



Recycle of electrolytically dissolved struvite as an alternative to enhance phosphate and nitrogen recovery from swine wastewater

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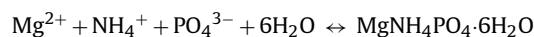
ABSTRACT

Operational parameters such as electric voltage, NaCl, reaction time (RT) and initial struvite amount were optimized for struvite dissolution with a designed electrolysis reactor, and the effect of recycling the dissolved solution on the performance of struvite crystallization was also assessed. The electrolytic reactor was made of plexiglas having titanium plate coated with iridium oxide as anode (surface area: 400 cm²) and stainless steel plates as cathodes. For reutilization of dissolved struvite, four runs were conducted with different recycle ratio of the solution. Optimum conditions for the electric voltage, NaCl, RT and initial struvite amount were 7 V, 0.06%, 1.5 h and 1.25 g/L, respectively. At the above optimized conditions, 49.17 mg/L phosphate (PO₄³⁻-P) was dissolved and ammonium–nitrogen (NH₄-N) got completely removed from the solution. When 0.0, 0.5, 1.0 and 2.0 moles of the dissolved struvite with respect to PO₄³⁻-P in swine wastewater were recycled along with 0.5 M magnesium chloride (MgCl₂), the PO₄³⁻-P removal was 63, 69, 71 and 79%, and NH₄-N was 9, 31, 40 and 53%, respectively. Hence, the performance of struvite formation process was proportionally increased. It is concluded that struvite can be re-dissolved by electrolysis and reused as a source of P and Mg.

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1. Introduction

Phosphorus (P) is a valuable and limited resource. It is estimated that there are seven billion tons of phosphate rock as P₂O₅ remaining in reserves that could be economically mined. The human population consumes as much as 40 million tons of P as P₂O₅ each year and P demand is increasing by 1.5% each year. Hence, global reserves of high-quality mined phosphate deposits are being gradually depleted. It is predicted that the resource could be exhausted in 100–250 years [1]. Consequently researchers are concerned for alternative and renewable source of P. Swine wastewater is considered to be a good source for P recovery because of the presence of high concentrations of P. Struvite crystallization is an ideal and efficient technique to remove and recover P from wastewater due to its high removal effectiveness and reaction rate. According to our previous study [2], if proper operation parameters were provided, about 90% P could be easily recovered as struvite from the swine wastewater. Struvite consists of equal molar concentrations of magnesium, ammonium and phosphate. The chemical reaction is expressed as follows [3]:



Since swine wastewater contains high amounts of NH₄-N with respect to orthophosphate (PO₄³⁻-P) (more than 20 times), the NH₄-N removal during crystallization of struvite is very low [2]. To enhance the NH₄-N removal, high amounts of external P and Mg source should be added. However, the high cost of Mg salts and P consumption for the effective removal of ammonia would become the main obstacle to the wide application of the struvite precipitation process [4]. Therefore, it is preferable to reduce the usage of Mg and P. If the struvite could be re-dissolved and ammonia could be completely removed from the struvite, the remaining Mg and P would not only be a good source for ammonia removal, but also decrease the external addition of Mg and P sources. In recent years, many researchers found that the residues of struvite decomposed by heating under alkali conditions could be used as P and Mg sources, reducing operation cost [5–8].

Electrolysis, a modern treatment technology, has also attracted a great deal of attention in the application of the wastewater treatment. It is reported that the electrolysis is a simple, reliable, cost-effective and promising technique [9]. The key process in electrolysis is the interchange of atoms and ions by the removal or addition of electrons from an external circuit. The electrolysis efficiency depends on several factors such as electric voltage, ionic concentration, electrode material and reaction time, and optimizing such factors play an important role towards the success of the process. This technology has been successfully used for the removal of ammonia from various types of wastewaters such as landfill

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leachate [10], tannery wastewater [11,12], municipal discharges [13], power plant effluents [14], and sludge digester effluents [15]. So, the electrolysis method would be a fine approach to completely remove ammonia from the struvite and recycle the residue as an alternate source of Mg and P. The removal mechanism of ammonia in the electrolytic process is poorly understood in terms of the oxidation route. A direct oxidation of ammonia to nitrogen gas has been observed by Panizza et al. [16]. The removal of ammonia also took place through an indirect oxidation route by both hydroxyl radicals and hypochlorous acid (HOCl) [13].

