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## Investigation of Nitrogen and Phosphorus Recovery from Swine Wastewater by Struvite Crystallization

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Swine wastewater is one of the environmental issues that negatively effect on the ecosystem and human health. Developing advanced technologies to treat and recover nutrients from swine wastewater have attracted the attention of scientists. This study investigated the simultaneous removal of nitrogen (N) and phosphorus (P) from swine wastewater by a magnesium ammonium phosphate hexahydrate (struvite, MgNH<sub>4</sub>PO<sub>4</sub>.6H<sub>2</sub>O) crystallization process. The optimal condition for precipitation of struvite was determined at pH 9.0, and Mg<sup>2+</sup>: NH<sub>4</sub><sup>+</sup>: PO<sub>4</sub><sup>3-</sup> ratio of 1.6:1:1.5, and reaction time of 30 minutes, the maximum removal of N and P reached 98.1  $\pm$  0.5% and 98.9  $\pm$  0.4%, respectively. The highest crystallization mass was obtained at 14.6  $\pm$  0.6 *g/l*. In addition, characterization of struvite produced at optimal conditions as analyzed via SEM–EDS. Also, the economic analysis indicated that the struvite crystallization process is cost–feasible and friendly – environmental. These findings illustrated that struvite precipitation is an efficient method for removing both N and P in actual swine wastewater. This paper demonstrates the novel advantages of green technology, contributing to environmental protection towards sustainable development.

Key words: Crystallization, Nutrient recovery, Optimal conditions, Struvite, Swine wastewater

### INTRODUCTION

Swine wastewater typically contains a high concentration of nitrogen (1257 - 3205 mg/l) and phosphorus (25 - 182 mg/l) that cause eutrophication in the receiving bodies of water such as rivers, streams, lakes, and wetlands (Feng et al., 2020; Shim et al., 2021). In Vietnam, the regulation for livestock wastewater was issued to control the N and P discharge in the environment. On the other hand, N and P are referred to as macronutrients, used as the fertilizer for agricultural activities. The worldwide total N fertilizer consumption has been increased from  $11.3 \times 10^6$  tons in 1961 to  $107.6 \times 10^{6}$  tons in 2013 (Lu & Tian, 2017). In recent years, global P fertilizers demand is expected to increase rapidly from  $14.5 \times 10^6$  tons in 2005 to  $22 - 27 \times 10^6$  tons in 2050 (Mogollón et al., 2018), whereas the natural sources will severely deplete in the coming decades. Thus, N and P recovery from wastewater sources is

# These authors contributed equally to this work.

extremely urgent.

Currently, many technologies could be applied to remove N and P from swine wastewater, such as chemical precipitation (Sudiarto et al., 2019), bioremediation (Jiang et al., 2020), physical separation (Sui et al., 2018). However, biological technologies have disadvantages, such as long processing time, large areas, and adaptation period for microorganisms and/or used plant species (Ren et al., 2021). Therefore, aiming to overcome the disadvantages of these above bioremediation technologies, some physical/chemical processes, including struvite precipitation (Kumar & Pal, 2015), ammonia stripping (Zhang et al., 2012), electrodialysis (Ippersiel et al., 2012), reverse osmosis (Lan et al., 2019), and microwave radiation (La et al., 2014) have been suggested to recover and remove N and P in the wastewater. Among these technologies, struvite crystallization has been widely applied thanks to its high removal efficiency for N and P in swine wastewater, short reaction period, and cost-feasibility (Folino et al., 2020; He et al., 2020; Le et al., 2021a; Liu et al., 2011).

Struvite is a crystalline substance involving magnesium, ammonium, and phosphate (e.g.,  $Mg^{2^+}$ ,  $NH_4^+$ , and  $PO_4^{3^-}$ ) in equal molar concentrations (Song *et al...*, 2011). It is a high–quality fertilizer due to its slow–release rate of nutrients, which helps to make it friendly environmental (Gong *et al...*, 2018). Struvite crystallization relies on several factors, in which the molar ratio of  $Mg^{2^+}$ :  $NH_4^+$ :  $PO_4^{3^-}$ , pH value, and reaction time are vital players during the process (Cheng *et al...*, 2019). These factors on struvite precipitation have been examined in previous studies (Nelson *et al...*, 2003; Suzuki *et al...*, 2007). For instance, Bao *et al...* (2011) investigated that the struvite crystal could be reached at pH from 8.0 to 9.0 and Mg:P ratio of 1:2 for nutrient recovery in swine wastewater.

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Mg content is relatively low in swine wastewater, leading to an appropriate Mg source to precipitate struvite crystals.

According to our preliminary survey in Vietnam, the swine wastewater was seriously polluted with high N and P concentrations. Our raw swine wastewater showed that the nitrogen concentration exceeded 13 times, whereas the P concentration was higher than 20 times compared to Vietnam's Regulation of the Effluent of Livestock (QCVN 62-MT:2016/BTNMT). Thus, struvite crystallization was conducted to investigate the efficiency of the proposed simultaneous removal of the N and P processes. This study aims to investigate the optimized conditions for the simultaneous treatment of both N and P in swine wastewater by using struvite precipitation. Based on batch experiments, the factors, which affect the treatment capacity of N and P, including pH, Mg: N: P molar ratio and reaction time, were investigated. In addition, the characterization of struvite crystal was also examined. The obtained results could recommend a basis for examining optimal parameters to simultaneously treat pollutants (i.e., N and P) to yield multi-nutrient products from swine wastewater as nutrient-abundant solutions.

#### MATERIALS AND METHODS

#### **Raw wastewater and chemicals**

Swine wastewater was collected at the anaerobically digested liquor, taken from a pig farm in Tay Ninh province, Vietnam, and kept in the refrigerator at  $5^{\circ}C$ . Before the experiment, the sieve removed coarse particles and suspended solids (0.45 mm pore size 47 mm diameter, Whatman). The physicochemical properties of the swine wastewater are shown in **Table 1**. In this study, 1.5M MgCl<sub>2</sub>.6H<sub>2</sub>O; 1.5M K<sub>2</sub>HPO<sub>4</sub>.3H<sub>2</sub>O; 5M NaOH of analytical grade were used in each experiment.

