Improvement of phosphorus release from sludge by combined electrochemical-EDTA treatment
Yunfeng Xu, Fanglu Hu, Xin Wang, Yangwei Qu, Lu Xu and Qiang Liu

ABSTRACT
In this paper, combined with the addition of ethylenediaminetetraacetic acid (EDTA), the electrochemical treatment of waste activated sludge (WAS) was investigated to explore its effect on the release of phosphorus (P) from WAS. The results showed that during the electrochemical treatment, the addition of EDTA could significantly promote the release of P from the WAS to the supernatant, the optimal amount of EDTA was 0.4 g/g total suspended solids (TSS), when the release of total dissolved phosphorus (TDP), organic phosphorus (OP) and molybdate reactive phosphorus (PO$_4^{3-}$/CO$_3$-P) were 187.30, 173.84 and 13.46 mg/L, respectively. OP was the most likely form of P to be released during this process. Moreover, combined electrochemical-EDTA treatment could promote the release of P and metal ions from extracellular polymeric substances (EPSs) to the supernatant, and increase the solubility and disintegration of sludge. EDTA chelated the metal ions of sludge flocs and phosphate precipitates to cause sludge floc decomposition, thereby promoting the release of P from WAS.

Key words | electrochemical-EDTA treatment, extracellular polymeric substances, metal ions, organophosphorus, phosphorus release, waste activated sludge

HIGHLIGHTS
- Successfully developed combined electrochemical-EDTA treatment technology to promote the release of P in WAS.
- OP was the most likely phosphorus form to be released.
- Changes of P and metal elements content in EPSs had been investigated.
- EDTA destroys sludge flocs and promotes P release by chelating heavy metals.
GRAPHICAL ABSTRACT

INTRODUCTION

Phosphorus (P) is an essential element for all living organisms. According to statistics, there are about 70 billion tons of phosphate rock available for mining worldwide. However, phosphate rock is a non-renewable resource; phosphate rock in the world is only enough for humans to continue mining for 50–100 years, currently (Cordell et al. 2009; Rittmann et al. 2011). Therefore, many scholars are devoted to researching efficient and sustainable phosphorus recovery technologies. Waste activated sludge (WAS) is a by-product of a wastewater treatment plant (WWTP), 90% of P in municipal sewage enters WAS after treatment (Bloecher et al. 2015). According to statistics, China produces more than 40 million tons of WAS per year (Tou et al. 2017), with the development of industrialization and urbanization, its output continues to increase. Thus, WAS is considered as a new P source material that can replace phosphate rock. In addition, the loss of a large amount of organic substances, nitrogen, phosphorus and other pollutants of WAS will cause water environment pollution (Wang et al. 2016; Zhang et al. 2017). Therefore, the recycle of P from WAS cannot only reduce the pollution of the receiving waters, but also realize the reuse of P.

The recovery technology of P from sludge mainly produce a phosphorus-rich supernatant (Xu et al. 2015), and the generation of phosphorus precipitation is considered to be the best way to recover P from the phosphorus-rich solution (Zou et al. 2017). There are some reported literatures using physical (e.g. freezing/thawing, ultrasonic), chemical (e.g. surfactant addition, acid/alkali treatment) or biological (e.g. thermophilic Geobacillus sp G1) method to promote the release of P in sludge (Pilli et al. 2015; He et al. 2016b; Wang et al. 2017; Xu et al. 2018; Zhu et al. 2018). In the common methods, P was recovered from WAS by adjusting pH, the results showed that the total phosphorus (TP) release percentages were 36.2% and 12.4% at pH = 2.0 and pH = 11.0, respectively (Xu et al. 2015). Fang indicated that P was released, as OH– replaced PO4−3 in Fe-P under an alkaline condition (Fang et al. 2018). However, these methods will lead to high cost and secondary pollution. In addition, highly hydrophilic extracellular polymeric substance (EPSs) in WAS usually accumulate in the form of highly stable and viscous colloidal flocs with negative charge (Zhang et al. 2016), it is difficult to release P directly from WAS. Very recently, electrochemical pretreatment (EP) has been widely used for its advantages such as high efficiency, cleanliness, flexibility, and environmental friendliness (Chiavola et al. 2015; Hasan et al. 2016; Ye et al. 2016). The principle of EP depends on ohmic heating, electrophoresis and electroosmosis (Zhen et al. 2017). It was reported that EP had a significant effect on sludge solubilization, the removal rates of soluble chemical oxygen demand (SCOD), total suspended solids (TSS) and volatile suspended solids (VSS) in sludge supernatant after EP were significant increased (Song et al. 2010; Yu et al. 2014; Ye et al. 2016). During EP process, the high polymers in WAS were converted to low-molecular-weight products and then easily degraded, and the microbial cells were completely ruptured and decomposed (Yu et al. 2014; Dereszewska et al. 2015). And under the optimal condition, the highest concentrations of PO4−3-P and OP released by WAS reached 5.020 mg/L and 1.888 mg/L, respectively, which were 2.86 and 4.93 times higher than those of raw sludge (Yang et al. 2020). In
addition, EP significantly increased the release of P from WAS during anaerobic fermentation (AF) (Xu et al. 2020).

