



Review

Potentials and challenges of phosphorus recovery as vivianite from wastewater: A review

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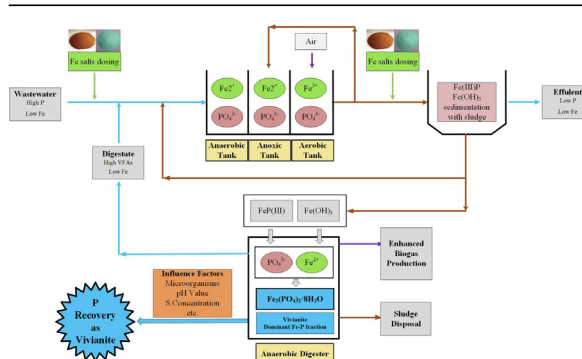
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HIGHLIGHTS

- Vivianite formation is a complex process and is influenced by various factors.
- P recovery as vivianite contributes to the sustainable use of P with high value.
- The potential to recover vivianite from wastewater in WWTPs is great.
- More research is required for the efficient vivianite recovery from wastewater.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to the shortage of phosphorus resources and the limitations of existing phosphorus recovery methods, phosphorus recovery in the form of vivianite has attracted considerable attention with its natural ubiquity, easy accessibility and foreseeable economic value. This review systematically summarizes the chemistry of vivianite, including the characteristics, formation process and influencing factors of the material. Additionally, the potential of phosphorus recovery as vivianite from wastewater has also been comprehensively examined from the prospects of economic value and engineering feasibility. In general, this method is theoretically and practically feasible, and brings some extra benefits in WWTPs. However, the insufficient understanding on vivianite recovery in wastewater/sludge decelerate the development and exploration of such advanced approach. Further researches and cross-field supports would facilitate the improvement of this technique in the future.

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1. Introduction

Phosphorus (P) is an essential element in living organisms and plays a vital role in life activities (Jalali and Jalali, 2016; Selbig, 2016). P is necessary for the growth and energy supply of human genetic processes, especially for the formation of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Besides, P is also necessarily involved in photosynthesis in plant bioprocesses, the utilization of sugar and starch, and the process of energy transfer (Sun et al., 2018).

With the continuous increase in global population, the demand for P is growing in the agricultural and industrial sectors (Heckenmüller et al., 2014). However, P is a limited and non-renewable resource. Approximately 20 million tons of phosphorus rocks are mined each year with consistently rising price (Cordell et al., 2011). Notably, P reserves and consumption have been studied by Mew MC (Mew, 2016), who predictably states that global P rock resources will be exhausted in the upcoming 50–100 years, resulting in surging market quotation (Cordell et al., 2009). Meanwhile, as premium-quality and easy-mining P rocks are gradually depleted, high-impurity and hard-mining rock would be extensively employed, which would furtherly escalate production costs (Desmidt et al., 2015). Under such circumstances, the recovery of P is imperatively crucial for both primary and secondary industries.

Wastewater treatment plants (WWTPs) are one of the most important convergence points of phosphorus claimed by two prominent rationales. Firstly, 1.3 million tons of P per year are removed via sewage treatment operating within the planet (Li and Li, 2017). It is estimated that recovering P from the wastewater could meet 15–20% of the global demand for phosphorus (Yuan et al., 2012). Hence, WWTPs could be critical P resources providers worldwide. Secondly, diminishing phosphorus pollution is essential to solve problems caused from eutrophication, a pivotal concern of sewage, given that nitrogen (N) and phosphorus (P) are two major pollutants in wastewater that induce eutrophication in natural waters. Particularly, eutrophication leads to a reduction in water quality and damages ecological structures, increasing the difficulty of treatment and the cost of water supply (Carpenter, 2008). Relevant studies show that the growth of algae contributing to water over-enrichment are more sensitive to P than N. If

the concentration of P increased slightly, the eutrophication would promptly occur whereas the impact of N would be relatively not remarkable (Schindler, 2006). Noticeably, being distinct from N, which could be internally reproduced by nitrogen fixation from microorganisms, the concentration of P within water is primarily determined by external influx. For this reason, to mitigate eutrophication, eliminating P content is more practical than reducing the content of N. Overall, P recovery from wastewater is extremely significant: such disposal can alleviate the stress of demand in P resources and simultaneously avoid water eutrophication. As a result, the recovery of P from wastewater is evidently a trending topic providing an example that Germany passed a new policy on October 3, 2017 mandating P recovery from all WWTPs; this policy is currently being implemented (BMUB, 2017).

At present, there are several common ways to recover P from wastewater; these approaches include crystallization (Bi et al., 2014; Huang et al., 2015), adsorption/desorption (Dai et al., 2014; Loganathan et al., 2014), acid/alkali leaching (Donatello and Cheeseman, 2013; Li et al., 2012), and thermochemical treatment (Adam et al., 2009; Herzel et al., 2016). Among these methods, crystallization is broadly applied, which adds extra reagents to form insoluble phosphate, e.g., struvite (magnesium ammonium phosphate, MAP) (Ye et al., 2017a). Partial WWTPs in Europe and North America have adopted this technique for P recovery (Desmidt et al., 2015). However, the crystallization of struvite might not be the optimal solution for P recovery associated with the following reasons: (1) low-value products with overweighing cost, (2) complex operating conditions, (3) unsatisfactory recovery efficacy (10–50%) and (4) the lack of an obvious advantage compared with other P recovery proceedings (Egle et al., 2015; Hao et al., 2013; Huang et al., 2017a; Lin et al., 2017a). Moreover, P recovery as struvite can only be conducted in WWTPs with enhanced biological P removal (EBPR) (Wilfert et al., 2015). In addition, iron (Fe) and aluminum (Al) salts need to be added into wastewater as flocculants to remove P and satisfy increasingly stringent discharge standards (Fan et al., 2018; Wilfert et al., 2015; Zhang et al., 2015). These metals further decline the recovery efficiency of struvite connected with their contest for P (Wilfert et al., 2018). Consequently, given that struvite may not be the best route for phosphorus recovery, it is imperative to develop other efficient and economic P recovery methods.

On the contrary, P recovery as vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) has received considerable attention from researchers due to its natural ubiquity, easy accessibility and foreseeable economic value (Wilfert et al., 2015, 2016, 2018). Vivianite has also been found in WWTPs sludge, especially in digested sludge, and accounts for the majority of the Fe–P bound fraction (Frossard et al., 1997; Poffet et al., 2008; Rasmussen and Nielsen, 1996; Wilfert et al., 2016, 2018). In addition, vivianite can be used in the electronics industry and agriculture with a high collection value (Cabeza et al., 2011; Johnston and Richards, 2003; Li et al., 2015; Rao and Varadaraju, 2015). These advantages imply the opportunities of the innovative and seemingly viable P recovery technique despite that the relevant studies on vivianite are relatively insufficient and scattered. For this reason, a comprehensive examination of P recovery as vivianite is demonstrated hereafter. The aim of this review is to (1) summarize vivianite chemistry in terms of the characteristics, formation process and influencing factors of vivianite to clarify the understanding of this material; (2) analyze the potential of P recovery as vivianite to explore the feasibility of this method; and (3) introduce the progress of existing research and provide some possible suggestions accordingly.

2. Vivianite chemistry

Vivianite chemistry should be correctly identified to analyze the feasibility and efficiency of vivianite in P recovery from wastewater/sludge. Specifically, in this section, the characteristics of vivianite, the vivianite formation process and the factors affecting vivianite formation are explained in detail.

2.1. Vivianite characteristics

Vivianite is one of the most common iron phosphate minerals which is often found in lake sediments or soil in Fe-rich and anaerobic environments (Cosmidis et al., 2014; Dijkstra et al., 2016; Rothe et al., 2014; Sapota et al., 2006; Vuillemin et al., 2013; Zhao et al., 2015). Vivianite is also detected in bogs (Nanzyo et al., 2010), hydrothermal deposits (K. A. Rodgers et al., 1993), and plant roots (Kusunoki et al., 2015; Nanzyo et al., 2013), and has been historically used in oil paintings (Cruz et al., 2018; Thali et al., 2011). In WWTPs, vivianite is the predominant iron phosphate compound in different sludge in which it has been traceably discovered, including activated sludge, excess sludge and digested sludge (Frossard et al., 1997; Poffet et al., 2008; Rasmussen and Nielsen, 1996; Wilfert et al., 2016).

Table 1 clarifies the main physical and chemical properties of vivianite crystal. The general formula of the mineral group is $\text{A}_3(\text{XO}_4)_2 \cdot 8\text{H}_2\text{O}$, where A corresponds to a divalent transition-metal cation such as iron (Fe), magnesium (Mg), zinc (Zn), or nickel (Ni) and X corresponds to phosphorus (P) or arsenic (As) (Fleischer and Mandarino Joseph, 1991).

In appearance, pure vivianite has a white transparent color in the original status and becomes opaque with a green or blue color when being exposed to air oxidation. Normally, Fe(II) becomes Fe(III) immediately at room temperature; when the concentration of Fe(III) accounts for half of the amount of total Fe, the oxidation process reaches an equilibrium status. Nevertheless, if the Fe(III) concentration was higher, vivianite would transform into *meta*-vivianite. When the oxidation process continues, the mineral will further transform into Fe^{3+} -rich *meta*-vivianite and eventually become an amorphous mineral (Rothe et al., 2016).

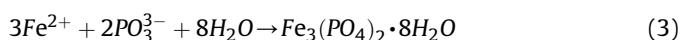
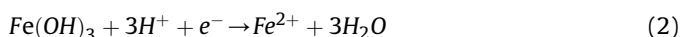
For pure vivianite, all inner iron is divalent (Fe^{2+}), constructing two distinct sites of the structure. In the first site, Fe^{2+} is surrounded by two oxygen atoms and four water molecules, forming an octahedral group. In the second site, Fe^{2+} is surrounded by four

oxygen atoms and two water molecules, again forming an octahedral group. Oxygen is a part of the phosphate group (PO_4^{3-}), which is a tetrahedron. The vivianite structure has chains of these octahedra and tetrahedra, forming sheets perpendicular to the crystal axis. These sheets are held by weak bonds, which indicates perfect cleavage between the sheets (Fig. 1) (Howie, 1998).

2.2. Vivianite formation process

As emphasized above, the two fundamental components of vivianite are Fe and P. In specific, Fe ions in natural water might be derived from the dissolution of iron minerals, while in wastewater, Fe ions often come from the dosing of Fe salt, which is adopted as a flocculating agent to remove P and achieve strictly regulated effluent standards (Fan et al., 2018; Wilfert et al., 2015; Zhang et al., 2015). Besides, Fe usually exists as Fe^{3+} in water in the form of $\text{Fe}(\text{OH})_3$ and hydrous ferric oxide (HFO) (Hansen and Poulsen, 1999). Differently, P in natural water could be derived from domestic sewage, industrial wastewater, aquaculture, agriculture, animals, plants and microorganisms, while in wastewater, P primarily comes from human excretions, household waste, phosphorus-based detergents and industrial pollution (Lotze et al., 2006; Smil, 2000; Withers and Jarvie, 2008). P in water typically presents as organic phosphorus, inorganic phosphorus, and polyphosphorus (McMahon et al., 2002).