**Table 1.** The characteristics of swine wastewater and Vietnam discharge standard limits

Parameter	Unit	Mean $\pm$ SD (n=3)	Vietnam's discharge standard limits
pН	_	$8.3 \pm 0.1$	6.0 - 9.0
Temperature	$^{\circ}\mathrm{C}$	$29.0 \pm 1.2$	50.0
$\mathrm{NH_4}^+$	mg/l	$674.9 \pm 73.0$	20.0
$PO_{4}^{3-}$	mg/l	$149.4 \pm 17.7$	4.0
$Ca^{2^+}$	mg/l	$29.1 \pm 4.1$	N/A
$Mg^{2^+}$	mg/l	$113.8 \pm 9.2$	N/A

Notes: N/A: Not available, SD: Standard deviation

### **Experimental procedure**

The schematic diagram of struvite crystallization is shown in **Fig. 1**. Batch experiments of struvite precipitation were examined at different pH values ranging from 8.0 - 10 (at Mg:P ratio of 1, and reaction time of 20 minute), changing Mg:N ratios (1:1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, and 2.0); pH = 9, Mg:P ratio of 1:1, reaction time 20 minute), different Mg:P ratios (1.6:1.2, 1.6:1.3, 1.6:1.4, 1.6:1.5, 1.6:1.6, 1.6:1.7, and 1.6:1.8); pH = 9, Mg:N ratio of 1:1, reaction time 20 minute), and reaction time (10, 20, 30, 40, and 50 minute; Mg:P ratio of 1.6; Mg:N ratio of 1.6:1, and pH = 9). For the experiment testing, the concentrations of P and Mg were added to maintain the molar ratio during the process. All these experiments were conducted at room temperature ( $25^{\circ}C$ ).



Fig. 1. Flowchart of experimentation to select the optimum conditions.

Fig. 2 shows the struvite crystallization process. In the jar-test experiments, 500 ml actual swine wastewater in each 1000 ml beakers were mixed with salts of  $1.5M \text{ MgCl}_2.6\text{H}_2\text{O}$  (Merck, 99%) and  $1.5M \text{ K}_2\text{HPO}_4.3\text{H}_2\text{O}$ (Merck, 99%) to ensure the theoretical molar ratio of Mg:N:P of 1:1:1, which was completely mixed using an impeller at 60 rpm. The pH of the solution was adjusted using 5M NaOH (Merck, 99%) and 1M HCl (Merck, 99%). The mixture was stirred at 60 rpm according to the timeline reaction and finally kept for settling for 30 minutes. After each experiment, the supernatant of the effluent was filtered through a membrane filter ( $0.45 \mu$ m) for component analysis. All experiments were conducted in triplicate.

#### **Analysis methods**

The anion and cation concentration of the influent and effluent levels were determined according to "Standard methods for examining water and wastewater" (Baird, 2017). The pH value was measured by EZDO 8200 portable pH meter (Taiwan). The struvite crystallization was washed with deionized water three times, dried in an oven at 50°C for 24 h, and then characterized by X-ray Diffraction (XRD, DXIII, Rigaku Co., Japan) under the operational condition: CuK $\alpha$  radiation source,  $\lambda = 1.5406$  Å, scanning rate 0.06° s<sup>-1</sup> at the angle



Fig. 2. Diagram of the struvite crystallization process.

of 10–70° ( $2\theta$ ). The precipitates particles' morphology and surface chemical composition were analyzed using the Scanning Electron Microscopy–Energy Dispersive X– ray Spectroscopy (SEM–EDS, S–4800, HI–9039–0006, Hitachi, Japan). In addition, this research utilized the most common statistical descriptive parameters such as mean and standard deviations (±SD). The data were analyzed by the SPSS 25 software package for Windows (SPSS Inc., Chicago, IL, USA). The removal efficiency (H, %) of NH<sub>4</sub><sup>+</sup> and PO<sub>4</sub><sup>3-</sup> were calculated using Equation (1) as follows:

$$H = \frac{C_o - C}{C_o} \times 100\%$$
(1)

Where,  $C_o$  and C are the initial and final concentration of  $NH_4^+$  and  $PO_4^{3-}$  (*mg/l*) in experiment samples, respectively.

#### **RESULTS AND DISCUSSION**

# Jar-tests for struvite precipitation

Effects of pH

The optimal pH for struvite precipitation was investigated through a batch experiment in which the pH range is from 8 to 10. It can be seen from Fig. 3 that the pH values of the solution have a great significant on NH<sub>4</sub> and  $PO_4^{3-}$  removal efficiency. The pH at 10 has the highest NH<sub>4</sub><sup>+</sup> removal efficiency among the five pH values, up to 81.5  $\pm$  3.4%. In contrast, the highest PO<sub>4</sub><sup>3-</sup> removal efficiency at pH 9.0 is up to 96.2  $\pm$  0.51%. The NH<sub>4</sub><sup>+</sup> removal efficiency increases proportionally with the pH value (Le et al., 2020). The difference in the removal efficiency of  $NH_4^+$  could be consistent with the sequence of pH adjustments in the solution. The previous investigations have illustrated that the removal capacity of NH<sup>+</sup> increases as the pH increases during struvite precipitation (Gong et al., 2018; Kim et al., 2017; Lee et al., 2015; Luo et al., 2019; Siciliano & Rosa, 2014).

On the other hand, when the pH changed from 8.0 to 9.0, the precipitate mass also increased from 5.48  $\pm$  1.2 g/l to 6.58  $\pm$  1.08 g/l. However, when the pH value was over 9.0, it was observed that the precipitate mass

decreased and reached 6.17  $\pm$  1.34 g/l at pH = 10 (**Fig. 3a**). Thus, the results demonstrated that NH<sub>4</sub><sup>+</sup> treatment efficiency rose with the pH value increase, but the precipitate mass slightly decreased. This was probably due to the dissociation of NH<sub>4</sub><sup>+</sup>. In the liquid phase, total ammonia–nitrogen (TAN) is in a state of equilibrium between ionized NH<sub>4</sub><sup>+</sup>–N and unionized NH<sub>3</sub> as Equation 2.

$$NH_4^+ \hookrightarrow NH_3 + H^+ \tag{2}$$

The pH value of the solution influenced this equilibrium. At the pH as alkaline, the unionized fraction increases significantly, and NH<sup>+</sup><sub>4</sub>-N is mainly in NH<sub>3</sub>. Therefore, the struvite crystallization reactions could occur in the wastewater containing NH<sub>4</sub><sup>+</sup>-N as a form of  $NH_4^+$ . Thus, the reaction was difficult to occur, causing the struvite mass to decrease slightly. In addition, the pH value of swine wastewater is a vital parameter for the formation of struvite crystallization, which affects not only the amount of precipitation but also its purity crystallization. Previous studies have reported that a variety of  $Mg^{2^+}$  and  $PO_4^{3^-}$  complex ions patterns in the solution (e.g., MgOH<sup>+</sup>, Mg (OH)<sub>3</sub>, MgH<sub>2</sub>PO<sub>4</sub>, H<sub>2</sub>PO<sub>4</sub>, and MgPO<sub>4</sub>) can be formed when the pH value of the solution is changed (Bouropoulos & Koutsoukos, 2000; Shaddel et al., 2019; Wang et al., 2005; Zhang et al., 2017). Side reactions occur easily at high pH, which reduces  $Mg^{2^+}$ ,  $NH_4^+$ , and  $PO_4^{3-}$  reaction. Therefore, pH 9.0 was optimal for struvite precipitation in our experiment.