However, due to the presence of metal ions such as Ca$^{2+}$, Mg$^{2+}$, Fe$^{3+}$ and Al$^{3+}$ in the supernatant, it is possible to form a precipitate with the free phosphate (Zou et al. 2017), so that the P content in the supernatant would not continuously increase. FePs and AlPs are the main components of inorganic phosphorus (IP), and the release of P in these two insoluble precipitates is difficult. Studies have shown that adding surfactants which can complex with metal ions was beneficial to reduce the precipitation of P and metal ions in the supernatant (Mulligan 2009). Surfactants could also effectively destroy the polymer matrix of sludge, and promoted the release of extracellular polymers (EP) (Liu & Lin 2011). Ethylenediaminetetraacetic acid (EDTA) is a typical metal ion chelating agent that can stably bind to metal ions (Liu & Lin 2013). Studies have reported that EDTA could significantly improve the release of polyphosphates from sewage sludge during thermal pretreatment (Zhang & Kuba 2014). And EDTA could bind to metal cations in the extracellular polymer of sludge and on the surface of cell membranes (Kavitha et al. 2015), resulting in sludge decomposition and intracellular material release. At the same time, adding EDTA was an effective method to release the soluble phosphorus in FePs and AlPs (Zhang et al. 2010; Ping et al. 2020). It can be seen that the full release of P in sludge is facilitated by the addition of EDTA.

This article used combined electrochemical-EDTA treatment, in order to promote the release of P in WAS. Under the optimal conditions of electrochemical treatment (voltage of 4.5 V and time of 60 min) (Yang et al. 2020), different doses of EDTA were added. The amount of P released in different forms was investigated to determine the optimal amount of EDTA added. And the solubility and disintegration of WAS were determined by SCOD, TSS and VSS. EPs is the main component of the WAS flocculation matrix, and P has significant accumulation in EPs (Cloete & Oosthuizen 2001; Zhang et al. 2015). Thus we also discussed the content changes of P and metals contents in EPs.

### MATERIALS AND METHODS

#### Sludge sample and characterization

The WAS used in this experiment was taken from the secondary sedimentation tank of a sewage treatment plant in Shanghai. Before the test, the sludge was filtered by a 1 × 1 mm screen to remove large particles such as sand and gravel in WAS. Then the sludge was left to stand for 24 h, after the supernatant was discarded, the remaining activated sludge was stored in a refrigerator at 4 °C for later use. The main characteristics of the sludge are shown in Table 1.

#### Experimental setup and procedures

The electrolytic cell device used in this experiment was 10 × 5.5 × 11 cm (L × W × H), and the electrode plates used for the cathode and anode were 5 × 13 cm Ti/RuO$_2$ mesh electrodes. In order to prevent the sludge from sinking during the experiment and causing the reaction to be incomplete, this experiment used a magnetic stirring method, and placed the electrolytic cell on a magnetic stirrer. 300 mL of WAS was taken into the electrolytic cell, set up five experimental groups, added 0.0, 0.2, 0.4, 0.6, 0.8 g/g TSS EDTA, and set the voltage to 4.5 V, the electrode spacing was 5 cm, and processed for 60 min (Yang et al. 2020). All the experiments were performed in triplicate.