Till date, according to our knowledge, there are no reports in the literature specifically on the applicability of electrolysis technology for struvite dissolution. Therefore, in the present study, operational parameters for electrolysis process to achieve the dissolution of Mg^{2+} and PO_4^{3-} -P from struvite as well as NH_4^+ removal were determined. In addition, the effectiveness of the recycling the electrolytically dissolved struvite on the performance of the crystallization process was also examined.

2. Materials and methods

2.1. System configuration

A schematic illustration of the experimental apparatus is shown in Fig. 1. The system consisted of an electrolytic reactor for struvite dissolution, struvite crystallization and recovery reactor for swine wastewater treatment and a purification system to recover pure struvite. The electrolytic reactor was made of Plexiglas and spigots were installed at the top and bottom of the reactor in order to facilitate the influent loading and effluent decanting, respectively. The working volume, height and diameter were 4.0 L, 120 cm and 8 cm, respectively. Ti plate coated with IrO_2 (thickness: 1 mm) was used as anode and placed at the center of the reactor. The anode surface area in the electrolytic reactor was 400 cm^2 ($100 \text{ cm}^2/\text{L}$, $100 \text{ cm} \times 4 \text{ cm}$). Two stainless steel plates (thickness: 1.2 mm) were used as cathodes, which were arranged parallel to each other on either side of the anode plate by an acrylic band. The distance between each electrode was fixed as 1 cm in order to obtain an efficient electric field. The apex of the reactor was sealed along with the electrodes by acrylic and silicone gel. The electricity was regulated by a digital DC power supply (DC 12 V 30 A, Model: WER 312) by connecting it with the electrodes. The struvite crystallization and recovery reactor had a reaction zone (A) and a settling zone (B). The working volume of the reactor and the inner reaction zone was 12.3 and 2.72 L, respectively. A spigot was installed at the bottom of the settling zone to retrieve the formed struvite crystals from the reactor.

2.2. Experimental procedure

Based on information from our previous study [2] on struvite purification, the sediment slurry was collected from the bottom of the reactor by centrifuging at 3000 rpm for 10 min. The obtained struvite-solid was dissolved into an acidic solution ($\text{pH} < 4.0$) after which the supernatant was collected. Then pH of the supernatant was increased over 10.0 by addition of 1 M NaOH solution to derive pure struvite crystal formation. Subsequently, the white crystals were recovered, washed for three times with distilled water ($\text{pH} 8.5$) and allowed to dry at room temperature. Pure struvite was collected and prepared for dissolution experiment.

Four factors (NaCl concentration, electric voltage, RT and struvite amount) affecting the pattern of struvite dissolution (PO_4^{3-} -P dissolution and NH_4 -N removal) in the designed electrolytic reactor were studied to optimize the operational parameters.

In the first set of experiment, the effect of NaCl and voltage on the electrolytic struvite dissolution was examined by gradually increasing the NaCl concentration (0.01, 0.02, 0.04, 0.06, and 0.08% or 0.1, 0.2, 0.4, 0.6 and 0.8 g/L) at three different voltages (5, 7 and 9 V, respectively). The electrolysis process was operated in a batch mode and the RT was 6 h and initial struvite amount of 1.25 g/L. Pure struvite and NaCl were mixed well with tap water ($\text{pH} 8.0$) before loading into the electrolytic reactor. The ideal NaCl and voltage level selected based on the obtained results was used for further investigation.

In the second set, the effect of RT and struvite amount on the electrolytic process for struvite dissolution was studied. For which different struvite amount (0.25, 0.50, 1.00, 1.25 and 2.50 g/L) was used and RT was taken as 2.5 h.

The electrolytically dissolved struvite is collected in the container and stored till further use. To test the effect of recycling of the electrolytically dissolved struvite (as the source of P and Mg) for swine wastewater treatment, four sets of experiment (one control and three runs) were carried out. For control only 0.5 M MgCl_2 with respect to the PO_4^{3-} -P in the swine wastewater and distilled water ($\text{pH} 8.0$) in the same volume as the recycled supernatant was added into the struvite crystallization reactor at the same time of influent feeding. Different recycle ratio of the dissolved struvite (i.e. 0.5, 1 and 2 M respectively) along with 0.5 M of MgCl_2 was loaded into the process in runs I, II and III. The detailed layout of the experimental design is presented in Table 1. The struvite crystallization and recovery reactor was operated in a continuous flow mode and 4 h RT. The reaction zone was continuously aerated through an air stone to achieve CO_2 air stripping, and the aeration rate of 0.73 L/L/min was controlled by an air flow meter. MgCl_2 as a source of Mg^{2+} was loaded into the reaction zone along with the influent and the recycled supernatant.