#### Effects of Mg:N:P molar ratios

Effect of molar ratios (e.g., N/P, Mg/P, etc.) is a critical factor in the struvite crystallization process (Liu *et al...*, 2008; Nelson *et al...*, 2003). Different Mg: N: P molar ratios affected the removal efficiency of  $NH_4^+$  and  $PO_4^{3-}$  significantly. To observe the effect of Mg: N: P molar ratio variations on  $NH_4^+$  and  $PO_4^{3-}$  removal efficiency, the experiments conducted at pH 9.0 were chosen in Section "Effects of pH". The  $NH_4^+$  and  $PO_4^{3-}$  removal were improved significantly with an increasing molar of  $Mg^{2^+}$  when the  $NH_4^+$ :PO<sub>4</sub><sup>3-</sup> ratio was fixed at 1:1 (**Fig. 3b**).



**Fig. 3.** Ammonium and phosphate removal, precipitate mass according to optimum operational factors for swine wastewater: (a) pH; (b) Mg<sup>2+</sup> : NH<sub>4</sub><sup>+</sup> molar ratio; (c) Mg<sup>2+</sup> : PO<sub>4</sub><sup>3-</sup> molar ratio; (d) reaction time.

However, the removal efficiency of  $NH_4^+$  decreased when the  $Mg^{2^+}$  molar increased from 1.3 to 1.6. While the removal efficiency of PO43- was stable and maintained at 99.7%. Therefore, if the molar of  $Mg^{2^+}$  were increased up to a specific value,  $PO_4^{3-}$  removal would not change. Marti et al.. (2008) reported that there could be many different kinds of magnesium phosphate precipitates except for struvite at different values of pH, for example, Mg  $(H_2PO_4)_2$ , MgHPO<sub>4</sub> or Mg<sub>3</sub>  $(PO_4)_2$  (Le *et al.*, 2021b). Thus, it is could be seen that more Mg does not necessarily mean more struvite. The molar of Mg<sup>2+</sup> chosen for the removal of  $NH_4^+$  and  $PO_4^{3-}$  in this experiment is 1.6. Besides, the Mg: N: P molar ratio was kept at 1.6:1:1, the precipitate mass was about 9.04  $\pm$  0.007 g/l, and this value did not illustrate the significant change with increasing Mg<sup>2+</sup> molar.

The effect of PO<sub>4</sub><sup>3-</sup> molar variations on removal efficiency of NH<sub>4</sub><sup>+</sup> and PO<sub>4</sub><sup>3-</sup> was confirmed at a fixed Mg<sup>2+</sup>: NH<sub>4</sub><sup>+</sup> ratio of 1.6:1 (**Fig. 3c**). Higher PO<sub>4</sub><sup>3-</sup> molar improved the removal of NH<sub>4</sub><sup>+</sup> but when the PO<sub>4</sub><sup>3-</sup> molar increased to 1.5, the removal efficiency of PO<sub>4</sub><sup>3-</sup> tended to decrease. On the contrary, the precipitate mass was raised from 16.8 ± 1 g/l to 17.8 ± 1.5 g/l with the above PO<sub>4</sub><sup>3-</sup> molar augmentation. However, more residual phosphate at higher PO<sub>4</sub><sup>3-</sup> molar (data not shown) was detected in the effluent. Thus, overdosing with the PO<sub>4</sub><sup>3-</sup> level can be lead to an adverse process for nutrient products from swine wastewater. The molar of PO<sub>4</sub><sup>3-</sup> chosen

for the removal of ammonium and phosphate is 1.5. Based on the results, we chose the optimum molar ratio of Mg: N: P was 1.6:1:1.5.

#### Effects of reaction time

The period of the reaction among  $Mg^{2^+}$ ,  $NH_4^+$ , and  $PO_4^{3-}$  to form struvite has been studied to establish the required optimal time. To observe the influence of reaction time on  $NH_4^+$  and  $PO_4^{3-}$  treatment efficiency, the experiments conducted at pH 9.0 and a molar ratio of 1.6  $Mg^{2^+}$ : 1  $NH_4^+$ : 1.5  $PO_4^{3-}$  were chosen in Sections "Effects of pH" and "Effects of Mg:N:P molar ratios".

**Fig. 3d** shows the variation of  $NH_4^+$  and  $PO_4^{3-}$ removal efficiency and the change of precipitate mass with increased reaction time. As the reaction time increased from 10 to 30 minutes, the highest removal efficiency of  $NH_4^+$  (98.1 ± 0.5%) and  $PO_4^{3-}$  (98.9 ± 0.4%) reached at 30 minutes, and then slightly decreased with the reaction time increased to 50 minutes. It can be observed that the reaction time had a negligible effect on the removal of  $NH_4^+$  and  $PO_4^{3-}$ , but had a light effect on the size of the struvite crystal. It was found from the results reported by Stratful et al. (2001) that when the reaction time was increasing (from 1 to 180 minutes), the size of crystals increased (from 0.1 to 3 mm). Although the increasing reaction time could increase the size of the struvite crystal, the excessing reaction time may break the crystallization system, leading to a



Fig. 4. The precipitation of (a) crystallization and (b) powder struvite product.

decrease not only the capability of struvite crystallization but also NH<sub>4</sub><sup>+</sup> and PO<sub>4</sub><sup>3-</sup> removal. In this study, the highest precipitate mass obtained was 14.6 ± 0.6 g/l, and the mass of precipitate did not change significantly when increasing the reaction time from 10 to 50 minutes. Similarly, Wang *et al.*. (2019) investigated the reaction time from 20 to 50 minutes during the struvite crystallization process. These results illustrated that the highest recovery of NH<sub>4</sub><sup>+</sup> (97.3%) and PO<sub>4</sub><sup>3-</sup> (98.2%) was obtained at 30 minutes. Therefore, the main factors such as pH, molar ratio, and retention time play a critical role that significantly effects on the recovery of NH<sub>4</sub><sup>+</sup> and PO<sub>4</sub><sup>3-</sup> from wastewater.