#### Analytical methods

The treated sludge was centrifuged (3,000 r/min, 10 min), the supernatant was taken through a 0.45 μm membrane, and various indicators in the supernatant and solid phase were measured. The measurement of pH, TSS, VSS, SCOD and TCOD were the same as previous publication (Xu et al. 2015; He et al. 2016a). The amounts of total dissolved phosphorus (TDP) and molybdate reactive phosphorus (free PO$_4^{3-}$-P) in the liquid were monitored following the standard method of ammonium molybdate spectrophotometry (GB11893-89, China), and organophosphorus (OP) was calculated from the difference between TDP and PO$_4^{3-}$-P (Juston & DeBusk 2001). The metal ions (Al$^{3+}$, Fe$^{3+}$, Mg$^{2+}$ and Ca$^{2+}$) in the sample were extracted with concentrated HNO$_3$, and the metal ion contents were determined by inductively coupled plasma emission spectroscopy (Prodigy, Liman Instrument Manufacturing Co., Ltd, USA). In this work, the EPs were

| Parameter | Mean    | Parameter | Mean       |
|-----------|---------|-----------|------------|
| pH        | 6.86 ± 0.21 | TP        | 490.82 ± 20.68 mg/L |
| TCOD      | 15.25 ± 0.20 g/L | SCOD      | 1.51 ± 0.11 g/L  |
| TSS       | 17.03 ± 0.38 g/L | VSS       | 10.91 ± 0.30 g/L |
| Al$^{3+}$ | 89.38 ± 4.35 mg/L | Ca$^{2+}$ | 72.08 ± 3.40 mg/L |
| Fe$^{3+}$ | 14.01 ± 2.90 mg/L | Mg$^{2+}$ | 26.84 ± 1.40 mg/L |
extracted by an improved thermal extraction method, the specific method can be found in a previous publication (Li & Yang 2007). And data was analyzed by Origin.

The contributions of OP and PO₄³⁻ released from solid to liquid were determined by Equations (1) and (2), respectively (Xu et al. 2015).

Released OP contribution (%)  
$$ \text{OP}_c = \frac{OP_c - OP_0}{OP_0} \times 100\% $$  

Released PO₄³⁻ contribution (%)  
$$ \text{PO}_4 = \frac{PO_4 - PO_{4,0}}{PO_{4,0}} \times 100\% $$

where OP (c, liquid) (mg/L) and PO₄³⁻ (c, liquid) (mg/L) were the contents of OP and PO₄³⁻ in the supernatant after treatment, respectively. OP (0, liquid) (mg/L) and PO₄³⁻ (0, liquid) (mg/L) were the OP and PO₄³⁻ contents of the supernatant in the raw sludge without treatment.

**RESULTS AND DISCUSSION**

Effect of combined electrochemical-EDTA treatment on phosphorus in sludge

Effect of EDTA dosages on phosphorus release from sludge

In order to verify that the combined electrochemical-EDTA treatment can promote the release of P from sludge, the sludge was treated with electrochemical treatment and combined electrochemical-EDTA treatment, the indicators of the raw sludge and treated sludges were compared. At this time, the reaction conditions were as follows: voltage was 5 V, time was 90 min, EDTA dosage was 0.4 g/g TSS. The results are shown in Table 2.

The release of TDP from the sludge treated with separate electrochemical treatment was 6.91 mg/L, the release of PO₄³⁻ -P was 5.02 mg/L, and the release of OP was 1.89 mg/L, which were 2.34, 2.00 and 4.30 times than those of the raw sludge, it showed that the electrochemical treatment can indeed increase the P released from sludge. In addition, a large amount of metal ions were released into the liquid phase after electrochemical treatment, which also confirmed the release of P. Furthermore, by combined Electrochemical-EDTA treatment, the amounts of TDP, OP and PO₄³⁻ -P released into the supernatant were 194.40 mg/L, 26.75 mg/L and 167.67 mg/L, which were 65.90, 10.65 and 381.07 times those of the raw sludge, respectively. The TDP release rate of WAS reached 39.6%, which was slightly higher than that of TDP released by acid method (36.2%) (Xu et al. 2015). This meant that during the combined electrochemical-EDTA treatment, the release of P could be significantly increased. And the SCOD value after combined electrochemical-EDTA treatment was the highest, followed by the electrochemical treatment, and the least was the SCOD value of the raw sludge, which indicated that the disintegration of sludge after combined electrochemical-EDTA treatment was the largest. Moreover, the values of TSS and VSS also reached the minimum after combined electrochemical-EDTA treatment indicating that the degree of sludge disintegration has reached the maximum at this time.

After confirming that combined electrochemical-EDTA treatment can promote the release of P from sludge, it was necessary to study the release of different forms of P in different EDTA additions to determine the optimum amount of EDTA. The results are shown in Figure 1.