In organic matter (OM)-rich and reducing environments, Fe^{3+} is reduced to Fe^{2+} by dissimilatory metal-reducing bacteria (DMRB), while organic phosphorus is converted to phosphate by anaerobic microorganisms (O'Loughlin et al., 2013; Rothe et al., 2016; Vuillemin et al., 2013). As these two microbial processes continue, a local environment is formed in which the concentrations of Fe^{2+} and PO_4^{3-} reach higher levels (Zhang et al., 2009). Once the value of solubility product (K_{sp}) has reached target requirement, the formation of vivianite would occur (Nriagu, 1972). Fig. 2 and Equations (1)–(3) also briefly describe this formation process in natural water.



2.3. Factors affecting vivianite formation

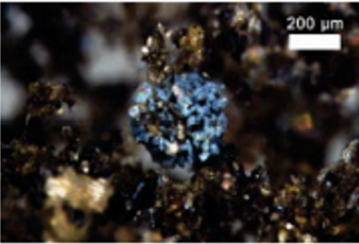

It is previously highlighted that the formation of vivianite is essentially a chemical process which can be affected by varied factors including microorganisms, pH value, sulfate (S) concentration, the molar ratio of Fe/P, temperature, reaction time, and alkalinity (An et al., 2014; Liu et al., 2018; Priambodo et al., 2017; Rothe et al., 2016), among which the first three are the highly outstanding factors and would be specifically analyzed below.

2.3.1. Microorganisms

Microorganisms play a significant part in constructing vivianite, both directly and indirectly.

The direct effects caused by microorganisms contain transformation from (1) Fe^{3+} to soluble Fe^{2+} via the reduction and electron transfer by dissimilatory metal-reducing bacteria (DMRB); (2) organic phosphorus to inorganic PO_4^{3-} by the anaerobic oxidation of methane (AOM); and (3) SO_4^{2-} to S^{2-} through the reduction by sulfate-reducing bacteria (SRB) (Fredrickson et al., 1998; O'Loughlin et al., 2013; Sánchez-Román et al., 2015; Vuillemin

Table 1
The properties of vivianite crystal.

Chemical name	Vivianite	
Formula	$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	
Aspect		
Structure	Nature (Rothe et al., 2016)	Synthetic (Liu et al., 2018) Monoclinic prism, Prismatic 2/m Refractive index $n_x = 1.579$, $n_y = 1.603$, and $n_z = 1.633$ Cleavage Perfect on [010] Unit cell $a = 10.086 \text{ \AA}$, $b = 13.441 \text{ \AA}$, $c = 4.703 \text{ \AA}$; $\beta = 104.27^\circ$; $Z = 2$ (Mori and Ito, 2010; Rodgers et al., 1993; Takagi et al., 1986)
Formula mass	501.61 g/mol	
Specific gravity	2.68	
Solubility constant	10^{-36} (practically insoluble in water) (Nriagu, 1972; Rousset and Jimmy, 2013)	
Analysis method	Scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS) X-ray diffraction (XRD) Mössbauer spectroscopy (Liu et al., 2018; Priambodo et al., 2017; Rousset and Carliell-Marquet, 2016; Wilfert et al., 2018; Wilfert et al., 2016)	

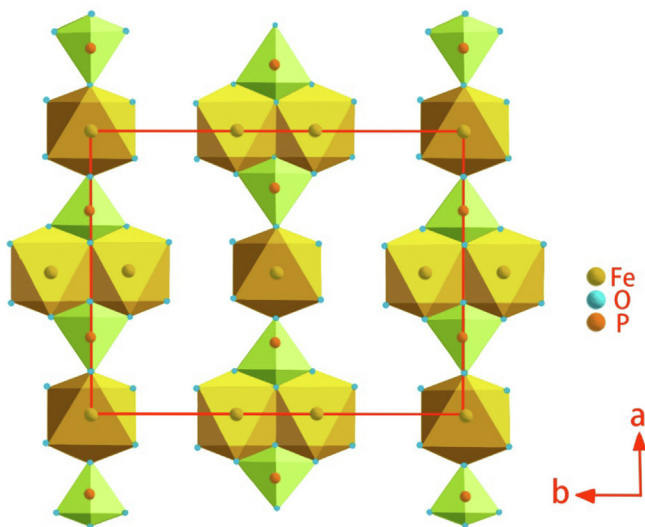


Fig. 1. Diagrammatic sketch of the vivianite structure.

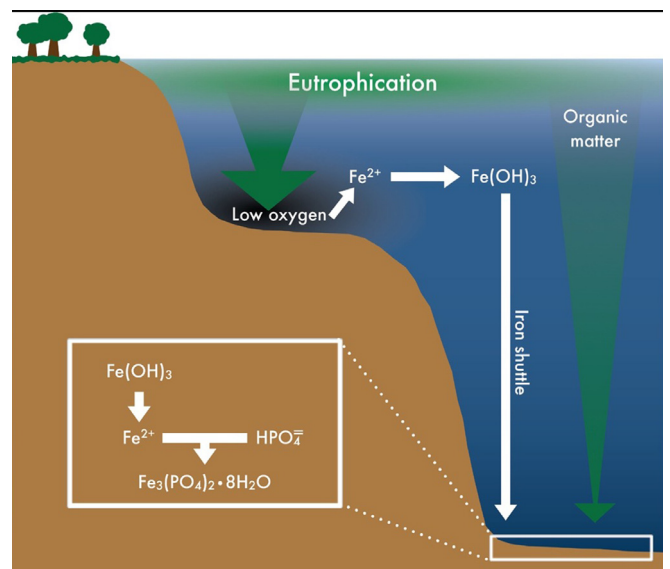


Fig. 2. Simplified vivianite formation process in natural water (Reed et al., 2016).

et al., 2013).

The indirect effects are connected with (1) the modification of the reducing environment by the consumption of electron acceptors such as O_2 , NO_3^- , and Fe^{2+} ; and (2) the production of CO_2 , which

lowers pH values.

Additionally, the cell surfaces of certain microorganisms can act as nucleation sites to induce vivianite formation (Azam and

Finneran, 2014). Microorganism activities can modify the surface microenvironment (pH, oxidation-reduction potential (ORP), ion concentration, etc.), which can also activate mineral formation (Sánchez-Román et al., 2015).

Fig. 3 (Rothe et al., 2016) shows the role of microorganisms in vivianite formation in which OM and Fe(III) (oxyhydr)oxides ($\text{Fe}(\text{O})\text{OH}$), both representing the major sources of orthophosphate and Fe^{2+} in aqueous solution, are the most vital components. Further, the increase in Fe^{2+} and orthophosphate concentrations by microorganisms in water is embraced by two processes: (A) the reduction of Fe^{3+} to Fe^{2+} by DMRB, and (B1) Fe^{2+} release by AOM (Egger et al., 2015), ultimately promoting vivianite formation. In contrast, the decrease in Fe^{2+} and orthophosphate concentrations by the modification of iron sulfides (FeS_x) includes the following two processes: (B2) AOM with SO_4^{2-} and (C) the reduction of SO_4^{2-} , which prevents vivianite formation. Moreover, process (D) illustrates that a decrease or increase in the concentration of both Fe^{2+} and orthophosphate by sorption and desorption thereby influences the formation of vivianite.

Microorganism-induced vivianite formation in wastewater and sludge has also been studied. Azam (Azam and Finneran, 2014) utilized *Geobacter metallireducens* in septic wastewater for phosphorus removal and mineral precipitation; the author discovered that the majority of the P (12–14 mM) was removed as vivianite mineral precipitation, while vivianite was indeed identified on the cell surfaces of microorganism by TEM-EDX. Wang (Wang et al., 2018) also selected *Geobacter* as the primary functional microorganism to engender vivianite formation, the results exposed that the *Geobacter* could reach higher vivianite recovery rates (20–48%) than sewage biomass (7–33%). Besides, Vardanyan (Vardanyan et al., 2018) investigated the influence of a number of aspects on P dissolution at low pH from dewatered anaerobic sludge (DWAS). Subsequently, the results exhibited that *chemolithotrophic acidophilic bacteria* dosing had a negative impact on P dissolution, whereas *acidophilic heterotrophic iron-reducing (HIR) bacteria* dosing increased P dissolution and maintained a low pH value. Additionally, it was pointed out that the Fe–P compound fraction in the sludge could be characterized as vivianite.

2.3.2. pH value

The influences of pH value acting on vivianite formation could be direct and indirect likewise. The former straightforwardly comprise changes in the ionic strength and the solubility product of vivianite to meet the conditions required for formation (An et al., 2014; Priambodo et al., 2017); while the latter implicitly interact with relative microorganism activities.

From the direct perspective, the following two graphs introduce the principles and procedures in depth. The solubility curves of ferrous hydroxide and ferrous phosphate are displayed in Fig. 4 (Priambodo et al., 2017). Lower pH values elevate the solubility of vivianite, which converts vivianite from solid into soluble Fe^{2+} and phosphate. Nonetheless, higher pH values restrain the formation of vivianite because of the competitive effects with $\text{Fe}(\text{OH})_2$ formation. The Pourbaix diagram of iron also indicates this competition. In specific, for vivianite formation, Fe^{2+} ions need an environment with reductive ORP conditions and a lower pH value (<9). The lower the pH value is, the wider the acceptable range of ORP values is. Furthermore, Li (Li et al., 2018a) examined the quantitative Fe speciation of anaerobic fermenters sludge samples under different pH values by the chemical measurements and XANES analysis along with the outcomes showed as Fig. 5. Under environment of pH 6.0, the Fe species were mainly in the solid phase and presented as vivianite (54.7%). However, when pH decreased, the Fe species were largely dissolved in supernatant. For instance, under