#### Struvite crystallization

#### Precipitation of struvite compounds

According to Bhuiyan *et al.*. (2007), the solubility product of struvite ( $K_{sp}$ ) was reported equal to  $10^{-13.26}$ , and the struvite precipitation can efficiently be achieved to remove nitrogen and phosphorus in wastewater. Furthermore, the simultaneous treatment of both ammonium ( $NH_4^+$ ) and phosphate ( $PO_4^{3-}$ ) in presenting ammonium from swine wastewater demonstrated efficient struvite precipitation. In this study, struvite product is a white crystal formed in light alkali conditions and slightly soluble in water (**Fig. 4**).

By checking the element's content (O, P, and Mg) showed the purity of recovered struvite compounds was high and was not impacted by Ca<sup>2+</sup> precipitation. Previous studies reported that  $Ca^{2+}$  could affect striate crystallization due to the integrated PO<sub>4</sub><sup>3-</sup> (Hao *et al...*, 2008; Liu & Wang, 2019; Shen et al., 2011; Song et al., 2007). In the condition of Ca:Mg molar ratios over 0.5, Ca<sup>2+</sup> could inhibit and affect the crystallization reaction as well as its purity (Song et al., 2007). In the present study, however, the Ca: Mg molar ratios varied from 0.28 to 0.67 (at the optimal condition of 0.45), showing a satisfying recovery of the good crystals. Thus, at optimal conditions such as pH = 9.0 and molar ratio of 1.6 Mg<sup>2+</sup>: 1  $NH_4^+$ : 1.5  $PO_4^{3-}$ , reaction time was determined at 30 minutes in the batch tests. Thus,  $NH_4^+$  can be combined with other ions such as  $Mg^{2+}$  and  $PO_4^{3-}$  to form struvite crystals. According to the crystallization process, precipitate mass obtained the highest value up to 14.6  $\pm$ 0.6 g/l. In addition, the struvite precipitation removed about 98.1  $\pm$  0.5% NH<sub>4</sub><sup>+</sup> and 98.9  $\pm$  0.4% PO<sub>4</sub><sup>3-</sup> in swine wastewater at optimal conditions. Our results showed that over 98% of the NH<sub>4</sub><sup>+</sup> and PO<sub>4</sub><sup>3-</sup> are recovered as struvite during the crystallization process. Therefore, it could be seen that the struvite crystallization can efficiently remove both nitrogen and phosphorus from swine wastewater.

#### Characterization of struvite precipitates

The XRD spectrum shown in **Fig. 5a** confirms the crystal phase of particles was struvite with  $2\theta$  peaks at 15.24°, 16.03°, 25.09°, 31.76°, and 38.09° for facets of (101), (002), (112), (211) and (213), respectively, and shows the characteristic peak of the K–struvite crystal (MgKPO<sub>4</sub>·6H<sub>2</sub>O), implying the co–precipitation of K struvite. Therefore, the cation of K<sup>+</sup> could have come from the high K–concentration (>300 ppm) of actual swine wastewater that is a minor impurity phase.

Fig. 5b shows the SEM images of struvite crystallization collected under optimal conditions (pH = 9.0, Mg:N:P of 1.6:1:1.5, and retention time 30 minute). The struvite precipitates have a butterfly shape with an average diameter of 0.7 mm. Under high magnification, the nuclei had needles, irregular and coarse shape structures.

The EDS spectrum of **Fig. 5c** shows that the main surface elements of particle were Cl, Mg, P, O, N, and K and no Na peak, implying that no magnesium sodium phosphate (NaMgPO<sub>4</sub>) was formed, and the atomic percentages of Mg, N, P, and O were 8.59%, 11.84%, 9.80%, and 53.65%, respectively. These results indicated a similar composition to struvite stoichiometry. Furthermore, the atomic ratio of potassium (K) accounts for 2.67%, suggesting that magnesium potassium phosphate (MgKPO<sub>4</sub>.6H<sub>2</sub>O) might co–precipitate with struvite.

In addition, the characterization of the struvite (e.g., size, crystal type) has been examined and compared the results to previous studies (**Table 2**). As a result, it could be seen that the main element content, size, and



Fig. 5. (a) XRD patterns, (b) SEM images [ $\times$ 500 magnification, scale bar = 100  $\mu$ m], and (c) EDS spectrum of struvite crystals product. (pH = 9.0, Mg<sup>2+</sup>:NH<sub>4</sub><sup>+</sup>:PO<sub>4</sub><sup>3-</sup> of 1.6:1:1.5, and 30 min).

Table 2. An overview of struvite crystallization from swine wastewa	ater
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No.	Additional chemicals	P/Mg molar ratio	pH range	Time	Reactor type	Major elements	Size (length)	Crystal type	References
1	$\begin{array}{l} \mathrm{MgCl}_{2},\\ \mathrm{K}_{2}\mathrm{HPO}_{4} \end{array}$	1:1.1	9.0	30 min	Batch	O (49.6%) P (18.5%) Mg (12.8%)	$100\mu{\rm m}$	Irregular shaped, coarse	This study
2	$\mathrm{MgCl}_{2},\ \mathrm{K}_{2}\mathrm{HPO}_{4}$	1:1.2	8.0-9.5	N/A	Batch	N/A	N/A	N/A	(Lee <i>et al.</i> , 2009)
3	$\mathrm{MgCl}_2$	1:1.2	8.0–9.0	5 weeks	Continuous flow	N/A	N/A	Irregular shaped, coarse	(Rahman <i>et al.</i> , 2011)
4	$Mg^{2+}$	1: 0.8–1.0	7.8-8.9	4 hours	Continuous flow	N/A	N/A	Irregular shape crys–tals	(Liu et al., 2011)
5	$Mg^{2^+}$	N/A	8.0-9.5	40 min	Batch	Mg, P, O	10–30 $\mu \mathrm{m}$	Tiny needle–shaped, irregular crystals	(Huang <i>et al.</i> , 2014)
6	$\mathrm{MgCl}_2$	1:1.2	8.5	N/A	Batch	P (28.6%) Mg (20.9%)	$\sim$ 50 $\mu$ m	Regulated crystals, coarse	(Wu et al., 2018)
7	$Mg^{2^+}$ , $PO_4^{3-}$	1:1.2	9.5	N/A	Batch	Mg, N, P	N/A	N/A	(Cai <i>et al.</i> , 2020)

Note: N/A – Not available.

crystal shapes were similar to the struvite crystallization process in the previous studies. Thus, the struvite forms of the precipitates were indicated as the well–detected crystals.