2.3. Sampling and analytical method

For struvite dissolution experiment, samples were taken at every 30 min from the electrolytic reactor and filtered immediately through membrane filter ($0.45 \mu\text{m}$). The filtrate was mixed with one drop of 1 N HCl before analysis. Samples were also collected from the influent and effluent storage buckets of the crystallization and recovery reactor daily. The samples were stored at 4°C until analysis for a week. All the samples were centrifuged at 3000 rpm for 5 min to separate the solids. The parameters studied immediately were total solids (TS) and suspended solids (SS), while supernatant of all the samples were analyzed for PO_4^{3-} -P and NH_4 -N with the auto water analyzer (Quick Chem 8500, LACHAT) later on. All analyses were performed according to standard methods [17].

2.4. Swine wastewater

The swine wastewater used during this study was collected from a local farm. The swine wastewater was stored in a 25 L container at 4°C until it was required. Prior to utilization, the swine wastewater was screened by a sieve with 0.5-mm mesh openings to remove large solids before being fed into the influent container. The characteristics of the swine wastewater used in this experiment are shown in Table 2.

3. Results and discussion

3.1. Effect of NaCl addition

In electrolysis process, the ionic conductivity of the solution is a significant parameter. Since the current passing through the circuit is a function of the conductivity under a certain applied

Table 1
Operational conditions for struvite crystallization reactor.

Parameters	Control	Run I	Run II	Run III
Struvite recycle ratio to $\text{PO}_4^{3-}\text{-P}$ (M)	0.0+ (DW)	0.5+ (DW)	1.0+ (DW)	2.0
MgCl_2 to $\text{PO}_4^{3-}\text{-P}$ (M)	0.5	0.5	0.5	0.5

DW, distilled water, added to maintain the volume of recycled struvite same in all the operations; $\text{PO}_4^{3-}\text{-P}$, ortho-phosphate.

Table 2
Characteristics of the swine wastewater.

Parameter	Mean	Maximum	Minimum	Std. Deviation
pH	8.31	8.41	8.19	0.05
$\text{PO}_4^{3-}\text{-P}$ (mg/L)	31.62	38.09	26.95	2.61
$\text{NH}_4\text{-N}$ (mg/L)	2623.50	2846.12	2403.52	68.01
TS (g/L)	10.73	12.13	9.62	0.63
SS (g/L)	2.21	3.30	1.66	0.35

$\text{PO}_4^{3-}\text{-P}$, orthophosphate; $\text{NH}_4\text{-N}$, ammonium nitrogen; TS, total solids; SS, suspended solids.

electric voltage hence, ionic conductivity of the solution affects the current efficiency, applied electric voltage and consumption of electric energy in the electric systems [18]. In the present study, NaCl was used as the supporting electrolyte because it increases the electric conductivity of the solution and thus reduces the energy consumption. Irdemez et al. [19] also reported that NaCl was the best electrolyte among four different types of chemicals, namely, NaCl, NaNO_3 , Na_2SO_4 , and CaCl_2 . Furthermore, Abdelwahab et al. [20] also reported that the presence of chloride ions could remove the passive oxide layer formed on the electrode surface.

On observing the pattern of $\text{PO}_4^{3-}\text{-P}$ dissolution at different NaCl concentration from Fig. 2a–c, it is evident that when the concentration of NaCl was increased from 0.01% to 0.08%, the $\text{PO}_4^{3-}\text{-P}$ concentration of the solution increased noticeably. At 0.01% and

0.02% NaCl, the $\text{PO}_4^{3-}\text{-P}$ dissolution is comparably lower. However, the $\text{PO}_4^{3-}\text{-P}$ amount (mg/L) in the solution increases considerably at 0.04, 0.06 and 0.08% NaCl concentration, but no much difference in $\text{PO}_4^{3-}\text{-P}$ dissolution was observed among those concentrations. From the above results it can be concluded that the addition of NaCl lead to an increase of $\text{PO}_4^{3-}\text{-P}$ concentration in the solution, which indicated that increased concentration of NaCl helped in better dissolution of the struvite. Bhuiyan et al. [21] stated that solubility of struvite changes with ionic strengths of solution. Wang et al. [22] also reported that the addition of NaCl to wastewater served as a useful technique to enhance the performance of electrolysis.