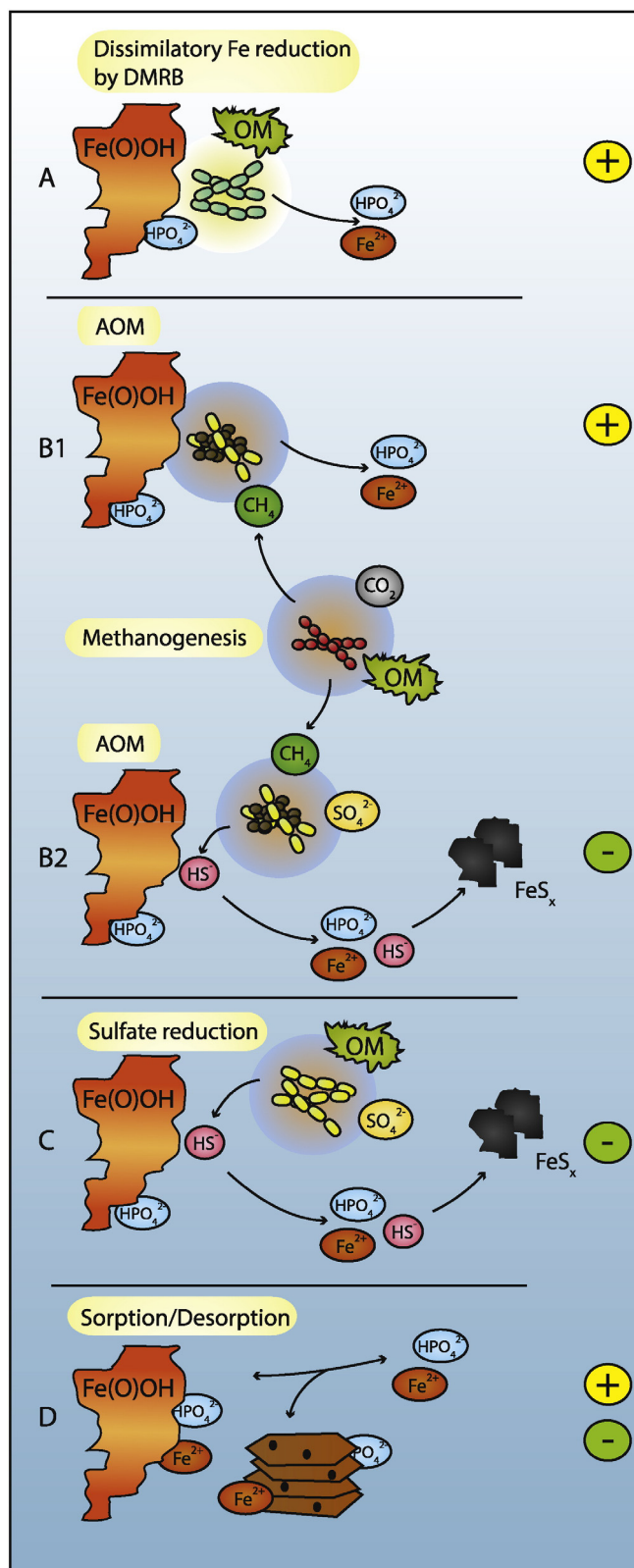


Fig. 3. Role of microorganisms in vivianite formation (Rothe et al., 2016).

environment of pH 3.0, soluble ferrous iron was accounted for the dominant Fe species (77.9%) and the vivianite was not observed.

From the indirect perspective, the pH value also has a remarkable impact on microorganisms as pH can affect the species,

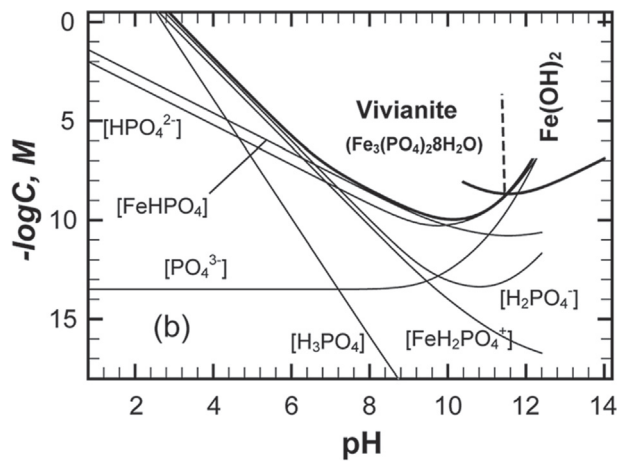


Fig. 4. Solubility curves of ferrous hydroxide and ferrous phosphate (Priambodo et al., 2017).

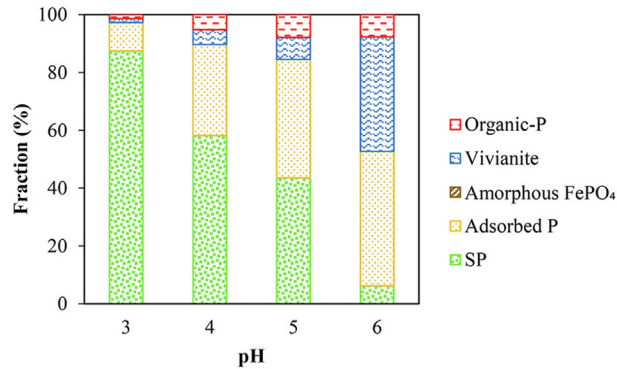


Fig. 5. Fe speciation of sludge samples under different pH values (Li et al., 2018a).

quantities and activities of microorganisms. Numerous studies have observed that iron-reducing microorganisms exist in different pH environments, ranging from extremely low to extremely high (García-Balboa et al., 2009; Gorlenko et al., 2004; Kusel et al., 1999; Lovley, 1991; Thorpe et al., 2012). For example, *Acidiphilium cryptum* JF-5 presents iron reduction ability in acidic sediments (Kusel et al., 1999), and Fe(III)-reducing *Serratia* species performs alkaline tolerance (Thorpe et al., 2012). Furthermore, in WWTPs sludge, pH has been detected to have some effects on the release of phosphorus by microorganisms (Latif et al., 2015, 2017; Vardanyan et al., 2018; Wong et al., 2002). Wong (Wong et al., 2002) explored that half of the phosphorus in anaerobic sludge could be released in the supernatant at a pH of 3.0, but negligible P was released at a pH of 6.0 through adding *Acidithiobacillus ferrooxidans* and $\text{FeS-O}_4 \cdot 7\text{H}_2\text{O}$. Similar results came out from research of Latif (Latif et al., 2015): the chemist observed that the highest soluble P content (75% of total phosphorus (TP)) existed in anaerobic sludge at a pH adjusted to 5.25, while the concentration of P approached initial conditions when pH was maintained at neutral conditions. In addition, Arevik (Vardanyan et al., 2018) proved that P dissolution would increase when dosing *acidophilic* HIR bacteria.

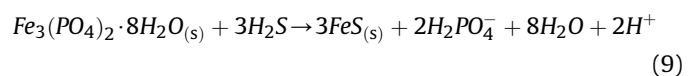
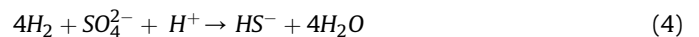
A jar-test procedure to achieve vivianite formation from different wastewaters has been adopted by researchers, and the favorable pH values acquired from these experiments are shown in Table 2. According to these results, the optimal pH value is between 6.0 and 8.0, which is suitable for conventional wastewater treatment and sludge anaerobic digestion (Wilfert et al., 2015).

Table 2
Favorable pH values for the formation of vivianite.

Type of wastewater	Favorable pH values	Reference
Synthetic wastewater	8.0	An et al. (2014)
Thin film transistor-liquid crystal display (TFT-LCD) wastewater	7.0–8.0	Priambodo et al. (2017)
Chemically enhanced primary sedimentation (CEPS)-sludge fermentation supernatant	8.0	Lin et al. (2017a)
Sludge fermentation supernatant	8.0	Li & Li (2017)
Sludge fermentation supernatant	8.0	Li et al. (2018b)
CEPS-sludge fermentation supernatant	7.5	Lin et al. (2017b)
Synthetic wastewater	7.0	Liu et al. (2018)
Septic wastewater	6.0–8.0	Azam & Finneran (2014)

2.3.3. Sulfate concentration

The sulfate concentration also has a critical impact on vivianite formation: sulfate can bind with Fe as mackinawite (FeS) to compete with P and reduce the production and purity of vivianite (Drobner et al., 1990; Gramp et al., 2010; Rothe et al., 2016). As indicated in Eqs (4)–(9), sulfate could firstly be reduced to HS^- by SRB under an anaerobic environment (Mizuno et al., 1998). Secondly, HS^- could be converted into H_2S or S^{2-} at different pH values (Appels et al., 2008; Yan et al., 2018). Fe^{2+} could next precipitate with HS^- and S^{2-} as FeS (Ganigué et al., 2018; Zhang et al., 2009). Notably, the Fe^{2+} in vivianite is favored to combine with H_2S , resulting that PO_4^{3-} re-dissolves into the liquid phase (O'Connell et al., 2015). Rothe (Rothe et al., 2015) studied the relationship between vivianite formation and sulfate concentration in the lake sediments of two hydrologically contrasting waters. As indicated in Fig. 6, the generation of vivianite is only observed at low S:Fe ratios (<1.1). The higher the S:Fe ratio is, the more Fe is bound with S as FeS , and the less Fe can contribute to vivianite formation (Rothe et al., 2016). Roussel (Roussel and Carliell-Marquet, 2016) also obtained similar results in the chemical modeling of sludge anaerobic digestion: higher S concentrations could act as a barrier to vivianite formation.



During the procedure of wastewater treatment and sludge anaerobic digestion, the Fe concentration can be controlled artificially to lower the S:Fe ratio and eliminate the blockage of this factor on vivianite formation. Additionally, the pH range for vivianite formation is much wider than that of FeS , hence the effect of S could be reduced by adjusting the pH to provide preferable conditions (Liu et al., 2018). Furthermore, the concentration of S in anaerobic supernatant is relatively lower than that of P because phosphorus-accumulating bacteria (PAOs) release phosphate into the liquid phase under an anaerobic environment (Lopez-Vazquez

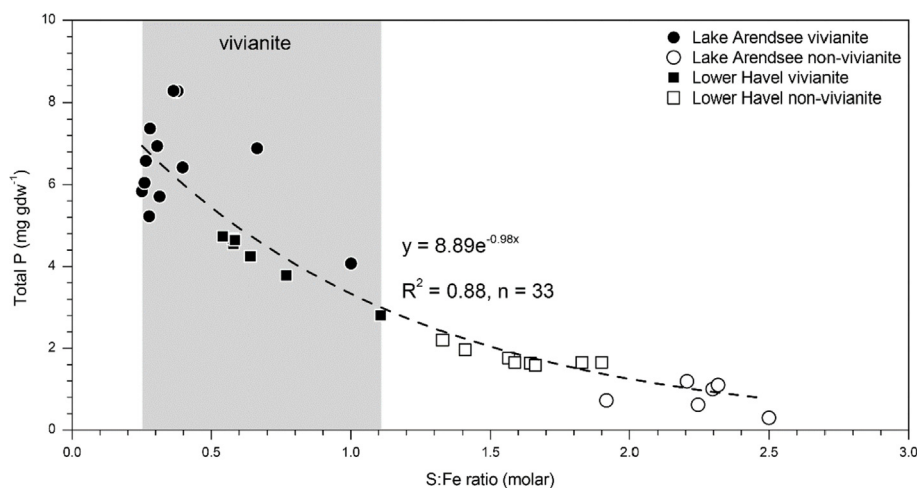


Fig. 6. Relationship between S:Fe molar ratio and vivianite occurrence in the sediment of Lake Arendsee and Lower Havel (Rothe et al., 2015).

et al., 2009). Therefore, according to the stoichiometric molar ratio of vivianite (Fe:P 1.5:1), the need for Fe may be much higher than that for sulfate (Fe:S 1:1). To sum up, the negative impact of S on vivianite formation in treatment processes does not seem to be greater than that in natural waters.

2.3.4. Other factors

Except for the factors discussed above, vivianite formation is also affected by other factors, such as Fe/P ratio, temperature and alkalinity.