#### Struvite crystallization mechanism

According to the diffusion reaction theory, the crystallization mechanism illustrated that crystal clusters and solute molecules are transported from the fluid phase into the solid surface and precipitating struvite compounds (Myerson, 2002). Also, Rahman *et al.*. (2014) showed that the struvite crystal process occurs through two chemical phases: nucleation (crystal birth) and crystal growth. Crystallization has occurred when mixing molecules such as  $Mg^{2+}$ ,  $NH_4^+$ , and  $PO_4^{3-}$  each other and its contact in clusters at a favorable pH to crystal growth. Thus, struvite is formed when  $Mg^{2^+}$ ,  $NH_4^+$ , and  $PO_4^{3-}$  obtained equal molar amounts as the following chemical reactions:

 $Mg^{2^{+}} + NH_{4}^{+} + PO_{4}^{3^{-}} + 6H_{2}O \rightarrow MgNH_{4}PO_{4} \cdot 6H_{2}O \qquad (3)$ 

$$Mg^{2^{+}} + NH_{4}^{+} + HPO_{4}^{2^{-}} + 6H_{2}O \rightarrow MgNH_{4}PO_{4} \cdot 6H_{2}O + H^{+}$$
(4)

$$Mg^{2^{+}} + NH_{4}^{+} + H_{2}PO_{4}^{-} + 6H_{2}O$$
  
$$\rightarrow MgNH_{4}PO_{4} \cdot 6H_{2}O + 2H^{+}$$
(5)

Where the ionic interactions among  $Mg^{2^+}$  and  $PO_4^{3-}$  complexes (i.e.,  $PO_4^{3-}$ ,  $HPO_4^{2-}$ ,  $H_2PO_4^{-}$ ) are seen as the cause of the formation of  $MgPO_4^{-}$ ,  $MgHPO_4$  and  $MgH_2PO_4^{+}$ . In



Fig. 6. Interaction of  $Mg^{2+}$ ,  $NH_4^+$ ,  $PO_4^{3-}$  in struvite crystallization.

Table 3.	Summary	of technologies for removal of swine wa	stewater nutrients
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Technology	Type of reactor	Added chemi- cals	pH value	HRT/SRT	Removal efficiency	Cost/Benefit	References
Struvite	Batch	MgCl <sub>2</sub> .6H <sub>2</sub> O K <sub>2</sub> HPO <sub>4</sub> .3H <sub>2</sub> O	9.0	30 min	98.1 ± 0.5% (NH <sub>4</sub> <sup>+</sup> ) 98.9 ± 0.4% (PO <sub>4</sub> <sup>3-</sup> )	0.20 USD/m <sup>3</sup>	This research
Struvite	Batch	$Mg^{2^+}$	8.0-9.5	40 min	82.0% (NH <sub>4</sub> <sup>+</sup> ) 98.0% (PO <sub>4</sub> <sup>3-</sup> )	-3.65 USD/m <sup>3</sup>	(Huang <i>et al.</i> , 2014)
Microwave radiation	Microwave oven	None	8.0 - 12.0	5 min	83.1% (NH <sub>4</sub> <sup>+</sup> )	N/A	(La et al., 2014)
Electrocoagulation	Fe electrode	None	8.2 - 9.2	61.8 – 118.2 min	55.0 – 91.0% (TP)	N/A	(Mores <i>et al.</i> , 2016)
Struvite	Batch	$\mathrm{MgCl}_2$	8.5	N/A	93.0% (NH <sub>4</sub> <sup>+</sup> ) 99.0% (PO <sub>4</sub> <sup>3-</sup> )	+1.35 USD/m <sup>3</sup>	(Wu et al., 2018)
Constructed wetlands	SFCW	None	N/A	11 days (HRT)	$87.7 - 97.9\% (NH_4^+)$	N/A	(Luo <i>et al.</i> , 2018)
Phyto-technologies	Floating aquatic plants	None	5.9 - 7.0	N/A	63.2% (TN) 36.2% (TP)	N/A	(Sudiarto <i>et al.</i> , 2019)
Membrane bioreactor	SMBR	None	7.5	20 days (SRT) 33–51 hours (HRT)	83.0–97.0% (NH <sub>4</sub> <sup>+</sup> )	N/A	(Xu et al., 2019)
Spraying technology	Experimental device	None	>7.0	N/A	88.4% (NH <sub>4</sub> <sup>+</sup> )	N/A	(Cao et al., 2019)
Microalgae cultivation	Batch culture	None	9.0	N/A	45.0% (NH <sub>4</sub> <sup>+</sup> ) 70.0% (PO <sub>4</sub> <sup>3-</sup> )	N/A	(Gracida– Valdepeña <i>et al.</i> , 2020)
Aerobic granular sludge	AGSBR	None	N/A	4 hours	81.2% (NH <sub>4</sub> <sup>+</sup> ) 97.4% (TP)	N/A	(Wang <i>et al.</i> , 2020)
Bioelectrochemical systems	MFC	None	$7.5 \pm 0.15$	24 hours (HRT)	$66.6 \pm 1.4\% (\text{NH}_{4}^{+})$ $32.1 \pm 2.8\% (\text{PO}_{4}^{3-})$	N/A	(Cheng <i>et al.</i> , 2021)
Biochar	Continuous flow	None	9.0	3 hours	$79.0 \pm 6.1\%$ (COD) $84.0 \pm 2.5\%$ (BOD <sub>5</sub> )	N/A	(Lap et al., 2021)

Notes: N/A: Not available, (-): Cost, (+): Benefit, TP: Total phosphorus, TN: Total nitrogen, COD: Chemical Oxygen Demand, BOD<sub>5</sub>: Biological Oxygen Demand

addition, the reaction kinetics of struvite crystallization which could be observed by the interaction of  $Mg^{2^+}$ ,  $NH_4^+$ , and  $PO_4^{3^-}$  ions are shown in **Fig. 6**. In these, the struvite crystallization process relies on many important factors such as concentrations of  $PO_4^{3^-}$ ,  $Mg^{2^+}$ ,  $NH_4^+$ , pH value, and Mg/P ratio, etc. (Desmidt *et al.*, 2013; Kozik *et al.*, 2013; Song *et al.*, 2007).