Fig. 2d–f showed that the $\text{NH}_4\text{-N}$ concentration decreases rapidly with increased level of NaCl in the solution. At 0.01% NaCl, no considerable change in $\text{NH}_4\text{-N}$ concentration (mg/L) was observed in the solution, whereas at 0.02%, $\text{NH}_4\text{-N}$ level started decreasing slowly. At 0.04% NaCl, $\text{NH}_4\text{-N}$ level decreases considerably and sharp depletion in $\text{NH}_4\text{-N}$ concentration was observed at 0.06 and 0.08%. Li and Liu [23] demonstrated that chloride present in electrolytic solution just played a catalytic role in $\text{NH}_4\text{-N}$ degradation rather than reacting directly with $\text{NH}_4\text{-N}$ and most of the $\text{NH}_4\text{-N}$ in the presence of chloride gets converted into N_2 gas. In addition, Vanlangendonck et al. [14] reported that $\text{NH}_4\text{-N}$ can be efficiently removed with an appropriate chloride concentration. Vlyssides and Isralildes [11] and Vlyssides et al. [13] also reported increased $\text{NH}_4\text{-N}$ depletion with increasing concentration of

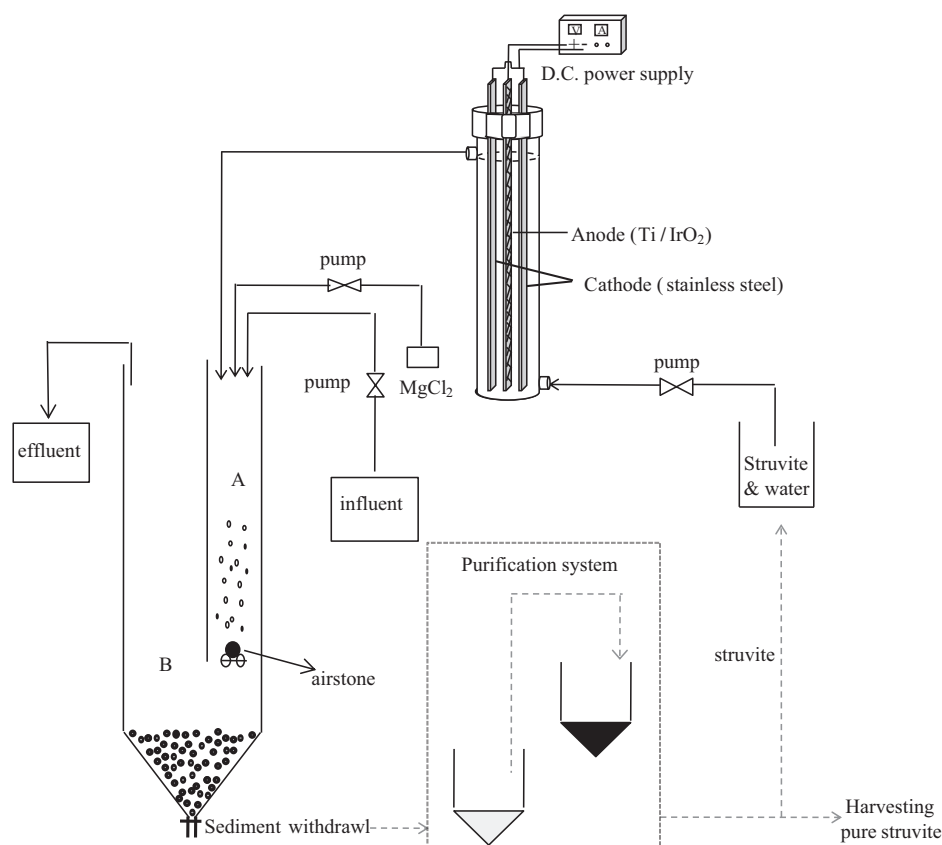


Fig. 1. Schematic illustration of the experimental apparatus.