The stoichiometric molar ratio of Fe:P in the chemical formula of vivianite is 1.5:1. Experimental data has implied that (1) the Fe^{2+} concentration in solution should slightly exceed the stoichiometric value since OH^- tends to combine with Fe^{2+} to form $\text{Fe}(\text{OH})_2$; (2) a small amount of Fe(II) might be oxidized into Fe(III), both of which may bring competition for the formation of vivianite (An et al., 2014; Priambodo et al., 2017). However, an overdosage of Fe increases supersaturation of $\text{Fe}(\text{OH})_3$, and the color of precipitates collected from jar tests changes from deep blue to dark brown as the Fe/P ratio enlarges (Priambodo et al., 2017). Therefore, the optimal Fe/P ratio range should be controlled between the values of 1.5 and 2.0.

Moreover, the solubility product (K_{sp}) has been studied by professionals with results indicating that K_{sp} did not exhibit apparent differences at different temperatures (from 5 °C to 90 °C) (Al-Borno and Tomson, 1994; Liu et al., 2018; Nriagu, 1972). Madsen (Madsen and Hansen, 2014) also verified this conclusion and noticed that vivianite aggregates were common under 25 °C, while single crystals occurred more frequently at a higher temperature.

Researches have shown that alkalinity, which was frequently discovered in sewage and anaerobic sludge supernatant, might compete with PO_4^{3-} for Fe^{2+} to precipitate siderite (FeCO_3) (Liu et al., 2015; Muserere et al., 2014). Significantly, An (An et al., 2014; Priambodo et al., 2017) added alkalinity (0–1000 mg/L) into Fe^{2+} - and PO_4^{3-} -containing synthetic wastewater and examined that the formation of vivianite was favored over the formation of FeCO_3 . Similar results were also presented by Liu (Liu et al., 2018), who experimentally claimed that higher alkalinity did not virtually prevent the formation of vivianite. Consequently, when P was recovered as vivianite, the competitive effects with alkalinity could be neglected. In contrast, alkalinity should be considered in the recovery of MAP (Jaffer et al., 2002; Tao et al., 2016; Wang et al., 2010).

3. Potential of phosphorus recovery as vivianite

3.1. Economic value of vivianite

Vivianite has attractive economic value because of its richness of P content, easy accessibility and slow release; this material has been employed in both the chemical and agricultural industries, and in other fields (Cabeza et al., 2011; Coccato et al., 2017; Johnston and Richards, 2003; Priambodo et al., 2017).

For instance, Li-ion battery could be reckoned as a promising candidate to power portable electronics as well as electric and hybrid vehicles, and the demand for this product is expected to climb up steadily in coming years (Flexer et al., 2018; Opitz et al., 2017). Vivianite is a fundamental source for the manufacture of lithium iron phosphate (LiFePO_4), which is increasingly being exploited as a precursor when fabricating Li-ion secondary batteries (Li et al., 2015; Ou et al., 2013; Priambodo et al., 2017; Rao and Varadaraju, 2015).

Vivianite can also be utilized as a slow-release fertilizer whose efficiency (Based on the calculation of P uptake by plants) is four to six times higher than that of calcium phosphate, and there is no obvious efficiency difference compared with other forms of recovered P fertilizer, for instance, struvite and hydroxyapatite. (Cabeza et al., 2011; Johnston and Richards, 2003). Yaya Fodoué (Fodoué et al., 2015) states that vivianite could boost the bean crop yield in Ngaoundere and could be considered as an ideal substitute for commonly used traditional chemical fertilizers. Similarly, vivianite was examined in corn planting by Craig Jowett (Jowett et al., 2018) with results disclosing that the P uptake of the corn was almost 8–16% greater than that observed for the control. In addition, recent research has proven that vivianite can efficiently alleviate chlorosis which is caused by iron deficiency conditions and is common in calcareous soil crops, leading to growth depression, leaf necrosis and crop death (Abadía et al., 2011; Díaz et al., 2010). Díaz (Díaz et al., 2009) conducted a three-year experiment to analyze the effectiveness of vivianite on grapevines; the author observed that vivianite could significantly mitigate Fe chlorosis and had a long-term durative effect for at least three years. An analogous conclusion was drawn by Santiago (Santiago et al., 2013) through experiments on strawberries presenting the slow loss of vivianite crystals since oxidization has led to an increase in micronutrients in the plants.

Last but not the least, making use of vivianite as a pigment can be traced back to the 13th and 14th centuries (Coccato et al., 2017;

Cruz et al., 2018). The market price of vivianite is outstandingly highest (approx. 10,000 €/ton), far beyond than other P-containing minerals and products (Alibaba, 2018). To summarize, the recovery of P from wastewater based on vivianite formation could not only contribute to the sustainable use of phosphorus but also provides potential economic opportunities.

3.2. Engineering feasibility of phosphorus recovery as vivianite

3.2.1. Theoretical and applicable basis for phosphorus recovery as vivianite

In the introduction part, this article highlights that wastewater contains a large amount of phosphorus which could meet 15–20% of the global demand and be an essential source for P recovery (Li and Li, 2017; Yuan et al., 2012). Nonetheless, current forms of P recovery, especially struvite, have multiple drawbacks and shortfalls including low product value, strict operating conditions, unsatisfactory recovery efficiency, limitations of utilization, etc., which negatively affect the development for P recovery (Egle et al., 2015; Hao et al., 2013; Huang et al., 2017a; Lin et al., 2017a; Wilfert et al., 2015). Regarding to P recovery as vivianite, the infant approach catching worldwide attention, its recovery potential need to be evaluated specifically as below.

From the perspective of vivianite formation, the dosing cost of iron salts is far cheaper than that of aluminum salts (Huang et al., 2017b) and is similar to that of calcium salts (Huang et al., 2015). However, P precipitation by calcium salts could lead to serious pipe blockage, which would drive up both the cost and the difficulty of treatment. Also, the iron is omnipresent in WWTPs and wastewater (0.5–1.5 mg/L), which could further reduce the dosing cost of external iron salts. Notably, unlike struvite, the formation of vivianite does not require strict operating conditions. Besides, the optimal pH value for vivianite formation is neutral (6.0–9.0), which is appropriate for conventional sewage or sludge treatment, whereas the suitable pH value for struvite is 8.0–9.5 (Huang et al., 2017a; Le Corre et al., 2009; Ye et al., 2017b), which means that adding alkali is required. Additionally, the recovery efficiency of vivianite can currently reach 62.1% with plenty of opportunities for future improvement (Li et al., 2018b; Priambodo et al., 2017), compared with the relatively low percentage (30–40%) of struvite from wastewater which is only possible in WWTPs with enhanced biological P removal (EBPR) (Egle et al., 2015). Currently, chemical phosphorus removal (CPR) is crucial along with increasingly stringent effluent standards; as a result, metals in sludge (iron, aluminum) may further reduce the struvite recovery efficiency (Kataki et al., 2016). Moreover, Fe generally participates in all stages of treatment process to enhance the wastewater treatment effectiveness of factors such as P removal and CH₄ production (Feng et al., 2014; Luo et al., 2018; Wang et al., 2017; Zhang et al., 2015) and to reduce the emission of odorous compounds, for example,

hydrogen sulfide (H₂S), which could be fatal to human beings after long exposure (Park and Novak, 2013; Wei et al., 2017, 2018). Nevertheless, considering the P recovery as struvite, Mg salts are only added in NH₄⁺- and PO₄³⁻-rich wastewater without other prominent advantages. Besides, the market price of P recovery product struvite (approx. 500 €/ton) is far cheaper than the vivianite (approx. 10,000 €/ton). Thus, vivianite may be more beneficial and profitable compared with P recovery as struvite as shown in Table 3.

In terms of WWTPs operating conditions, P recovery from wastewater as vivianite is theoretically feasible based on the following reasons:

- (1) wastewater contains a large amount of P while PAOs and lysed microorganisms could also release P in an anaerobic environment (65–96 mg/L) and in the digester (137–177 mg/L), respectively (Lopez-Vazquez et al., 2009; Wang et al., 2018);
- (2) iron salts are often filled in wastewater as flocculants to remove the P to satisfy strict effluent standards, where iron can enhance the efficiency of anaerobic digestion in terms of parameters including CH₄ production, H₂S control, dewatering ability, volatile solid removal, and pharmaceutical and personal care product (PPCP) degradation (Feng et al., 2014; Luo et al., 2018; Suanon et al., 2017; Wang et al., 2017; Wei et al., 2018);
- (3) the pH values in different WWTP units are typically neutral, which is proper for microorganisms and vivianite formation (Wilfert et al., 2015);
- (4) the presence of sulfide in treatment process does not seem to affect the vivianite formation;
- (5) organic pollutants in wastewater can be used as a carbon source and electron donor for DMRB, which is widely exist in nature, to respectively reproduce themselves and reduce Fe³⁺ to Fe²⁺ (Feng et al., 2014; Karri et al., 2005).

The Fe–P fraction in different WWTP sludge has been studied by several researchers with results presented in Table 4 (Frossard et al., 1997; Poffet et al., 2008; Roussel and Carliell-Marquet, 2016; Wilfert et al., 2016). Compared with non-dosing sludge, vivianite in dosing sludge accounts for at least half of the Fe–P fraction. Meanwhile, the content of vivianite in digested sludge is much greater than that in activated sludge, which means that Fe(III) in sludge could be reduced to Fe(II) and bind with P as vivianite in anaerobic digestion. In particular, the conversion of the Fe fraction within anaerobic digester is described in Fig. 7 in which Fe³⁺ and PO₄³⁻ are reduced, dissolved and re-precipitated as vivianite through the biological activities of DMRB and other reducing microorganisms after the step that the sludge containing Fe³⁺ compounds is fed into the digester. Moreover, vivianite is relatively

Table 3
P recovery as vivianite against the struvite.

P recovery methods	Vivianite	Struvite
Chemical equation	$3\text{Fe}^{2+} + 2\text{PO}_4^{3-} + 8\text{H}_2\text{O} \rightleftharpoons \text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	$\text{Mg}^{2+} + \text{PO}_4^{3-} + \text{NH}_4^+ + 6\text{H}_2\text{O} \rightleftharpoons \text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$
pH	6.0–9.0	8.0–9.5
Extra reagents dosing	Fe salts (Fe is also omnipresent in WWTPs and wastewater)	Mg salts
Applicable treatment process	Conventional treatment process	EBPR
Recovery efficiency	62% (MBR with co-fermentation)	30–40%
The value of products (€/t)	10,000	500
Additional benefits	Phosphorus removal, Sludge flocculation, Odors elimination, Enhance digestion efficiency	

Table 4
Fe–P fraction in different WWTPs sludge.