After adding 0.2, 0.4, 0.6, 0.8 g EDTA/g TSS, respectively, the TDP, PO₄³⁻ -P and OP in the sludge supernatant increased with the addition of EDTA after electrochemical treatment. When the added EDTA reached 0.4 g/g TSS, the released P reached the maximum; since then, with the increase of EDTA, the released P has remained basically unchanged. When 0.4 g/g TSS of EDTA was added, the release of TDP, OP and PO₄³⁻ -P were 187.50, 173.84 and 13.46 mg/L, respectively. Different from the electrochemical treatment alone, the concentration of OP in the sludge supernatant was much higher than the concentration of PO₄³⁻ -P. After adding EDTA, more OP can be released

### Table 2: Various indicators of sludge under different conditions

| Processing group | TDP (mg/L) | PO₄³⁻ -P (mg/L) | OP (mg/L) | Ca²⁺ (mg/L) | Mg²⁺ (mg/L) | Fe³⁺ (mg/L) | Al³⁺ (mg/L) | SCOD (g/L) | TSS (g/L) | VSS (g/L) |
|------------------|------------|----------------|-----------|-------------|-------------|-------------|-------------|------------|-----------|-----------|
| Raw              | 2.95       | 2.51           | 0.44      | 40.10       | 28.30       | 3.10        | 25.00       | 1.58       | 15.50     | 8.40      |
| Electrochemical  | 6.91       | 5.02           | 1.89      | 64.50       | 30.20       | 10.70       | 64.60       | 2.78       | 16.18     | 10.67     |
| Electrochemical-EDTA | 194.40   | 26.73          | 167.67    | 65.70       | 30.60       | 155.80      | 29.60       | 2.88       | 10.60     | 4.50      |
into the liquid phase. This was because that EDTA can combine with most metal ions to release macromolecular organic substances that were originally linked by metal bridging, which promoted the decomposition of sludge and increased the release of P (Kavitha et al. 2013; He et al. 2016a). In addition, EDTA could kill cells and promoted the release of OP on cell surface (Zou et al. 2017). In general, with the electrochemical treatment, EDTA could effectively and greatly promote the release of P from the sludge into the liquid phase, and it was less affected by the supernatant metal ions. As the added EDTA increased, the released P increased; when it reached 0.4 g/g TSS, the released P reached a maximum. Different from the separate electrochemical treatment, the amount of OP released from the sludge by adding EDTA was much larger than that of PO₄³⁻-P.

Effect on release contributions of OP and PO₄³⁻-P

Phosphate precipitation is considered to be the best way to recover P from phosphorus-rich solutions (Zou et al. 2017). Previous studies have shown that OP in solution can be converted to PO₄³⁻-P under the action of microorganisms (He et al. 2016a, 2016b). Therefore, it is necessary to study the soluble PO₄³⁻-P and OP of the sludge, and explore their contributions to the release during the electrochemical process. The release contributions of PO₄³⁻-P and OP from solid to liquid are shown in Figure 2.

As can be seen from Figure 2, with the amount of EDTA added increased, the release contribution of PO₄³⁻ and OP increased, and the released contribution of OP reached 99.68% when the additional amount was 0.2 g/g TSS. And it would keep this level as the amount of EDTA increased. The released PO₄³⁻ was 75.9% at 0.2 g/g TSS, and when the additional amount was 0.4 g/g TSS, it reached 81.4%, and then remained at about 82%. The addition of EDTA could make the PO₄³⁻ and OP in the sludge get better releasing, and the release contributions reached a higher level than that of electrochemical treatment. This was mainly because EDTA would chelate heavy metals on EPSs and cell membrane, thus destroy sludge flocs and cell membrane, and promote the release of OP (Ping et al. 2020). Moreover, EDTA had strong complexation ability and would compete for heavy metals in insoluble metal phosphates, such as Fe and Al (Zou et al. 2017; Ping et al. 2020).

Effect on phosphorus components in sludge solid phase

The results of different forms of phosphorus in the sludge solid phase after different dosages of EDTA combined with electrochemical treatment are shown in Figure 3.

It can be seen from Figure 3 that the component of non-apatite inorganic phosphorus (NAIP) and OP in the solid phase accounted for more than 80% of TP, so there was more releasable P in the sludge solid phase. The proportion of NAIP was the largest of the four different phosphorus forms, which remained around 65%, indicating that the amount of released NAIP was less in this process. The proportion of OP in the solid phase of sludge without EDTA was 15.85%. With the increase of EDTA, the proportion of OP in the solid phase of sludge decreased gradually, which reduced to 12%. It indicated that OP was released into the supernatant after combined electrochemical-EDTA treatment.