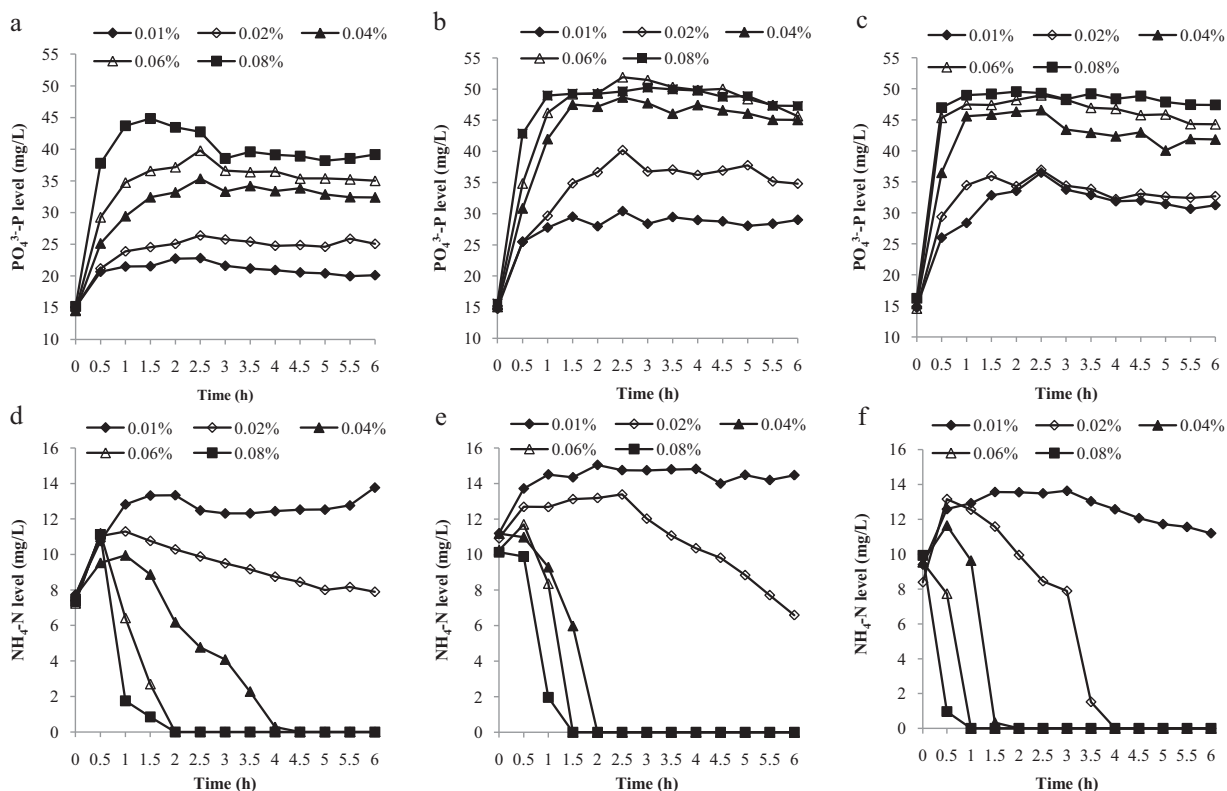
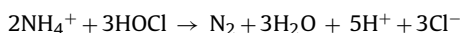
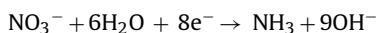
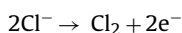
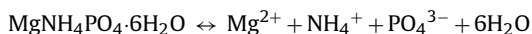


Fig. 2. Effect of NaCl and voltage on struvite dissolution (a and d) 5V, (b and e) 7V, (c and f) 9V.

initial chloride. The removal of $\text{NH}_4\text{-N}$ in the present study might be due to the conversion of the dissolved $\text{NH}_4\text{-N}$ into N_2 gas during electrolysis.

It is well known that when electrochemical degradation proceeds by direct redox reactions on the electrode, the electrolysis of NaCl solution results in very strong oxidants of HOCl/OCl^- that could ensure indirect oxidation in the solution [24,25]. With the addition of NaCl to the solution, chlorine forms at the anode and it is then converted to hypochlorous acid and hypochlorite [26,27]. The overall reaction occurring in an aqueous solution during electrolysis can be expressed as follows:



Hence, from the present study it can be concluded that a concentration of 0.06% NaCl would be optimum to achieve the $\text{PO}_4^{3-}\text{-P}$ dissolution and complete removal of NH_4^+ from the struvite within short time of electrolysis.