WWTPs	Location	Treatment process	Sludge Type	Analysis method	Vivianite accounted for Fe–P fraction	Reference
Orléans Thonon Chateauroux	France	CPR with FeSO ₄ addition	Digested sludge Digested sludge Dewatered sludge	SEM XRD Mössbauer spectroscopy	67% 60% 43%	Frossard et al. (1997)
Bern	Switzerland	CPR with FeClSO ₄ addition	Liquid sludge Dried granules	XRD	80% of the total Fe content was Fe(II) 20%	Poffet et al. (2008)
Leeuwarden	Netherlands	EBPR	Activated sludge Digested sludge	SEM-EDX XRD	9–26% 18–36%	Wilfert et al. (2016)
Nieuwveer		AB technology with Fe addition	A-stage surplus sludge B-stage surplus sludge Digested sludge	Mössbauer spectroscopy	52–55% 37–43% 47–59%	
Seven WWTPs	UK	Not mentioned	Digested sludge (Non-Fe-dosed, mixed and Fe-dosed)	SEM-EDS XRD	At least 50% of Fe identified as vivianite in nonsulfide anaerobic digester (AD) More than 90% of Fe identified as vivianite when CPR was included in upstream wastewater treatment	Roussel & Carliell-Marquet (2016)
Several MWTPs	Europe	Not mentioned	Excess and digested sludge	SEM-EDX XRD Mössbauer spectroscopy ICP-OES	Fe(II) as the dominant form of iron (>90%) in digested sewage sludge 70–90%	Wilfert et al. (2018)

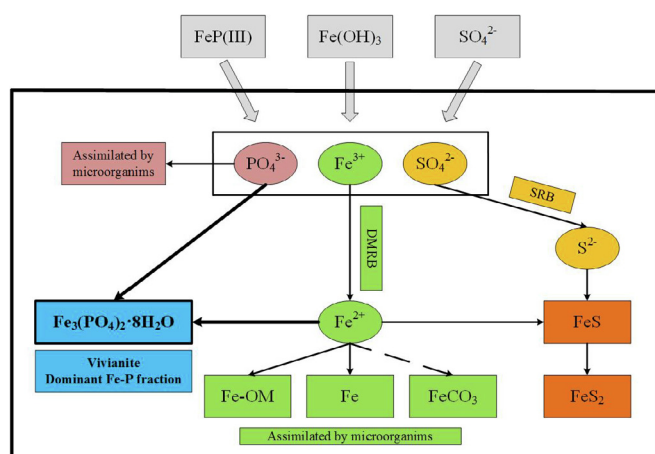


Fig. 7. Illustration of Fe behavior in anaerobic digested sludge.

stable in the aerobic environment associated with the slow oxidation reaction and the limitation of oxygen diffusion in sludge flocs (Roldan et al., 2002). Noticeably, the Fe content shows a positive correlation with the vivianite content in digested sludge. Among a series of digested sludge samples, the one with the highest Fe content (molar ratio Fe:P = 2.5) is detected that 70–90% of the total P was bound in vivianite (Wilfert et al., 2018). These evidences imply that vivianite is the dominant Fe–P fraction in sludge, which provides a realistic basis for the feasibility of P recovery as vivianite.

Therefore, P recovery as vivianite has both theoretical basis and realistic foundation; this approach is competitive compared with other P recovery methods because of its considerable advantages. P recovery as vivianite could offer an innovative route for P recovery with excellent potential and strong feasibility.

3.2.2. Difficulties of phosphorus recovery as vivianite and the possible solutions

During the procedure of wastewater treatment, vivianite forms in the sludge phase, which means that vivianite mixes with sludge as small particles (crystals and aggregates, size 10–150 μm) and is difficult to separate naturally (Wilfert, 2018). Furthermore, these

particles consist of some impurities, for instance, magnesium or calcium, which tend to change the characteristics of vivianite. Remarkably, although pure vivianite can remain stable for several weeks or even years after exposure, vivianite with impurities would be fully oxidized within only 48 h (Miot et al., 2009; Rouzies and Millet, 1993; Wilfert et al., 2018). Hence, both recovery and corresponding methods for vivianite separation and purification are necessary to apply in reality. However, studies of vivianite recovery are relatively few and inadequate with currently existing researches summarized in Table 5.

As presented in Table 5, existing studies mainly focus on Fe(III) reduction in anaerobic digestion/fermentation. Firstly, as a result of the occurrence of Fe(III) reduction and the disintegration of sludge flocs in anaerobic conditions, the pH value is dropped below 5.0, and Fe²⁺ is the predominant Fe fraction (Li et al., 2018b). Also, owing to the high solubility of the Fe(II)–P complex, P and Fe in the sludge are subsequently dissolved and released into the supernatant. Then, through adjusting the pH value of supernatant to 7.0–8.0, Fe²⁺ and PO₄³⁻ would recombine to form a precipitate as vivianite for P recovery (Lin et al., 2017b). At the same time, the remaining supernatant is also comprised of a large amount of volatile fatty acids (VFAs) (Luo et al., 2018), which could (1) be used as an external carbon source for denitrification in biological nutrient removal (BNR) (Frison et al., 2013; Zheng et al., 2018); and (2) facilitate polyhydroxyalkanoate (PHA) biosynthesis (Cai et al., 2009; Munir and Jamil, 2018).

In spite that the maximum P recovery efficiency can reach 62.1% of TP with a growing potential (Li et al., 2018b), among current researches, regrettably, the purity, size, structure and other specific parameters of the recovered vivianite are not evaluated, and how to further separate and purify the vivianite is not presented either. The lack of knowledge and theory in this part would be the barrier of P recovery as vivianite, for which this article accordingly demonstrates three possible methods below as directions of future research.

Crystallization processes might be an ideal way to recover vivianite in Fe²⁺- and PO₄³⁻-containing water in consideration of their simple design, convenient operation, high recovery efficiency and few environmental risks (Dai et al., 2017; Peng et al., 2018; Tarayre et al., 2016). In specific, Vivianite can be crystallized effectively at pH 7.0, following that simple chemical precipitation becomes the dominant reaction. The addition of quartz grains as seeds could

Table 5
Existing studies of P recovery from wastewater as vivianite.

Iron source	Type of wastewater	Treatment process	P recovery as vivianite	References
Ferrihydrite-Fe(III)	Anaerobic digestion supernatant	Anaerobic digestion	Not observed (even at higher saturation index values > 14)	(Cheng et al., 2015; Cheng et al., 2017)
Ferric citrate	Septic system wastewater	Microbial activity (<i>Geobacter metallireducens</i> strain GS-15)	Significant phosphate (12–14 mM) was removed as vivianite	Azam & Finneran (2014)
FeCl ₃	Raw sewage	CEPS and sludge fermentation	23% P recovery efficiency	Lin et al. (2017a)
FeCl ₃	Raw sewage	CEPS and sludge fermentation	31% P recovery efficiency	Lin et al. (2017b)
FeCl ₃	Municipal wastewater	Sequencing batch reactor (SBR) and sludge fermentation with food waste	55.7% P recovery efficiency	Li & Li (2017)
FeCl ₃	Raw sewage	Membrane bioreactor with iron dosing and acidogenic co-fermentation	62.1% P recovery efficiency	(Li et al., 2018a, 2018b)
FeSO ₄	TFT-LCD wastewater	Fluidized-bed crystallization	95% P removal efficiency 63% P crystallization ratio 0.45 mm average size pure vivianite	Priambodo et al. (2017)
Ferric citrate	Septic system wastewater	Microbial activity (<i>Geobacter</i> and Sewage Biomass)	<i>Geobacter</i> -inoculated presented higher vivianite recovery rates (20–48%) than sewage biomass (7–33%) Highest vivianite yield of 4.3 mM (<i>Geobacter</i> -inoculated with Fe:P = 1:1)	Wang et al. (2018)

accelerate crystallization and reduce the need for supersaturation (Liu et al., 2018). These substances were also employed as a seed material in a fluidized-bed crystallizer (FBC) by Priambodo (Priambodo et al., 2017), to recover P as vivianite from TFT-LCD wastewater containing 500 ± 10 ppm P, achieving 95% P removal efficiency and 63% P crystallization ratio. Compared with chemical precipitation, despite that the vivianite recovered by FBC had a larger size (0.45 mm) and lower water content, studies on the mechanism of vivianite crystallization are rare, which needs deeper exploring for the rapid formation and growth of vivianite crystals.

In theory, magnetic separation could also be an approach for vivianite separation from sludge because vivianite is paramagnetic. Nonetheless, the magnetism of paramagnetic materials is extremely weak, and consequently the energy consumption required to maintain a strong magnetic field might be entirely high (Frederichs et al., 2003). Also, Bouderbala (Nguyen, 2017) investigated the solution with a Frantz separator to separate vivianite from sludge; as a result, this machine, which could only be operated with dried materials, had a low separation efficiency due to the aggregation of OM with vivianite in sludge. On the contrary, Magnetic Jones plates, which could be widely manipulated with wet materials in mineral industry, were utilized by Wilfert (Wilfert et al., 2018; Wilfert, 2018) to separate vivianite from digested sewage sludge, and the system achieved a relatively high efficiency (approx. 60%). However, the magnetic characteristics of vivianite particles in sludge are not completely clear, while the removal of OM that is aggregated with the vivianite remains as a serious problem. Therefore, it is severely necessary to gather more detailed information about vivianite characteristics, such as the production, purity and size of vivianite crystals, and the optimal operating conditions to enhance the separation efficiency.

Last but not the least, separation by centrifugation using differences in density may be another feasible way to recover vivianite since this substance is the dominant mineral in CPR-digested sludge and the density of vivianite and sludge is respectively 2.68 g/cm^3 and 1 g/cm^3 . Centrifugation has also been universally utilized for sludge dewatering, which means P recovery may be incorporated with sludge dewatering by improving and optimizing the centrifugal process to develop a new and economic separation method (Ruiz-Hernando et al., 2013).

4. Conclusions and prospects

The shortage of phosphorus resources is gradually becoming a

widely recognized issue and has attracted worldwide attention. Vivianite phosphorus recovery as an innovative practice has been creatively raised due to its natural ubiquity, easy accessibility and foreseeable economic value. The formation of vivianite not only requires a Fe- and P-rich environment but is also restricted by various influencing factors (microorganisms, pH values, the concentration of sulfate, etc.). These demands can be satisfied in WWTPs, which provide a novel and profitable route for P recovery.

However, studies on vivianite formation and phosphorus recovery from wastewater are inadequate and still in their infancy. The sludge system is extremely complicated and comprises of many processes (physical, chemical, biological, etc.), while insufficient understanding on vivianite utilization in wastewater/sludge decelerate the development and exploration of such advanced approach.

Thus, further research should focus on:

- (1) exploring the influencing factors of vivianite formation in depth, particularly the crystallization mechanism, in order to optimize the operating conditions precisely;
- (2) promoting the different separation and purification procedures of vivianite to improve the recovery efficiency;
- (3) consolidating with other treatment processes to enhance the applicability;
- (4) assessing the monetary benefits and environmental risks.