In this study, experimental results showed the highly  $NH_4^+$  and  $PO_4^{3-}$  recovered efficiency at pH = 9.0. After conducting  $Mg^{2^+}$  and  $PO_4^{3-}$  changes, we chose the optimal molar ratio of  $Mg^{2^+}$ :  $NH_4^+$ :  $PO_4^{3-}$  was 1.6:1:1.5. According to the crystallization process, precipitate mass obtained the highest value up to  $14.6 \pm 0.6 g/l$  from swine wastewater. Thus, it could be confirmed that the mechanism of struvite formation is strongly dependent on the interaction of  $Mg^{2^+}$ ,  $NH_4^+$ , and  $PO_4^{3-}$  ions and pH value. In addition, based on struvite precipitation, crystals could be considered to recover organic nutrients (e.g., TOC,  $NH_4^+$ , and  $PO_4^{3-}$ ) in swine wastewater (Suzuki *et al.*, 2007).

# Comparison of recovery performance of different technologies

As shown in **Table 3**, the struvite technology performed better than the different technologies for the removal of nutrients, and the removal rate can reach as high as 98% in the struvite process.  $NH_4^+$  is completely removed via chemical crystallization, and the product is applied as a fertilizer for agriculture (Kim et al., 2017). In contrast, the biological methods remove  $NH_4^+$  from wastewater by metabolism, accumulation in biomass, and cell synthesis (Metcalf et al., 2014). Besides, the treatment time of biological methods is also longer than that of the struvite technology. On the other hand, physicochemical processes can achieve high NH4+ removal efficiency and fast reaction time such as microwave, but the mechanism of NH<sub>3</sub> removal was suggested as the formation of molecular NH<sub>3</sub> and the subsequent evaporation of NH<sub>3</sub> by microwave radiation (Lin et al., Regarding physicochemical methods such as 2009). microwave radian, spraying, and electrocoagulation are difficult to apply in full scale because it requires much energy to operate. This suggests that struvite technology is one of the current and potential treatment technologies for swine wastewater in developing countries.

#### CONCLUSIONS

The recovery of nitrogen and phosphorus from the actual swine wastewater was conducted by struvite crystallization. Under pH of 9.0, Mg:N:P of 1.6:1:1.5, and reaction time of 30 minute, the treatment efficiencies of  $NH_4^+$  and  $PO_4^{3-}$  were 98.1  $\pm$  0.5% and 98.9  $\pm$  0.4%, respectively. The formed particles (with an average size of 0.70 mm) have proven to be a struvite phase of MgNH<sub>4</sub>PO<sub>4</sub>.6H<sub>2</sub>O with a precipitated mass value up to 14.6  $\pm$  0.6 g/l. The particle form of the precipitates was confirmed by XRD analysis and indicated that their struvite crystals could be further recycled as a slow–release fertilizer for agricultural practice in developing countries

(e.g., Vietnam, China, India). Also, cost–analysis (0.20 USD/m<sup>3</sup>) indicated that struvite crystallization is a great potential technology for nutrient recovery from swine wastewater.

### AUTHOR CONTRIBUTIONS

Nguyen Minh KY and Huynh Tan NHUT: conceptualization, investigation, methodology, draft manuscript. Nguyen Trung HIEP and Nguyen Tri Quang HUNG: investigation, methodology, reviewing and editing. Bui Quoc LAP and Chitsan Lin: conceptualization, supervision of methodology and experimental activities, revision of the manuscript and played the role of the corresponding author. Tran Thi Minh TAM: methodology. Akinori OZAKI advised methodology and supported to the manuscript arrangement and revision.

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#### REFERENCES

- Baird, R. B. 2017. Standard Methods for the Examination of Water and Wastewater, 23rd. Water Environment Federation, American Public Health Association, American
- Bao, X.-D., Ye, Z.-L., Ma, J.-H., Chen, S.-H., Lin, L.-F., Yan, Y.-J. 2011. Effect of pH on precipitate composition during phosphorus recovery as struvite from swine wastewater. *Huan jing ke xue*, **32**(9): 2598–2603
- Bhuiyan, M., Mavinic, D., Beckie, R. 2007. A solubility and thermodynamic study of struvite. *Environmental technology*, 28(9): 1015–1026
- Bouropoulos, N. C., Koutsoukos, P. G. 2000. Spontaneous precipitation of struvite from aqueous solutions. *Journal of Crystal Growth*, **213**(3–4): 381–388
- Cai, J., Ye, Z.-L., Ye, C., Ye, X., Chen, S. 2020. Struvite crystallization induced the discrepant transports of antibiotics and antibiotic resistance genes in phosphorus recovery from swine wastewater. *Environmental Pollution*, **266**: 115361
- Cao, L., Wang, J., Zhou, T., Li, Z., Xiang, S., Xu, F., Ruan, R., Liu, Y. 2019. Evaluation of ammonia recovery from swine wastewater via a innovative spraying technology. *Bioresource technology*, 272: 235–240
- Cheng, D., Ngo, H., Guo, W., Chang, S., Nguyen, D., Kumar, S. 2019. Microalgae biomass from swine wastewater and its conversion to bioenergy. *Bioresource technology*, **275**: 109–122
- Cheng, D., Ngo, H. H., Guo, W., Chang, S. W., Nguyen, D. D., Liu, Y., Liu, Y., Deng, L., Chen, Z. 2021. Evaluation of a continuous flow microbial fuel cell for treating synthetic swine wastewater containing antibiotics. *Science of The Total Environment*, **756**: 144133
- Desmidt, E., Ghyselbrecht, K., Monballiu, A., Rabaey, K., Verstraete, W., Meesschaert, B. D. 2013. Factors influencing urease driven struvite precipitation. *Separation and Purification Technology*, **110**: 150–157
- Feng, C., Zhang, S., Wang, Y., Wang, G., Pan, X., Zhong, Q., Xu, X., Luo, L., Long, L., Yao, P. 2020. Synchronous removal of

ammonium and phosphate from swine wastewater by two agricultural waste based adsorbents: Performance and mechanisms. *Bioresource technology*, **307**: 123231