3.2. Effect of applied electric voltage

Since another important parameter that can strongly affect the performance of the electrolysis is the applied electric voltage, the effect of the voltage on struvite dissolution was studied at 5, 7 and

9V with 0.06% NaCl concentration, 6 h RT and struvite amount of 1.25 g/L. It can be seen from Fig. 3a that at 5V, the $\text{PO}_4^{3-}\text{-P}$ dissolution was comparably lower than 7 and 9V, however, slight decrease in $\text{PO}_4^{3-}\text{-P}$ concentration was observed when the applied electric voltage was increased from 7V to 9V. Hence, it can be concluded that the electric voltage affects the $\text{PO}_4^{3-}\text{-P}$ dissolution. Moreover, the results (Fig. 3b) show that the electric voltage also strongly influence the $\text{NH}_4\text{-N}$ removal from the solution. $\text{NH}_4\text{-N}$ depletion was positively correlated with the applied electric voltage. The required treatment times for complete removal of $\text{NH}_4\text{-N}$ from the solution were 2.0, 1.5 and 1.0 h at 5, 7 and 9V, respectively. Liu et al. [28] stated that higher electric voltage increased the rate of Cl^- losing electron at anodes, which could improve higher $\text{NH}_4\text{-N}$ oxidation rate. Mollah et al. [29] reported that the current density is the most important parameter for controlling the reaction rate within an electrochemical reactor. Since the current density went up with the electric voltage, resulting in the increased energy consumption, the optimum value of the applied electric voltage was selected as 7V considering the efficiency and energy consumption.

3.3. Effect of reaction time and struvite amount

Because RT is another vital factor affecting the treatment efficiencies of the electrolysis process [30], the effect of RT on the struvite dissolution was investigated with 7V, 0.06% NaCl concentration and different struvite amount (0.25, 0.50, 1.00, 1.25 and 2.50 g/L). As shown in Fig. 4a, the $\text{PO}_4^{3-}\text{-P}$ concentration increased with the increase of RT. It could be easily observed that with initial struvite amount of 0.25 g/L, $\text{PO}_4^{3-}\text{-P}$ reached maximum level at 0.5 h and no effect of RT was noticed later on. However, with increased struvite amount i.e. 0.50–1.00 g/L, the $\text{PO}_4^{3-}\text{-P}$ level reached maximum at 1.0 h and not much difference in $\text{PO}_4^{3-}\text{-P}$ concentration was noticed by extending the RT up to 2.5 h. At 1.25 and 2.50 g/L of initial struvite amount, $\text{PO}_4^{3-}\text{-P}$ dissolution

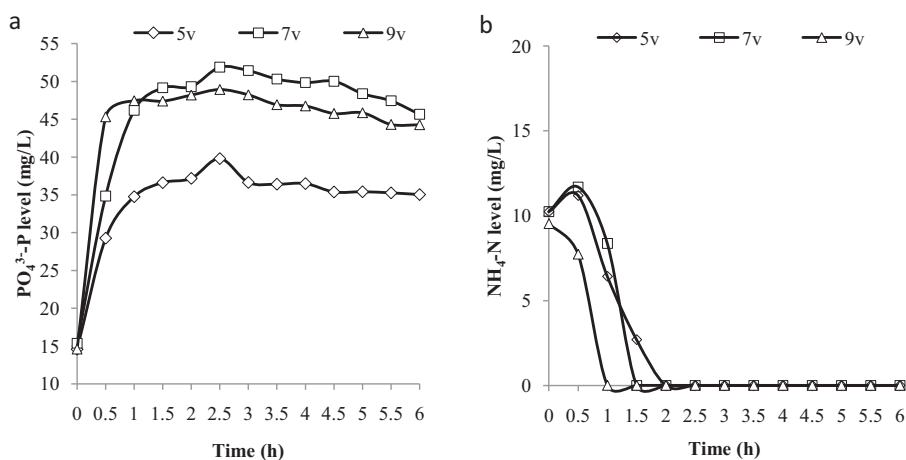


Fig. 3. Effect of electric voltage on struvite dissolution at 0.06% NaCl and initial struvite amount of 1.25 g/L: (a) phosphorous concentration (mg/L) and (b) ammonia concentration (mg/L).