Figure 1 | Concentration of different forms of P in supernatant treated by electrochemical treatment combined with different doses of EDTA.

Figure 2 | Effect of the treatment of electrochemical combination of EDTA with different additions on the release contributions of PO₄³⁻ and OP.

Figure 3 | Concentration of different forms of P in supernatant treated by electrochemical treatment combined with different doses of EDTA.
treatment, thereby reducing the content of OP in the solid phase. In addition, the presence of microorganisms in the activated sludge might also convert the OP into PO$_4^{3-}$/C$_0$-P (He et al. 2016a, 2016b), and PO$_4^{3-}$/C$_0$-P would be released to the supernatant. The flocculation structure of WAS after combined electrochemical-EDTA treatment would be destroyed by strongly chelating heavy metals (Zou et al. 2013; Ping et al. 2020).

Generally, four different forms of phosphorus in the solid phase exhibited different releasability during combined electrochemical-EDTA treatment. OP was most likely to be released into the liquid phase as a kind of phosphorus, which was consistent with the value of OP in the liquid phase above. On the contrary to the EP, the amount of OP released by combined electrochemical-EDTA treatment was much larger than that of PO$_4^{3-}$/C$_0$-P (Yang et al. 2020).

Effect of combined electrochemical-EDTA treatment on EPSs

Changes of phosphorus components in EPSs

In order to investigate the effect of EDTA treatment on the release of phosphorus from the EPSs of sludge, this paper studied the content of different forms of phosphorus in the EPSs of sludge treated by electrochemical treatment combined with different amounts of EDTA, as shown in Figure 4.

It can be seen from Figure 4 that in the tightly bound extracellular polymeric substances (TB-EPSs) and loosely bound extracellular polymeric substances (LB-EPSs), the contents of different forms of P present different trends. The content of P in TB-EPSs decreased with the increasing EDTA addition. This was because under the combined treatment of electrochemistry and EDTA, the floc structure of the sludge was destroyed and some EPSs were also destroyed (Zhou et al. 2013; Yang et al. 2015), so the P in the TB-EPSs was released.

Unlike the case of TB-EPSs, the P content in LB-EPSs showed an increasing trend with the increase of EDTA, which was the same as previous study which used rhamnolipid to promote the release of P from WAS (He et al. 2016b). This was due to the loose structure and good rheological property of LB-EPSs outside the extracellular polymer structure, which received the P released from TB-EPSs, and thus the concentration of P increased (Zhou et al. 2013; Yang et al. 2015).

Changes of metal content in EPSs

Ca$^{2+}$, Mg$^{2+}$, Al$^{3+}$ and Fe$^{3+}$ are the main metal ions in the sludge that affect P release, the changes of these metal ions are shown in Figure 5.

Figure 3 | Proportion of different forms of P in solid phase of sludge after different additions of EDTA combined with electrochemical treatment.

Figure 4 | Changes of P fractions and species in TB-EPSs and LB-EPSs.
content in EPSs and sludge supernatant at different EDTA additions were studied. The results are shown in Figures 5 and 6.

The concentration of metals in the sludge supernatant and EPSs after combined electrochemical-EDTA treatment increased greatly, and the optimal amount of EDTA added was 0.4 g/g TSS. Among them, the release of Fe$^{3+}$ was much more than that of Ca$^{2+}$, Mg$^{2+}$ and Al$^{3+}$. This was because Fe-EDTA had a greater stability constant than Al-EDTA, Ca-EDTA, and Mg-EDTA, so Fe$^{3+}$ was preferentially complexed by EDTA (Zou et al. 2010). Studies have shown that metal ions such as Ca$^{2+}$ and Mg$^{2+}$ could promote the stability of sludge and EPSs matrix structure (Sheng et al. 2010; Yan et al. 2015). Therefore, the release of metal might destroy the stability of the matrix structure of the sludge and extracellular polymer, which also contributed to the solubilization of sludge.