- Folino, A., Zema, D. A., Calabrò, P. S. 2020. Organic matter removal and ammonia recovery by optimised treatments of swine wastewater. *Journal of Environmental Management*, 270: 110692
- Gong, W., Li, Y., Luo, L., Luo, X., Cheng, X., Liang, H. 2018. Application of struvite–MAP crystallization reactor for treating cattle manure anaerobic digested slurry: nitrogen and phosphorus recovery and crystal fertilizer efficiency in plant trials. *International journal of environmental research and public health*, **15**(7): 1397
- Gracida–Valdepeña, M. L., Navarro–Aguirre, F., Herrera–Acosta, K., Ulloa–Mercado, G., Meza–Escalante, E., Plascencia–Jatomea, R., González–Meza, G., Serrano–Palacios, D. 2020. Nutrient removal from swine wastewater using a thermotolerant strain of Chlorella sp. grown under outdoor conditions. *Journal of Chemical Technology & Biotechnology*, **95**(4): 1243–1249
- Hao, X.–D., Wang, C.–C., Lan, L., Van Loosdrecht, M. 2008. Struvite formation, analytical methods and effects of pH and Ca2+. Water Science and technology, 58(8): 1687–1692
- He, C., Chen, Y., Liu, C., Jiang, Y., Yin, R., Qiu, T. 2020. The role of reagent adding sequence in the NH 4+–N recovery by MAP method. *Scientific reports*, **10**(1): 1–6
- Huang, H., Xiao, D., Pang, R., Han, C., Ding, L. 2014. Simultaneous removal of nutrients from simulated swine wastewater by adsorption of modified zeolite combined with struvite crystallization. *Chemical Engineering Journal*, **256**: 431–438
- Ippersiel, D., Mondor, M., Lamarche, F., Tremblay, F., Dubreuil, J., Masse, L. 2012. Nitrogen potential recovery and concentration of ammonia from swine manure using electrodialysis coupled with air stripping. *Journal of environmental management*, **95**: S165–S169
- Jiang, M., Westerholm, M., Qiao, W., Wandera, S. M., Dong, R. 2020. High rate anaerobic digestion of swine wastewater in an anaerobic membrane bioreactor. *Energy*, **193**: 116783
- Kim, D., Min, K. J., Lee, K., Yu, M. S., Park, K. Y. 2017. Effects of pH, molar ratios and pre-treatment on phosphorus recovery through struvite crystallization from effluent of anaerobically digested swine wastewater. *Environmental Engineering Research*, **22**(1): 12–18
- Kozik, A., Hutnik, N., Piotrowski, K., Mazienczuk, A., Matynia, A. 2013. Precipitation and crystallization of struvite from synthetic wastewater under stoichiometric conditions. *Advances* in Chemical Engineering and Science, **3**(4): 20
- Kumar, R., Pal, P. 2015. Assessing the feasibility of N and P recovery by struvite precipitation from nutrient-rich wastewater: a review. *Environmental Science and Pollution Research*, **22**(22): 17453–17464
- La, J., Kim, T., Jang, J. K., Chang, I. S. 2014. Ammonia nitrogen removal and recovery from swine wastewater by microwave radiation. *Environmental Engineering Research*, **19**(4): 381–385
- Lan, L., Kong, X., Sun, H., Li, C., Liu, D. 2019. High removal efficiency of antibiotic resistance genes in swine wastewater via nanofiltration and reverse osmosis processes. *Journal of envi*ronmental management, 231: 439–445
- Lap, B. Q., Thinh, N. V. D., Hung, N. T. Q., Nam, N. H., Dang, H. T. T., Ba, H. T., Ky, N. M., Tuan, H. N. A. 2021. Assessment of Rice Straw–Derived Biochar for Livestock Wastewater Treatment. *Water, Air, & Soil Pollution*, 232(4): 1–13
- Le, V.-G., Vo, D.-V.N., Nguyen, N.-H., Shih, Y.-J., Vu, C.-T., Liao, C.-H., Huang, Y.-H. 2021a. Struvite Recovery from Swine Wastewater using Fluidized–Bed Homogeneous Granulation Process. Journal of Environmental Chemical Engineering, 9: 105019
- Le, V.-G., Vu, C.-T., Shih, Y.-J., Bui, X.-T., Liao, C.-H., Huang, Y.-H. 2020. Phosphorus and potassium recovery from human urine using a fluidized bed homogeneous crystallization (FBHC) process. *Chemical Engineering*, **384**: 123282
- Le, V. G., Vo, D. V. N., Tran, H. T., Duy Dat, N., Luu, S. D., Rahman,

M. M., Huang, Y. H., Vu, C. T. 2021b. Recovery of Magnesium from Industrial Effluent and Its Implication on Carbon Capture and Storage. *ACS Sustainable Chemistry Engineering*, **9**(19): 6732–6740