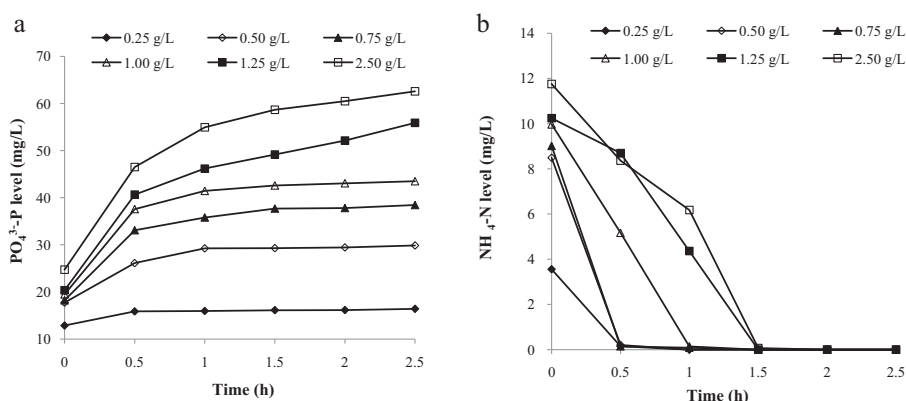


Fig. 4. Struvite dissolution at 7V and 0.06% NaCl: (a) phosphorous concentration (mg/L) and (b) ammonia concentration (mg/L) with reaction time.

increases with increase in time. In addition, from Fig. 4b it is evident that $\text{NH}_4\text{-N}$ concentration in the solution decreased considerably with the increase in RT. With initial struvite amount of 1.25 and 2.50 g/L, $\text{NH}_4\text{-N}$ completely depleted from the solution in 1.5 h. Hence, to summarize, longer electrolysis times (>1.5 h) unnecessarily linger the process of electrolysis for struvite dissolution. Therefore, an electrolysis time of 1.5 h was considered to be optimal RT for high $\text{PO}_4^{3-}\text{-P}$ dissolution and complete $\text{NH}_4\text{-N}$ depletion, with due concern to the energy consumption.

The results from Fig. 5 clearly show that with increase in struvite amount, the $\text{PO}_4^{3-}\text{-P}$ level increased in the solution. The dissolved amount ($C_T - C_0$; final $\text{PO}_4^{3-}\text{-P}$ concentration–initial $\text{PO}_4^{3-}\text{-P}$ concentration) of $\text{PO}_4^{3-}\text{-P}$ during 1.5 h electrolysis was 3.26, 11.55, 19.46, 23.08 and 28.79 mg/L at 0.25, 0.50, 0.75, 1.00 and 1.25 g/L respectively, reaching plateau beyond 1.25 g/L of struvite amount. Therefore, 1.25 g/L was considered suitable struvite amount for the dissolution through the designed electrolytic reactor. Under the above optimized parameters (7 V, 0.06% NaCl, 1.5 h and 1.25 g/L), 49.17 mg/L $\text{PO}_4^{3-}\text{-P}$ was dissolved, whereas $\text{NH}_4\text{-N}$ was completely depleted in the solution.

3.4. Recycle ratio of struvite

To examine the effectiveness of reutilization of the dissolved struvite by electrolysis method on crystallization, different recycle ratio (0.0, 0.5, 1.0 and 2.0 M) of dissolved struvite with respect to $\text{PO}_4^{3-}\text{-P}$ in influent was pumped with 0.5 M of MgCl_2 into the crystallization reactor. From Table 3, it can be seen that with increase

