should be released from the solid phase to the supernatant firstly. Subsequently, P can be recycled through recrystallization as struvite ($MgNH_4PO_4{\cdot}6H_2O$) (Hao et al., 2013; Huang et al., 2015). On the other hand, as an environmentally friendly and less energy-intensive process, anaerobic fermentation (AF) has been widely used for sludge treatment because of its effective sludge reduction and resource recovery (Siddique and Wahid, 2018). In fact, a part of P stored in PAOs and sludge floc can be spontaneously released by anaerobic fermentation. To

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Abbreviation

HVPD	High voltage pulsed discharge
WAS	Waste activated sludge
AF	Anaerobic fermentation
SOP	Soluble ortho-P
TP	Total P
IP	Inorganic P
OP	Organic P
AP	Apatite P
NAIP	Non-apatite inorganic P
SCOD	Soluble chemical oxygen demand
TCOD	Total chemical oxygen demand
TSS	Total suspended solids
VSS	Volatile suspended solids

accelerate the sludge hydrolysis rate and enhance the phosphorous release efficiency, various WAS pretreatment methods have been investigated and developed to disrupt the flocculent structure of complex WAS such as physical (e.g., heat, microwave), chemical (e.g., acid/alkali pretreatment), and combined pretreatment technologies (Cui and Shen, 2012; Lin et al., 2018; Wang et al., 2017). Among the numerous WAS pretreatment methods, high-voltage pulsed discharge (HVPD) with both physical and chemical treatment characteristics is one of the hot spot; it can generate a high-voltage electric field and strong oxidizing free radicals with slight temperature variation and less time consumption (Bian et al., 2009). Hence, HVPD can not only break the floc structure to disintegrate complex organic matter into smaller and more easily biodegradable masses, but it can also directly breakdown parts of the cell membrane and cell wall to promote the release of cell substances such as proteins, amino acids, and phospholipids (Salerno et al., 2009).

Recently, researchers studied the positive effect of HVPD pretreatment on the sludge bioavailability to enhance the energy capture (e.g., methane/short-chain fatty acids) during anaerobic fermentation (Choi et al., 2006; Ki et al., 2015; Lee and Rittmann, 2011). However, in these studies, the release performance of P was regarded to be a simplified process and only the final total P concentrations were analyzed. The release mechanism of various forms of P has not been investigated. In fact, the P release performance is a dynamic equilibrium process during WAS fermentation due to the decay of cells and the dissolution of various forms of P (Zou et al., 2017). The HVPD pretreatment is expected to benefit the P release both during the pretreatment itself but also during enhanced AF. Therefore, the authors were motivated to study how HVPD pretreatment improves the P release from WAS.

The main objectives of this study were to investigate to what extent HVPD pretreatment and AF enhance the P release and anaerobic biodegradability of WAS and to explore the effect of HVPD pretreatment via AF on the speciation and fraction variation of P in WAS. The results will further the understanding of the P recovery from WAS that was pretreated by HVPD and its future application.

2. Materials and methods

2.1. Source of WAS

The WAS was collected from the secondary sedimentation tank of the Shanghai Quyang WWTP, China. The WAS was first concentrated by settling for 24 h at 4 °C and was then filtered through a 1 mm sieve to eliminate larger impurities. The characteristics of the WAS are shown in Table 1.

2.2. HVPD pretreatment

The HVPD apparatus was designed and setup at the Dalian University of Technology. The schematic diagram of the HVPD is illustrated in Fig. S1. The pulsed discharge voltage, pulse frequency, and pulse forming capacitance (Cp) were 40 kV, 400 Hz, and 4 nF, respectively. The separation distance (*d*) between the needle anodes and plate electrode was 5 mm. The total treated volume of WAS was 100 mL. The pretreatment time was 15 min. The energy consumption of the HVPD was calculated as follows (Jiang et al., 2014; Zou et al., 2016):

$$E_0 = 0.5CU^2 \tag{1}$$

$$E_1 = ftE_0 \tag{2}$$

$$G = E_1/V \tag{3}$$

where E_0, E_1, and G reflect the energy consumption of the high-voltage pulse, J; C is the electric capacity, pF; U is the discharge voltage, kV; $\boldsymbol{f}$ is the frequency; t is the treatment time; and V is the volume of the WAS.

2.3. Batch fermentation tests

Eighteen identical reactors were made from plexiglass with a total volume of 100 mL and effective volume of 80 mL. Nine reactors were filled with WAS after HVPD treatment and the others were filled with untreated WAS (control sample) with an original pH of 6.8. The reactors were flushed with nitrogen gas for 5 min to remove oxygen and then all reactors were sealed with butyl rubber stoppers and stirred in a water bath shaker (120 rpm/min) at 35 °C for 8 days. Three duplicates of all tests were carried out.

2.4. Phosphorus fractions in the liquid and solid

The sludge mixed liquor samples were firstly centrifuged at 4030 g for 5 min. Subsequently, the supernatant was stored at 4 °C prior to analysis and the remaining solid residues were dried at 105 °C in a heater until a constant weight was reached. The sludge solid was then ground using a ball mill and the powdered samples were sieved with a nylon fiber sieve to obtain the WAS samples, which were separated and stored at ambient temperature in polyethylene vessels in a desiccator. The TP concentration of P in the liquid and solid phases is generally defined as soluble ortho-P in the liquid [$SOP_{(L)}$] and total P in the solid [$TP_{(s)}$].

The Standards, Measurements, and Testing (SMT) extraction protocol was applied in this study to analyze the P fractions. The SMT extraction protocol and equations used for the calculations are based on (Ruban et al., 1999; Xie et al., 2011). Based on the SMT method, the P content in the solid can be divided into the following five fractions: total P ($TP_{(S)}$), inorganic P (IP), organic P (OP), non-apatite inorganic P (NAIP: the fraction associated with oxides and hydroxides of Al, Fe, and Mg), and apatite P (AP: the fraction associated with Ca).

2.5. Other analyses

The soluble chemical oxygen demand (SCOD), protein, $SOP_{(L)}$, and metal ions were tested after the sludge samples were centrifuged at 10080 g for 10 min and then filtered through a 0.45 μm