Figures 5 and 6 show the similar trends, and the metal contents in the sludge supernatant were higher than that in EPSs. With the increase of EDTA, more microbial cells and extracellular polymers in sludge were destroyed, and metal ions such as Ca$^{2+}$, Mg$^{2+}$, Al$^{3+}$ and Fe$^{3+}$ were released. At the same time, as a chelating agent, EDTA could also interact with the metal ions in the precipitate combine to form a metal chelate (Mulligan 2009). The chelates were mainly distributed in the liquid phase, and part of them were adsorbed in EPSs, thus the metal contents in both the supernatant and EPSs increased.

**Effect of combined electrochemical-EDTA treatment on solubility and disintegration of sludge**

The SCOD of sludge increased with the increase of EDTA (Figure 7), which indicated that the combination could effectively promote the release of organics of WAS. Electrochemical treatment would decompose sludge flocs and destroy cells (Song et al. 2010; Yu et al. 2014; Ye et al. 2016), electrochemical treatment also could swell the colloidal structure of sludge, and most complex organic compounds were degraded into monomers (Zhen et al. 2017). Meanwhile EDTA could break the bond bridge connection between organics of EPSs and cells by chelating metal ions, thus destroy the floc structure of sludge (Kavitha et al. 2015). Moreover, adding EDTA would increase the...
percentage of dead cells, the main components of cells (proteins, polysaccharides and other organic substances) would be released (Zhen et al. 2014; Zou et al. 2017). Thus combined electrochemical-EDTA treatment resulted the concentration of SCOD increased.

TSS and VSS are the basic indicators for measuring sludge degradation and decrement. After the combined treatment, the TSS and VSS of the sludge decreased with the increase of EDTA added (Figure 8). EDTA could not only destroy EPSs, but also dissolve the insoluble calcium, magnesium and iron salts (Ping et al. 2020). Therefore, the declining trend of TSS after EDTA treatment was obvious. Meanwhile, on the basis of EDTA treatment, the further use of electrochemical treatment effectively promoted the destruction of sludge cells, so that a large amount of substances in the cells were released. Generally, the solubility and disintegration of sludge increased after combined treatment.

CONCLUSIONS

In this paper, the feasibility of combined electrochemical-EDTA treatment to promote the release of P in WAS was studied, the effect of EDTA on the release of P and its mechanism were explored, and the changes of P and metal content in EPSs during this process were also discussed. The results showed that EDTA could significantly promote the release of P and heavy metals of WAS, with the increase of EDTA dosage, the release of P increased. And the optimal addition of EDTA was 0.4 g/g TSS, at this time, the different forms of P have been well released, and OP was the most likely form of P to be released from WAS. In addition, electrochemical-EDTA treatment can promote the release of P and metal ions from EPSs to the supernatant, and improve the solubility and disintegration of sludge. EDTA can destroy sludge flocs and cells through chelation, and compete for heavy metals with insoluble phosphate, thus promoting the release of P in WAS. Although electrochemical-EDTA treatment has not achieved the lowest cost, it still has good application value to recover P from WAS and remove heavy metals.

ACKNOWLEDGEMENT

This research was financially supported by National Natural Science Foundation of China (41472312, 21878183).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Bloecher, C., Niewersch, C. & Melin, T. 2012 Phosphorus recovery from sewage sludge with a hybrid process of low pressure wet oxidation and nanofiltration. Water Research 46, 2009–2019.
Chiavola, A., Ridolfi, A., D’Amato, E., Bongirolami, S., Cima, E., Sirini, P. & Gavasci, R. 2015 Sludge reduction in a small wastewater treatment plant by electro-kinetic disintegration. Water Science and Technology 72, 364–370.
Cloete, T. E. & Oosthuizen, D. J. 2004 The role of extracellular exopolymers in the removal of phosphorus from activated sludge. Water Research 35, 3595–3598.
Cordell, D., Drangert, J.-O. & White, S. 2009 The story of phosphorus: global food security and food for thought. Global Environmental Change-Human and Policy Dimensions 19, 292–305.
Dereszewska, A., Cytawa, S., Tomczak-Wandzel, R. & Medrzycka, K. 2015 The effect of anionic surfactant concentration on activated sludge condition and phosphate release in biological treatment plant. Polish Journal of Environmental Studies 24, 83–91.
Fang, L., Li, J.-s., Donatello, S., Cheeseman, C. R., Wang, Q., Poon, C. S. & Tsang, D. C. W. 2018 Recovery of phosphorus from incinerated sewage sludge ash by combined two-step extraction and selective precipitation. Chemical Engineering Journal 348, 74–83.
Hasan, S. W., Ahmed, I., Housani, A. A. & Giwa, A. 2016 Molecular and ionic-scale chemical mechanisms behind the
role of nitrocyl group in the electrochemical removal of heavy metals from sludge. *Scientific Reports* **6**, 31828.