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References

- Abadía, J., Vázquez, S., Rellánálvarez, R., Eljendoubi, H., Abadía, A., Alvarezfernández, A., Lópezmillán, A.F., 2011. Towards a knowledge-based correction of iron chlorosis. *Plant Physiol. Biochem.* 49 (5), 471.
- Adam, C., Peplinski, B., Michaelis, M., Kley, G., Simon, F.G., 2009. Thermochemical treatment of sewage sludge ashes for phosphorus recovery. *Waste Manag.* 29 (3), 1122–1128.
- Al-Borno, A., Tomson, M.B., 1994. The temperature dependence of the solubility product constant of vivianite. *Geochem. Cosmochim. Acta* 58 (24), 5373–5378.
- Alibaba, 2018. Quotation of the Vivianite.
- An, J.-S., Back, Y.-J., Kim, K.-C., Cha, R., Jeong, T.-Y., Chung, H.-K., 2014. Optimization for the removal of orthophosphate from aqueous solution by chemical

- precipitation using ferrous chloride. *Environ. Technol.* 35 (13), 1668–1675.
- Appels, L., Baeyens, J., Degreve, J., Dewil, R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Prog. Energy Combust. Sci.* 34 (6), 755–781.
- Azam, H.M., Finneran, K.T., 2014. Fe(III) reduction-mediated phosphate removal as vivianite (Fe-3(PO4)2)center dot 8H(2)O in septic system wastewater. *Chemosphere* 97, 1–9.
- Bi, W., Li, Y.Y., Hu, Y.Y., 2014. Recovery of phosphorus and nitrogen from alkaline hydrolysis supernatant of excess sludge by magnesium ammonium phosphate. *Bioresour. Technol.* 166, 1–8.
- BMUB, 2017. New Sewage Sludge Ordinance Has Entered into Force. Federal Ministry of Environment.
- Cabeza, R., Steingrobe, B., Roemer, W., Claassen, N., 2011. Effectiveness of recycled P products as P fertilizers, as evaluated in pot experiments. *Nutrient Cycl. Agroecosyst.* 91 (2), 173–184.
- Cai, M., Chua, H., Zhao, Q., Shirley, S.N., Ren, J., 2009. Optimal production of polyhydroxyalkanoates (PHA) in activated sludge fed by volatile fatty acids (VFAs) generated from alkaline excess sludge fermentation. *Bioresour. Technol.* 100 (3), 1399–1405.
- Carpenter, S.R., 2008. Phosphorus control is critical to mitigating eutrophication. *Proc. Natl. Acad. Sci. U.S.A.* 105 (32), 11039–11040.
- Cheng, X., Chen, B., Cui, Y., Sun, D., Wang, X., 2015. Iron(III) reduction-induced phosphate precipitation during anaerobic digestion of waste activated sludge. *Separ. Purif. Technol.* 143, 6–11.
- Cheng, X., Wang, J., Chen, B., Wang, Y., Liu, J., Liu, L., 2017. Effectiveness of phosphate removal during anaerobic digestion of waste activated sludge by dosing iron(III). *J. Environ. Manag.* 193, 32–39.
- Coccatto, A., Moens, L., Vandenabeele, P., 2017. On the stability of mediaeval inorganic pigments: a literature review of the effect of climate, material selection, biological activity, analysis and conservation treatments. *Herit. Sci.* 5 (1), 12.
- Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. *Glob. Environ. Chang.* 19 (2), 292–305.
- Cordell, D., Rosemarin, A., Schroder, J.J., Smit, A.L., 2011. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. *Chemosphere* 84 (6), 747–758.
- Cosmidis, J., Benzerara, K., Morin, G., Busigny, V., Lebeau, O., Jézéquel, D., Noël, V., Dublet, G., Othmane, G., 2014. Biomineralization of iron-phosphates in the water column of Lake pavin (Massif central, France). *Geochem. Cosmochim. Acta* 126 (2), 78–96.
- Cruz, A.J., Eires, E., Dias, L., Desterro, T., Rego, C., 2018. Identification of vivianite, an unusual blue pigment, in a sixteenth century painting and its implications. *Color Res. Appl.* 43 (2), 177–183.
- Dai, L.C., Wu, B., Tan, F.R., He, M.X., Wang, W.G., Qin, H., Tang, X.Y., Zhu, Q.L., Pan, K., Hu, Q.C., 2014. Engineered hydrochar composites for phosphorus removal/recovery: lanthanum doped hydrochar prepared by hydrothermal carbonization of lanthanum pretreated rice straw. *Bioresour. Technol.* 161, 327–332.
- Dai, H., Lu, X., Peng, Y., Yang, Z., Zhssu, H., 2017. Effects of supersaturation control strategies on hydroxyapatite (HAP) crystallization for phosphorus recovery from wastewater. *Environ. Sci. Pollut. Control Ser.* 24 (6), 5791–5799.
- Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B., 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. *Crit. Rev. Environ. Sci. Technol.* 45 (4), 336–384.
- Díaz, I., Barrón, V., Campillo, M.C.D., Torrent, J., 2009. Vivianite (ferrous phosphate) alleviates iron chlorosis in grapevine. *Vitis* 48 (3), 107–113.
- Díaz, I., Barrón, V., del Campillo, M.C., Torrent, J., 2010. Testing the ability of vivianite to prevent iron deficiency in pot-grown grapevine. *Sci. Hortic.* 123 (4), 464–468.
- Dijkstra, N., Slomp, C.P., Behrends, T., 2016. Vivianite is a key sink for phosphorus in sediments of the Landsort Deep, an intermittently anoxic deep basin in the Baltic Sea. *Chem. Geol.* 438, 58–72.
- Donatello, S., Cheeseman, C.R., 2013. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): a review. *Waste Manag.* 33 (11), 2328–2340.
- Drobner, E., Huber, H., Wächtershäuser, G., Rose, D., Stetter, K.O., 1990. Pyrite formation linked with hydrogen evolution under anaerobic conditions. *Nature* 346 (6286), 742–744.
- Egger, M., Rasigraf, O., Sapart, C.J., Jilbert, T., Jetten, M.S.M., Röckmann, T., Veen, C.V.D., Bändä, N., Kartal, B., Ettwig, K.F., 2015. Iron-Mediated anaerobic oxidation of methane in brackish coastal sediments. *Environ. Sci. Technol.* 49 (1), 277–283.
- Egle, L., Rechberger, H., Zessner, M., 2015. Overview and description of technologies for recovering phosphorus from municipal wastewater. *Resour. Conserv. Recycl.* 105, 325–346.
- Fan, J., Zhang, H., Ye, J.S., Ji, B., 2018. Chemical stress from Fe salts dosing on biological phosphorus and potassium behavior. *Water Sci. Technol.* 77 (5), 1222–1229.
- Feng, Y.H., Zhang, Y.B., Quan, X., Chen, S., 2014. Enhanced anaerobic digestion of waste activated sludge digestion by the addition of zero valent iron. *Water Res.* 52, 242–250.
- Fleischer, M., Mandarino Joseph, A., 1991. Glossary of Mineral Species 1991. The Mineralogical Record.
- Flexer, V., Baspineiro, C.F., Galli, C.I., 2018. Lithium recovery from brines: a vital raw material for green energies with a potential environmental impact in its mining and processing. *Sci. Total Environ.* 639, 1188–1204.
- Fodoué, Y., Nguetnkam, J.P., Tchameni, R., Basga, S.D., Penaye, J., 2015. Assessment of the fertilizing effect of vivianite on the growth and yield of the bean “phaseolus vulgaris” on oxisols from Ngaoundere (central North Cameroon). *Int. Res. J. Earth Sci.* 3 (4), 18–26.
- Frederichs, T., von Döbeneck, T., Bleil, U., Dekkers, M.J., 2003. Towards the identification of siderite, rhodochrosite, and vivianite in sediments by their low-temperature magnetic properties. *Phys. Chem. Earth* 28 (16–19), 669–679.
- Fredrickson, J.K., Zachara, J.M., Kennedy, D.W., Dong, H., Onstott, T.C., Hinman, N.W., Li, S.M., 1998. Biogenic iron mineralization accompanying the dissimilatory reduction of hydrous ferric oxide by a groundwater bacterium. *Geochem. Cosmochim. Acta* 62 (19–20), 3239–3257.
- Frison, N., Di Fabio, S., Cavinato, C., Pavan, P., Fatone, F., 2013. Best available carbon sources to enhance the via-nitrite biological nutrients removal from supernatants of anaerobic co-digestion. *Chem. Eng. J.* 215, 15–22.
- Frossard, E., Bauer, J.P., Lothe, F., 1997. Evidence of vivianite in FeSO4-flocculated sludges. *Water Res.* 31 (10), 2449–2454.
- Ganigué, R., Jiang, G., Liu, Y., Sharma, K., Wang, Y.-C., Gonzalez, J., Nguyen, T., Yuan, Z., 2018. Improved sulfide mitigation in sewers through on-line control of ferrous salt dosing. *Water Res.* 135, 302–310.
- García-Balboa, C., Pedraza, A., Blázquez, M.L., Gonzalez, F., Muñoz, J.A., Ballester, A., 2009. The role of iron bacteria on weathering and attenuation processes at acidic environments. *Water Air Soil Pollut.* 199 (1–4), 203–217.
- Gorlenko, V., Tsapin, A., Namsaraev, Z., Teal, T., Tourova, T., Engler, D., Mielke, R., Nealsen, K., 2004. Anaerobranca californiensis sp nov., an anaerobic, alkalithermophilic, fermentative bacterium isolated from a hot spring on Mono Lake. *Int. J. Syst. Evol. Microbiol.* 54, 739–743.
- Gramp, J.P., Bigham, J.M., Jones, F.S., Tuovinen, O.H., 2010. Formation of Fe-sulfides in cultures of sulfate-reducing bacteria. *J. Hazard Mater.* 175 (1), 1062–1067.
- Hansen, H.C.B., Poulsen, I.F., 1999. Interaction of synthetic sulphate “Green rust” with phosphate and the crystallization of vivianite. *Clay Clay Miner.* 47 (3), 312–318.
- Hao, X., Wang, C., van Loosdrecht, M.C.M., Hu, Y., 2013. Looking beyond struvite for P-recovery. *Environ. Sci. Technol.* 47 (10), 4965–4966.
- Heckenmüller, M., Narita, D., Klepper, G., 2014. Global availability of phosphorus and its implications for global food supply: an economic overview. *Kiel Work. Pap. No.1897*.
- Herzel, H., Kruger, O., Hermann, L., Adam, C., 2016. Sewage sludge ash - a promising secondary phosphorus source for fertilizer production. *Sci. Total Environ.* 542, 1136–1143.
- Howie, R.A., 1998. Dana's new Mineralogy eighth edition. *Mineral. Mag.* 62 (3), 431–432.
- Huang, H.M., Liu, J.H., Ding, L., 2015. Recovery of phosphate and ammonia nitrogen from the anaerobic digestion supernatant of activated sludge by chemical precipitation. *J. Clean. Prod.* 102, 437–446.
- Huang, H.M., Zhang, D.D., Li, J., Guo, G.J., Tang, S.F., 2017a. Phosphate recovery from swine wastewater using plant ash in chemical crystallization. *J. Clean. Prod.* 168, 338–345.
- Huang, H.M., Zhang, D.D., Zhao, Z.J., Zhang, P., Gao, F.M., 2017b. Comparison investigation on phosphate recovery from sludge anaerobic supernatant using the electrocoagulation process and chemical precipitation. *J. Clean. Prod.* 141, 429–438.
- Jaffer, Y., Clark, T.A., Pearce, P., Parsons, S.A., 2002. Potential phosphorus recovery by struvite formation. *Water Res.* 36 (7), 1834–1842.
- Jalali, M., Jalali, M., 2016. Relation between various soil phosphorus extraction methods and sorption parameters in calcareous soils with different texture. *Sci. Total Environ.* 566, 1080–1093.
- Johnston, A.E., Richards, I.R., 2003. Effectiveness of different precipitated phosphates as phosphorus sources for plants. *Soil Use Manag.* 19 (1), 45–49.
- Jowett, C., Soltseva, I., Wu, L.L., James, C., Glasauer, S., 2018. Removal of sewage phosphorus by adsorption and mineral precipitation, with recovery as a fertilizing soil amendment. *Water Sci. Technol.* 77 (8), 1967–1978.
- Karri, S., Sierra-Alvarez, R., Field, J.A., 2005. Zero valent iron as an electron-donor for methanogenesis and sulfate reduction in anaerobic sludge. *Biotechnol. Bioeng.* 92 (7), 810–819.
- Kataki, S., West, H., Clarke, M., Baruah, D.C., 2016. Phosphorus recovery as struvite: recent concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer potential. *Resour. Conserv. Recycl.* 107, 142–156.
- Kusel, K., Dorsch, T., Acker, G., Stackebrandt, E., 1999. Microbial reduction of Fe(III) in acidic sediments: isolation of Acidiphilium cryptum JF-5 capable of coupling the reduction of Fe(III) to the oxidation of glucose. *Appl. Environ. Microbiol.* 65 (8), 3633–3640.
- Kusunoki, A., Nanzyo, M., Kanno, H., Takahashi, T., 2015. Effect of water management on the vivianite content of paddy-rice roots. *Soil Sci. Plant Nutr.* 61 (6), 910–916.
- Latif, M.A., Mehta, C.M., Batstone, D.J., 2015. Low pH anaerobic digestion of waste activated sludge for enhanced phosphorus release. *Water Res.* 81, 288–293.
- Latif, M.A., Mehta, C.M., Batstone, D.J., 2017. Influence of low pH on continuous anaerobic digestion of waste activated sludge. *Water Res.* 113, 42–49.
- Le Corre, K.S., Valsami-Jones, E., Hobbs, P., Parsons, S.A., 2009. Phosphorus recovery from wastewater by struvite crystallization: a review. *Crit. Rev. Environ. Sci. Technol.* 39 (6), 433–477.
- Li, R.-h., Li, X.-y., 2017. Recovery of phosphorus and volatile fatty acids from wastewater and food waste with an iron-flocculation sequencing batch reactor and acidogenic co-fermentation. *Bioresour. Technol.* 245 (Part A), 615–624.
- Li, H., Li, C.C., Liu, W.J., Zou, S.X., 2012. Optimized alkaline pretreatment of sludge before anaerobic digestion. *Bioresour. Technol.* 123, 189–194.