- Lee, E. Y., Oh, M. H., Yang, S.-H., Yoon, T. H. 2015. Struvite crystallization of anaerobic digestive fluid of swine manure containing highly concentrated nitrogen. Asian–Australasian Journal of Animal Sciences, 28(7): 1053
- Lee, J., Rahman, M., Ra, C. 2009. Dose effects of Mg and PO4 sources on the composting of swine manure. *Journal of haz*ardous materials, **169**(1–3): 801–807
- Lin, L., Yuan, S., Chen, J., Xu, Z., Lu, X. 2009. Removal of ammonia nitrogen in wastewater by microwave radiation. *Journal of hazardous materials*, **161**(2–3): 1063–1068
- Liu, X., Wang, J. 2019. Impact of calcium on struvite crystallization in the wastewater and its competition with magnesium. *Chemical Engineering Journal*, **378**: 122121
- Liu, Y., Kwag, J.-H., Kim, J.-H., Ra, C. 2011. Recovery of nitrogen and phosphorus by struvite crystallization from swine wastewater. *Desalination*, 277(1–3): 364–369
- Liu, Z., Zhao, Q., Lee, D.-J., Yang, N. 2008. Enhancing phosphorus recovery by a new internal recycle seeding MAP reactor. *Bioresource technology*, **99**(14): 6488–6493
- Luo, P., Liu, F., Zhang, S., Li, H., Yao, R., Jiang, Q., Xiao, R., Wu, J. 2018. Nitrogen removal and recovery from lagoon–pretreated swine wastewater by constructed wetlands under sustainable plant harvesting management. *Bioresource technology*, **258**: 247–254
- Lu, C., Tian, H. 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. *Earth System Science Data*, 9(1): 181–192
- Luo, Z., Wang, D., Yang, J., Huang, H., Su, G. 2019. Nitrogen removal from digested piggery wastewater using fermented superphosphate within the pretreatment stage and an MAP fertilizer pot test. *Journal of Cleaner Production*, **212**: 372–380
- Marti, N., Bouzas, A., Seco, A., Ferrer, J. 2008. Struvite precipitation assessment in anaerobic digestion processes. *Chemical Engineering Journal*, **141**(1–3): 67–74
- Metcalf, Eddy, Abu–Orf, M., Bowden, G., Burton, F. L., Pfrang, W., Stensel, H. D., Tchobanoglous, G., Tsuchihashi, R., AECOM. 2014. Wastewater engineering: treatment and resource recovery. McGraw Hill Education
- Mogollón, J. M., Beusen, A. H. W., van Grinsven, H. J. M., Westhoek, H., Bouwman, A. F. 2018. Future agricultural phosphorus demand according to the shared socioeconomic pathways. *Global Environmental Change*, **50**: 149–163
- Mores, R., Treichel, H., Zakrzevski, C. A., Kunz, A., Steffens, J., Dallago, R. M. 2016. Remove of phosphorous and turbidity of swine wastewater using electrocoagulation under continuous flow. *Separation and Purification Technology*, **171**: 112–117
- Myerson, A. 2002. Handbook of industrial crystallization. Butterworth–Heinemann
- Nelson, N. O., Mikkelsen, R. L., Hesterberg, D. L. 2003. Struvite precipitation in anaerobic swine lagoon liquid: effect of pH and Mg: P ratio and determination of rate constant. *Bioresource Technology*, 89(3): 229–236
- Rahman, M. M., Liu, Y., Kwag, J.-H., Ra, C. 2011. Recovery of struvite from animal wastewater and its nutrient leaching loss in soil. *Journal of hazardous materials*, **186**(2–3): 2026–2030
- Rahman, M. M., Salleh, M. A. M., Rashid, U., Ahsan, A., Hossain, M. M., Ra, C. S. 2014. Production of slow release crystal fertilizer from wastewaters through struvite crystallization–A review. *Arabian journal of chemistry*, 7(1): 139–155
- Ren, B., Wang, T., Zhao, Y. 2021. Two-stage hybrid constructed wetland-microbial fuel cells for swine wastewater treatment and bioenergy generation. *Chemosphere*, **268**: 128803
- Shaddel, S., Ucar, S., Andreassen, J.–P., Østerhus, S. W. 2019. Engineering of struvite crystals by regulating supersaturation– correlation with phosphorus recovery, crystal morphology and process efficiency. *Journal of Environmental Chemical Engineering*, 7(1): 102918

- Shen, Y., Ogejo, J., Bowers, K. 2011. Abating the effects of calcium on struvite precipitation in liquid dairy manure. *Transactions of the ASABE*, **54**(1): 325–336
- Shim, S., Reza, A., Kim, S., Won, S., Ra, C. 2021. Nutrient recovery from swine wastewater at full-scale: An integrated technical, economic and environmental feasibility assessment. *Chemosphere*, 277: 130309
- Siciliano, A., Rosa, S. D. 2014. Recovery of ammonia in digestates of calf manure through a struvite precipitation process using unconventional reagents. *Environmental technology*, **35**(7): 841–850
- Song, Y.-H., Qiu, G.-L., Yuan, P., Cui, X.-Y., Peng, J.-F., Zeng, P., Duan, L., Xiang, L.-C., Qian, F. 2011. Nutrients removal and recovery from anaerobically digested swine wastewater by struvite crystallization without chemical additions. *Journal of hazardous materials*, **190**(1–3): 140–149
- Song, Y., Yuan, P., Zheng, B., Peng, J., Yuan, F., Gao, Y. 2007. Nutrients removal and recovery by crystallization of magnesium ammonium phosphate from synthetic swine wastewater. *Chemosphere*, **69**(2): 319–324
- Stratful, I., Scrimshaw, M., Lester, J. 2001. Conditions influencing the precipitation of magnesium ammonium phosphate. *Water research*, **35**(17): 4191–4199
- Sudiarto, S. I. A., Renggaman, A., Choi, H. L. 2019. Floating aquatic plants for total nitrogen and phosphorus removal from treated swine wastewater and their biomass characteristics. *Journal of environmental management*, 231: 763–769
- Sui, Q., Jiang, C., Yu, D., Chen, M., Zhang, J., Wang, Y., Wei, Y. 2018. Performance of a sequencing–batch membrane bioreactor (SMBR) with an automatic control strategy treating high– strength swine wastewater. *Journal of hazardous materials*, 342: 210–219

- Suzuki, K., Tanaka, Y., Kuroda, K., Hanajima, D., Fukumoto, Y., Yasuda, T., Waki, M. 2007. Removal and recovery of phosphorous from swine wastewater by demonstration crystallization reactor and struvite accumulation device. *Bioresource technol*ogy, **98**(8): 1573–1578
- Wang, F., Fu, R., Lv, H., Zhu, G., Lu, B., Zhou, Z., Wu, X., Chen, H. 2019. phosphate Recovery from swine Wastewater by a struvite precipitation electrolyzer. *Scientific reports*, 9(1): 1–10
- Wang, J., Burken, J. G., Zhang, X., Surampalli, R. 2005. Engineered struvite precipitation: Impacts of component-ion molar ratios and pH. *Journal of Environmental Engineering*, **131**(10): 1433–1440
- Wang, X., Chen, Z., Shen, J., Kang, J., Zhang, X., Li, J., Zhao, X. 2020. Effect of carbon source on pollutant removal and microbial community dynamics in treatment of swine wastewater containing antibiotics by aerobic granular sludge. *Chemosphere*, 260: 127544
- Wu, Z., Zou, S., Zhang, B., Wang, L., He, Z. 2018. Forward osmosis promoted in-situ formation of struvite with simultaneous water recovery from digested swine wastewater. *Chemical Engineering Journal*, **342**: 274–280
- Xu, Z., Song, X., Li, Y., Li, G., Luo, W. 2019. Removal of antibiotics by sequencing-batch membrane bioreactor for swine wastewater treatment. *Science of The Total Environment*, 684: 23–30
- Zhang, L., Lee, Y.-W., Jahng, D. 2012. Ammonia stripping for enhanced biomethanization of piggery wastewater. *Journal of hazardous materials*, **199**: 36–42
- Zhang, T., Jiang, R., Deng, Y. 2017. Phosphorus recovery by struvite crystallization from livestock wastewater and reuse as fertilizer: a review. *In:* "Physico–Chemical Wastewater Treatment and Resource Recovery", IntechOpen, pp. 135–152