He, Z.-W., Liu, W.-Z., Wang, L., Tang, C.-C., Guo, Z.-C., Yang, C.-X. & Wang, A.-J. 2016a Clarification of phosphorus fractions and phosphorus release enhancement mechanism related to pH during waste activated sludge treatment. *Bioresource Technology* **222**, 217–225.

He, Z.-W., Liu, W.-Z., Wang, L., Yang, C.-X., Guo, Z.-C., Zhou, A.-J., Liu, J.-Y. & Wang, A.-J. 2016b Role of extracellular polymeric substances in enhancement of phosphorus release from waste activated sludge by rhamnolipid addition. *Bioresource Technology* **202**, 59–66.

Juston, J. M. & DeBusk, T. A. 2021 Evidence and implications of the background phosphorus concentration of submerged aquatic vegetation wetlands in stormwater treatment areas for everglades restoration. *Water Resources Research* **47**, 173–178.

Kavitha, S., Kumar, S. A., Yogalakshmi, K. N., Kaliappan, S. & Banu, J. R. 2015 Effect of enzyme secreting bacterial pretreatment on enhancement of aerobic digestion potential of waste activated sludge interceded through EDTA. *Bioresource Technology* **150**, 210–219.

Li, X. Y. & Yang, S. F. 2007 Influence of loosely bound extracellular polymeric substances (EPS) on the flocculation, sedimentation and dewaterability of activated sludge. *Water Research* **41**, 1022–1030.

Liu, C.-C. & Lin, Y.-C. 2013 Reclamation of copper-contaminated soil using EDTA or citric acid coupled with dissolved organic matter solution extracted from distillery sludge. *Environmental Pollution* **178**, 97–101.

Mulligan, C. N. 2009 Recent advances in the environmental applications of biosurfactants. *Current Opinion in Colloid & Interface Science* **14**, 372–378.

Pilli, S., Yan, S., Tyagi, R. D. & Surampalli, R. Y. 2015 Thermal pretreatment of sewage sludge to enhance anaerobic digestion: a review. *Critical Reviews in Environmental Science and Technology* **45**, 669–702.

Ping, Q., Lu, X., Li, Y. & Mannina, G. 2020 Effect of complexing agents on phosphorus release from chemical-enhanced phosphorus removal sludge during anaerobic fermentation. *Bioresource Technology* **301**, 122745.

Rittmann, B. E., Mayer, B., Westerhoff, P. & Edwards, M. 2011 Capturing the lost phosphorus. *Chemosphere* **84**, 846–853.

Sheng, G.-P., Yu, H.-Q. & Li, X.-Y. 2010 Extracellular polymeric substances (EPS) of microbial aggregates in biological wastewater treatment systems: a review. *Biotechnology Advances* **28**, 882–894.

Song, L.-J., Zhu, N.-W., Yuan, H.-P., Hong, Y. & Ding, J. 2010 Enhancement of waste activated sludge aerobic digestion by electrochemical pre-treatment. *Water Research* **44**, 4371–4378.

Tou, F., Yang, Y., Feng, J., Niu, Z., Pan, H., Qin, Y., Guo, X., Meng, X., Liu, M. & Hochella, M. F. 2017 Environmental risk implications of metals in sludges from waste water treatment plants: the discovery of vast stores of metal containing nanoparticles. *Environmental Science & Technology* **51**, 4831–4840.

Wang, X., Li, M., Liu, J. & Qu, J. 2016 Occurrence, distribution, and potential influencing factors of sewage sludge components derived from nine full-scale wastewater treatment plants of Beijing. *China. Journal of Environmental Sciences–China* **45**, 233–239.

Wang, Y., Zhang, T., Westerhoff, P., Jiang, R., Ren, H., Yang, Y. & Li, Z. 2017 Microwave-assisted digestion and NaOH treatment of waste-activated sludge to recover phosphorus by crystallizing struvite. *Environmental Technology* **38**, 1211–1222.

Xu, Y., Hu, H., Liu, J., Luo, J., Qian, G. & Wang, A. 2015 Ph dependent phosphorus release from waste activated sludge: contributions of phosphorus speciation. *Chemical Engineering Journal* **267**, 260–265.