- Li, Y., Geng, G., Hao, J., Zhang, J., Yang, C., Li, B., 2015. Optimized synthesis of LiFePO₄ composites via rheological phase assisted method from FePO₄ with acetic acid as dispersant. *Electrochim. Acta* 186, 157–164.
- Li, R.-h., Cui, J.-l., Li, X.-d., Li, X.-y., 2018a. Phosphorus removal and recovery from wastewater using Fe-dosing bioreactor and cofermentation: investigation by X-ray absorption near-edge structure spectroscopy. *Environ. Sci. Technol.* 52 (24), 14119–14128.
- Li, R.-h., Wang, X.-m., Li, X.-y., 2018b. A membrane bioreactor with iron dosing and acidogenic co-fermentation for enhanced phosphorus removal and recovery in wastewater treatment. *Water Res.* 129, 402–412.
- Lin, L., Li, R.-h., Li, Y., Xu, J., Li, X.-y., 2017a. Recovery of organic carbon and phosphorus from wastewater by Fe-enhanced primary sedimentation and sludge fermentation. *Process Biochem.* 54, 135–139.
- Lin, L., Li, R.-h., Yang, Z.-y., Li, X.-y., 2017b. Effect of coagulant on acidogenic fermentation of sludge from enhanced primary sedimentation for resource recovery: comparison between FeCl₃ and PACl. *Chem. Eng. J.* 325, 681–689.
- Liu, X.Y., Xiang, L.C., Song, Y.H., Qian, F., Meng, X.G., 2015. The effects and mechanism of alkalinity on the phosphate recovery from anaerobic digester effluent using dolomite lime. *Environ. Earth Sci.* 73 (9), 5067–5073.
- Liu, J., Cheng, X., Qi, X., Li, N., Tian, J., Qiu, B., Xu, K., Qu, D., 2018. Recovery of phosphate from aqueous solutions via vivianite crystallization: thermodynamics and influence of pH. *Chem. Eng. J.* 349, 37–46.
- Loganathan, P., Vigneswaran, S., Kandasamy, J., Bolan, N.S., 2014. Removal and recovery of phosphate from water using sorption. *Crit. Rev. Environ. Sci. Technol.* 44 (8), 847–907.
- Lopez-Vazquez, C.M., Oehmen, A., Hooijmans, C.M., Brdjanovic, D., Gijzen, H.J., Yuan, Z.G., van Loosdrecht, M.C.M., 2009. Modeling the PAO-GAO competition: effects of carbon source, pH and temperature. *Water Res.* 43 (2), 450–462.
- Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S.M., Kirby, M.X., Peterson, C.H., Jackson, J.B.C., 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* 312 (5781), 1806–1809.
- Lovley, D.R., 1991. Dissimilatory Fe(III) and Mn(IV) reduction. *Microbiol. Rev.* 55 (2), 259–287.
- Luo, J., Zhang, Q., Wu, L., Feng, Q., Fang, F., Xue, Z., Li, C., Cao, J., 2018. Improving anaerobic fermentation of waste activated sludge using iron activated persulfate treatment. *Bioresour. Technol.* 268, 68–76.
- Madsen, H.E.L., Hansen, H.C.B., 2014. Kinetics of crystal growth of vivianite, Fe₃(PO₄)₂·8H₂O, from solution at 25, 35 and 45°C. *J. Cryst. Growth* 401, 82–86.
- McMahon, K.D., Dojka, M.A., Pace, N.R., Jenkins, D., Keasling, J.D., 2002. Polyphosphate kinase from activated sludge performing enhanced biological phosphorus removal. *Appl. Environ. Microbiol.* 68 (10), 4971–4978.
- Mew, M.C., 2016. Phosphate rock costs, prices and resources interaction. *Sci. Total Environ.* 542 (Part B), 1008–1012.
- Miot, J., Benzerara, K., Morin, G., Bernard, S., Beyssac, O., Larquet, E., Kappler, A., Guyot, F., 2009. Transformation of vivianite by anaerobic nitrate-reducing iron-oxidizing bacteria. *Geobiology* 7 (3), 373–384.
- Mizuno, O., Li, Y.Y., Noike, T., 1998. The behavior of sulfate-reducing bacteria in acidogenic phase of anaerobic digestion. *Water Res.* 32 (5), 1626–1634.
- Mori, H., Ito, T., 2010. The structure of vivianite and symplectite. *Acta Crystallogr.* 3 (1), 1–6.
- Munir, S., Jamil, N., 2018. Polyhydroxyalkanoates (PHA) production in bacterial co-culture using glucose and volatile fatty acids as carbon source. *J. Basic Microbiol.* 58 (3), 247–254.
- Muserere, S.T., Hoko, Z., Nhapi, I., 2014. Characterisation of raw sewage and performance assessment of primary settling tanks at Firlle Sewage Treatment Works, Harare, Zimbabwe. *Phys. Chem. Earth* 67–69, 226–235.
- Nanzyo, M., Yaginuma, H., Sasaki, K., Ito, K., Aikawa, Y., Kanno, H., Takahashi, T., 2010. Identification of vivianite formed on the roots of paddy rice grown in pots. *Soil Sci. Plant Nutr.* 56 (3), 376–381.
- Nanzyo, M., Onodera, H., Hasegawa, E., Ito, K., Kanno, H., 2013. formation and dissolution of vivianite in paddy field soil. *Soil Sci. Soc. Am. J.* 77 (4), 1452–1459.
- Nguyen, V.H., 2017. Characterization of Magnetically Separated Material from Sludge – A Comparison to Current Phosphate Fertilizer and Phosphate Rock. Vol. Bachelor of Engineering. van Van Hall Larenstein University of Applied Sciences.
- Nriagu, J.O., 1972. Stability of vivianite and ion-pair formation in the system Fe₃(PO₄)₂-H₃PO₄-H₂O. *Geochem. Cosmochim. Acta* 36 (4), 459–470.
- O'Connell, D.W., Jensen, M.M., Jakobsen, R., Thamdrup, B., Andersen, T.J., Kovacs, A., Hansen, H.C.B., 2015. Vivianite formation and its role in phosphorus retention in Lake Orn, Denmark. *Chem. Geol.* 409, 42–53.
- O'Loughlin, E.J., Boyanov, M.L., Flynn, T.M., Gorski, C.A., Hofmann, S.M., McCormick, M.L., Scherer, M.M., Kemner, K.M., 2013. Effects of bound phosphate on the bioreduction of lepidocrocite (γ-FeOOH) and maghemite (γ-Fe₂O₃) and formation of secondary minerals. *Environ. Sci. Technol.* 47 (16), 9157–9166.
- Opitz, A., Badami, P., Shen, L., Vignarooban, K., Kannan, A.M., 2017. Can Li-Ion batteries be the panacea for automotive applications? *Renew. Sustain. Energy Rev.* 68, 685–692.
- Ou, X., Gu, H., Wu, Y., Lu, J., Zheng, Y., 2013. Chemical and morphological transformation through hydrothermal process for LiFePO₄ preparation in organic-free system. *Electrochim. Acta* 96 (Suppl. C), 230–236.
- Park, C.M., Novak, J.T., 2013. The effect of direct addition of iron(III) on anaerobic digestion efficiency and odor causing compounds. *Water Sci. Technol.* 68 (11), 2391–2396.
- Peng, L., Dai, H., Wu, Y., Peng, Y., Lu, X., 2018. A comprehensive review of phosphorus recovery from wastewater by crystallization processes. *Chemosphere* 197, 768–781.
- Poffet, M.S., Käser, K., Jenny, T.A., 2008. Thermal runaway of dried sewage sludge granules in storage tanks. *Chim. Int. J. Chem.* 62 (1–2), 29–34.
- Priambodo, R., Shih, Y.-J., Huang, Y.-H., 2017. Phosphorus recovery as ferrous phosphate (vivianite) from wastewater produced in manufacture of thin film transistor-liquid crystal displays (TFT-LCD) by a fluidized bed crystallizer (FBC). *RSC Adv.* 7 (65), 40819–40828.
- Rao, S.R., Varadaraju, U.V., 2015. Hydrothermal synthesis of LiFePO₄ nanorods composed of nanoparticles from vivianite precursor and its electrochemical performance for lithium ion battery applications. *Bull. Mater. Sci.* 38 (5), 1–4.
- Rasmussen, H., Nielsen, P.H., 1996. Iron reduction in activated sludge measured with different extraction techniques. *Water Res.* 30 (3), 551–558.
- Reed, D.C., Gustafsson, B.G., Slomp, C.P., 2016. Shelf-to-basin iron shuttling enhances vivianite formation in deep Baltic Sea sediments. *Earth Planet. Sci. Lett.* 434, 241–251.
- Rodgers, K.A., Kobe, H.W., Childs, C.W., 1993. Characterization of vivianite from catavi, llallagua Bolivia. *Mineral. Petrol.* 47 (2–4), 193–208.
- Roldan, R., Barron, V., Torrent, J., 2002. Experimental alteration of vivianite to lepidocrocite in a calcareous medium. *Clay Miner.* 37 (4), 709–718.
- Rothe, M., Frederichs, T., Eder, M., Kleeberg, A., Hupfer, M., 2014. Evidence for vivianite formation and its contribution to long-term phosphorus retention in a recent lake sediment: a novel analytical approach. *Biogeosciences* 11 (18), 5169–5180.
- Rothe, M., Kleeberg, A., Gruneberg, B., Friese, K., Perez-Mayo, M., Hupfer, M., 2015. Sedimentary sulphur: iron ratio indicates vivianite occurrence: a study from two contrasting freshwater systems. *PLoS One* 10 (11), 18.
- Rothe, M., Kleeberg, A., Hupfer, M., 2016. The occurrence, identification and environmental relevance of vivianite in waterlogged soils and aquatic sediments. *Earth Sci. Rev.* 158, 51–64.
- Roussel, J., Carliell-Marquet, C., 2016. Significance of Vivianite Precipitation on the Mobility of Iron in Anaerobically Digested Sludge, vol. 4.
- Roussel, Jimmy, 2013. Metal Behaviour in Anaerobic Sludge Digesters Supplemented with Trace Nutrients. University of Birmingham.
- Rouzies, D., Millet, J.M.M., 1993. Mössbauer study of synthetic oxidized vivianite at room temperature. *Hyperfine Interact.* 77 (1), 19–28.
- Ruiz-Hernando, M., Martinez-Elorza, G., Labanda, J., Llorens, J., 2013. Dewaterability of sewage sludge by ultrasonic, thermal and chemical treatments. *Chem. Eng. J.* 230, 102–110.
- Sánchez-Román, M., Puente-Sánchez, F., Parro, V., Amils, R., 2015. Nucleation of Fe-rich phosphates and carbonates on microbial cells and copolymeric substances. *Front. Microbiol.* 6, 1024.
- Santiago, A.D., Carmona, E., Quintero, J.M., Delgado, A., 2013. Effectiveness of mixtures of vivianite and organic materials in preventing iron chlorosis in strawberry. *Spanish J. Agric. Res.* 11 (1), 208–216.
- Sapota, T., Aldahan, A., Al-Aasm, I.S., 2006. Sedimentary facies and climate control on formation of vivianite and siderite microconcretions in sediments of Lake Baikal, Siberia. *J. Paleolimnol.* 36 (3), 245–257.
- Schindler, D.W., 2006. Recent advances in the understanding and management of eutrophication. *Limnol. Oceanogr.* 51 (1), 356–363.
- Selbig, W.R., 2016. Evaluation of leaf removal as a means to reduce nutrient concentrations and loads in urban stormwater. *Sci. Total Environ.* 571, 124–133.
- Smil, V., 2000. Phosphorus in the environment: natural flows and human interferences. *Annu. Rev. Energy Environ.* 25, 53–88.
- Suanon, F., Sun, Q., Li, M.Y., Cai, X., Zhang, Y.C., Yan, Y.J., Yu, C.P., 2017. Application of nanoscale zero valent iron and iron powder during sludge anaerobic digestion: impact on methane yield and pharmaceutical and personal care products degradation. *J. Hazard Mater.* 321, 47–53.
- Sun, D.Q., Hale, L., Kar, G., Soolanayakanahally, R., Adl, S., 2018. Phosphorus recovery and reuse by pyrolysis: applications for agriculture and environment. *Chemosphere* 194, 682–691.
- Tao, W.D., Fattah, K.P., Huchzermeier, M.P., 2016. Struvite recovery from anaerobically digested dairy manure: a review of application potential and hindrances. *J. Environ. Manag.* 169, 46–57.
- Takagi, S., Mathew, M., Brown, W.E., 1986. Crystal structures of bohierrite and synthetic Mg₃(PO₄)₂·8H₂O. *Am. Mineral.* 71 (9–10), 1229–1233.
- Tarayre, C., De Clercq, L., Charlier, R., Michels, E., Meers, E., Camargo-Valero, M., Delvigne, F., 2016. New perspectives for the design of sustainable bioprocesses for phosphorus recovery from waste. *Bioresour. Technol.* 206, 264–274.
- Thali, M.J., Lux, B., Löscher, S., Rösing, F.W., Hürlimann, J., Feer, P., Dirnhofer, R., Königsdorfer, U., Zollinger, U., 2011. "Brienzli" - the blue Vivianite man of Switzerland: time since death estimation of an adipocere body. *Forensic Sci. Int.* 211 (1), 34–40.
- Thorpe, C.L., Morris, K., Boothman, C., Lloyd, J.R., 2012. Alkaline Fe(III) reduction by a novel alkali-tolerant Serratia sp isolated from surface sediments close to Sellafield nuclear facility, UK. *FEMS Microbiol. Lett.* 327 (2), 87–92.
- Vardanyan, A., Kafa, N., Konstantinidis, V., Shin, S.G., Vyrides, I., 2018. Phosphorus dissolution from dewatered anaerobic sludge: effect of pHs, microorganisms, and sequential extraction. *Bioresour. Technol.* 249, 464–472.
- Vuillemin, A., Ariztegui, D., Coninck, A.S.D., Lücke, A., Mayr, C., Schubert, C.J., Team, T.P.S., 2013. Origin and significance of diagenetic concretions in sediments of Laguna Potrok Aike, southern Argentina. *J. Paleolimnol.* 50 (3), 275–291.
- Wang, C.C., Hao, X.D., Guo, G.S., van Loosdrecht, M.C.M., 2010. Formation of pure struvite at neutral pH by electrochemical deposition. *Chem. Eng. J.* 159 (1–3),

- 280–283.
- Wang, D., Wang, Y., Liu, Y., Ngo, H.H., Lian, Y., Zhao, J., Chen, F., Yang, Q., Zeng, G., Li, X., 2017. Is denitrifying anaerobic methane oxidation-centered technologies a solution for the sustainable operation of wastewater treatment plants? *Bioresour. Technol.* 234, 456–465.
- Wang, S., An, J., Wan, Y., Du, Q., Wang, X., Cheng, X., Li, N., 2018. Phosphorus competition in bioinduced vivianite recovery from wastewater. *Environ. Sci. Technol.* 52 (23), 13863–13870.
- Wei, Y.Y., Dai, J., Mackey, H.R., Chen, G.H., 2017. The feasibility study of autotrophic denitrification with iron sludge produced for sulfide control. *Water Res.* 122, 226–233.
- Wei, J., Hao, X.D., van Loosdrecht, M.C.M., Li, J., 2018. Feasibility analysis of anaerobic digestion of excess sludge enhanced by iron: a review. *Renew. Sustain. Energy Rev.* 89, 16–26.
- Wilfert, P.K., 2018. Phosphate Recovery from Sewage Sludge Containing Iron Phosphate. Delft University of Technology. PhD.
- Wilfert, P., Kumar, P.S., Korving, L., Witkamp, G.-J., van Loosdrecht, M.C.M., 2015. The relevance of phosphorus and iron chemistry to the recovery of phosphorus from wastewater: a review. *Environ. Sci. Technol.* 49 (16), 9400–9414.
- Wilfert, P., Mandalidis, A., Dugulan, A.I., Goubitz, K., Korving, L., Temmink, H., Witkamp, G.J., Van Loosdrecht, M.C.M., 2016. Vivianite as an important iron phosphate precipitate in sewage treatment plants. *Water Res.* 104, 449–460.
- Wilfert, P., Dugulan, A.I., Goubitz, K., Korving, L., Witkamp, G.J., Van Loosdrecht, M.C.M., 2018. Vivianite as the main phosphate mineral in digested sewage sludge and its role for phosphate recovery. *Water Res.* 144, 312–321.
- Withers, P.J.A., Jarvie, H.P., 2008. Delivery and cycling of phosphorus in rivers: a review. *Sci. Total Environ.* 400 (1–3), 379–395.
- Wong, J.W.C., Xiang, L., Chan, L.C., 2002. PH requirement for the bioleaching of heavy metals from anaerobically digested wastewater sludge. *Water Air Soil Pollut.* 138 (1–4), 25–35.
- Yan, L., Ye, J., Zhang, P., Xu, D., Wu, Y., Liu, J., Zhang, H., Fang, W., Wang, B., Zeng, G., 2018. Hydrogen sulfide formation control and microbial competition in batch anaerobic digestion of slaughterhouse wastewater sludge: effect of initial sludge pH. *Bioresour. Technol.* 259, 67–74.
- Ye, Y., Ngo, H.H., Guo, W., Liu, Y., Li, J., Liu, Y., Zhang, X., Jia, H., 2017a. Insight into chemical phosphate recovery from municipal wastewater. *Sci. Total Environ.* 576, 159–171.
- Ye, Z.L., Deng, Y.J., Lou, Y.Y., Ye, X., Zhang, J.Q., Chen, S.H., 2017b. Adsorption behavior of tetracyclines by struvite particles in the process of phosphorus recovery from synthetic swine wastewater. *Chem. Eng. J.* 313, 1633–1638.
- Yuan, Z.G., Pratt, S., Batstone, D.J., 2012. Phosphorus recovery from wastewater through microbial processes. *Curr. Opin. Biotechnol.* 23 (6), 878–883.
- Zhang, L., Keller, J., Yuan, Z., 2009. Inhibition of sulfate-reducing and methanogenic activities of anaerobic sewer biofilms by ferric iron dosing. *Water Res.* 43 (17), 4123–4132.
- Zhang, Z.H., Wang, Y., Leslie, G.L., Waite, T.D., 2015. Effect of ferric and ferrous iron addition on phosphorus removal and fouling in submerged membrane bioreactors. *Water Res.* 69, 210–222.
- Zhao, J., Wang, D., Li, X., Yang, Q., Chen, H., Zhong, Y., Zeng, G., 2015. Free nitrous acid serving as a pretreatment method for alkaline fermentation to enhance short-chain fatty acid production from waste activated sludge. *Water Res.* 78, 111–120.
- Zheng, X., Zhou, W.N., Wan, R., Luo, J.Y., Su, Y.L., Huang, H.N., Chen, Y.G., 2018. Increasing municipal wastewater BNR by using the preferred carbon source derived from kitchen wastewater to enhance phosphorus uptake and short-cut nitrification-denitrification. *Chem. Eng. J.* 344, 556–564.