Xu, Q., Liu, X., Wang, D., Wu, Y., Wang, Q., Liu, Y., Li, X., An, H., Zhao, J., Chen, F., Zhong, Y., Yang, Q. & Zeng, G. 2018 Free ammonia-based pretreatment enhances phosphorus release and recovery from waste activated sludge. *Chemosphere* **213**, 276–284.

Xu, Y., Zhou, Q., Wang, X., Yang, M., Fang, Y. & Lu, Y. 2020 An efficient strategy of phosphorus recovery: electrochemical pretreatment enhanced the anaerobic fermentation of waste activated sludge. *Chemosphere* **268**, 129391–129391.

Yan, L., Liu, Y., Wen, Y., Ren, Y., Hao, G. & Zhang, Y. 2015 Role and significance of extracellular polymeric substances from granular sludge for simultaneous removal of organic matter and ammonia nitrogen. *Bioresource Technology* **179**, 460–466.

Yang, C., Liu, W., He, Z., Thangavel, S., Wang, L., Zhou, A. & Wang, A. 2015 Freezing/thawing pretreatment coupled with biological process of thermophilic Geobacillus sp G1: acceleration on waste activated sludge hydrolysis and acidification. *Bioresource Technology* **175**, 509–516.

Yang, M., Chen, J., Wang, X., Sun, Y., Xu, Y. & Liu, Q. 2020 Enhancement of phosphorus release from waste activated sludge by electrochemical treatment. *Environmental Technology* **41**, 1–29.

Ye, C., Yuan, H., Dai, X., Lou, Z. & Zhu, N. 2016 Electrochemical pretreatment of waste activated sludge: effect of process conditions on sludge disintegration degree and methane production. *Environmental Technology* **37**, 2935–2944.

Yu, B., Xu, J., Yuan, H., Lou, Z., Lin, J. & Zhu, N. 2014 Enhancement of anaerobic digestion of waste activated sludge by electrochemical pretreatment. *Fuel* **130**, 279–285.

Zhang, M. Y. & Kuba, T. 2014 Inhibitory effect of metal ions on the poly-phosphate release from sewage sludge during thermal treatment. *Environmental Technology* **35**, 1157–1164.

Zhang, T., Bowers, K. E., Harrison, J. H. & Chen, S. 2010 Releasing phosphorus from calcium for struvite fertilizer production from anaerobically digested dairy effluent. *Water Environment Research* **82**, 34–42.

Zhang, H.-L., Fang, W., Wang, Y.-P., Sheng, G.-P., Xia, C.-W., Zeng, R. J. & Yu, H.-Q. 2015 Species of phosphorus in the extracellular polymeric substances of EBPR sludge. *Bioresource Technology* **142**, 714–718.

Zhang, W., Cao, B., Wang, D., Ma, T., Xia, H. & Yu, D. 2016 Influence of wastewater sludge treatment using combined peroxycetic acid oxidation and inorganic coagulants.
re-flocculation on characteristics of extracellular polymeric substances (EPS). Water Research 88, 728–739.
Zhao, J., Li, Y., Chen, X. & Li, Y. 2018 Effects of carbon sources on sludge performance and microbial community for 4-chlorophenol wastewater treatment in sequencing batch reactors. Bioresource Technology 255, 22–28.
Zhen, G., Lu, X., Li, Y.-Y. & Zhao, Y. 2014 Combined electrical-alkali pretreatment to increase the anaerobic hydrolysis rate of waste activated sludge during anaerobic digestion. Applied Energy 128, 93–102.
Zhou, A., Yang, C., Guo, Z., Hou, Y., Liu, W. & Wang, A. 2013 Volatile fatty acids accumulation and rhamnolipid generation in situ from waste activated sludge fermentation stimulated by external rhamnolipid addition. Biochemical Engineering Journal 77, 240–245.
Zhu, X., Yang, Q., Li, X., Zhong, Y., Wu, Y., Hou, L., Wei, J., Zhang, W., Liu, Y., Chen, C. & Wang, D. 2018 Enhanced dewaterability of waste activated sludge with Fe(II)-activated hypochlorite treatment. Environmental Science and Pollution Research 25, 27628–27638.
Zou, J., Zhang, L., Wang, L. & Li, Y. 2017 Enhancing phosphorus release from waste activated sludge containing ferric or aluminum phosphates by EDTA addition during anaerobic fermentation process. Chemosphere 171, 601–608.

First received 2 November 2020; accepted in revised form 10 March 2021. Available online 22 March 2021