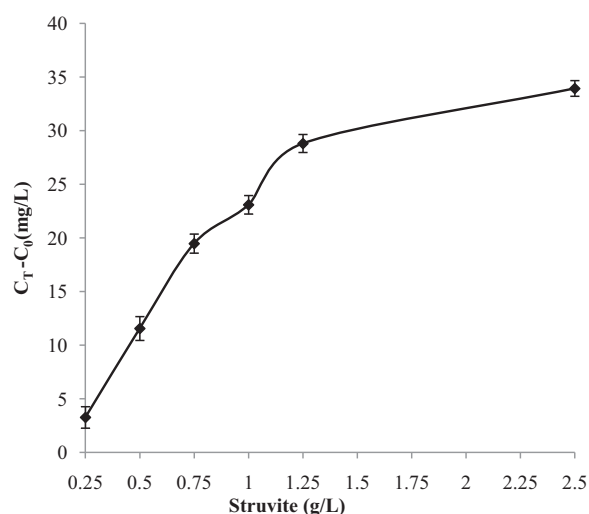


Fig. 5. Phosphate dissolution at 7V and 0.06% NaCl with different struvite amount (g/L); C_T , final $\text{PO}_4^{3-}\text{-P}$ concentration; C_0 , initial $\text{PO}_4^{3-}\text{-P}$ concentration.

in the recycle ratio, the $\text{PO}_4^{3-}\text{-P}$ removal (%) increases. In run I, the $\text{PO}_4^{3-}\text{-P}$ removal was 69%, which is significantly ($p < 0.01$) higher than that of control (63%), however no significant difference was found between run I and II. In run III, the $\text{PO}_4^{3-}\text{-P}$ removal (79%) was significantly higher than run I and II. Similarly, the percent $\text{NH}_4\text{-N}$ removal was significantly increased with the increase

Table 3
Effect of different molar ratio of recycled struvite on swine wastewater treatment.

	pH		PO ₄ ³⁻ -P (mg/L)		Removal (%)	NH ₄ -N (mg/L)		Removal (%)
	Influent	Effluent	Influent	Effluent		Influent	Effluent	
C	8.37 ± 0.59	8.78 ± 0.08	33.68 ± 2.51	12.36 ± 1.01	63 ^a	2612 ± 21	2358 ± 58	9 ^a
R I	8.37 ± 0.06	8.68 ± 0.09	31.02 ± 2.90	9.60 ± 1.13	69 ^b	2624 ± 86	1806 ± 46	31 ^b
R II	8.39 ± 0.05	8.61 ± 0.06	30.98 ± 2.28	8.71 ± 0.81	71 ^b	2647 ± 33	1587 ± 26	40 ^c
R III	8.36 ± 0.04	8.51 ± 0.06	30.79 ± 1.69	6.27 ± 1.14	79 ^c	2610 ± 97	1216 ± 54	53 ^d

C, control; R I, Run I; R II, Run II; R III, Run III; PO₄³⁻-P, Ortho phosphate; NH₄-N, ammonium nitrogen; ±standard deviation of mean (*n* = 16); unequal superscripts in same column shows significant difference at *p* < 0.01.

Table 4
Comparison of cost between dissolved struvite recycling process and pure chemical addition.

Chemical used	Price (USD/Kg)	Cost for the dissolved struvite recycling (USD)*	Cost for pure chemicals (USD)**
MgCl ₂ ·6H ₂ O	10.20		13.35
KH ₂ PO ₄	21.72		19.05
NaCl	3.77	9.07	
Energy consumption	0.049/kWh	2.07	
Total		11.34	32.40

* Cost of 1 m³ solution of dissolved struvite by electrolysis.

** Cost of pure chemicals used to make 1 m³ solution.

of recycle ratio (*p* < 0.01), showing 9, 31, 40 and 53% in C, run I, II and III, respectively. Thus results clearly revealed that recycle ratio affect the percent PO₄³⁻-P and NH₄-N removal significantly (*p* < 0.01). The correlation coefficient (*R*²) value for NH₄-N and PO₄³⁻-P removal was found to be 0.91 and 0.98, respectively, indicating that the struvite crystallization can be enhanced gradually with increased recycle ratio of dissolved struvite as Mg and P source. Since swine wastewater contains high amounts of NH₄-N compared to PO₄³⁻-P and Mg this may affect the stoichiometric conditions for struvite precipitation and thus affect the efficiency [2]. Therefore, after efficiently removing the NH₄-N from struvite by electrolysis, addition of the remaining Mg and PO₄³⁻-P increase the Mg:PO₄³⁻-P molar ratio compared to NH₄-N which lead to more struvite formation and thus more NH₄-N removal from the swine wastewater. Furthermore, seeding the dissolved struvite solution might have added small struvite particles, which leads to increase absorption of PO₄³⁻-P and thus faster growth rate of struvite [32]. In addition increased concentration of Mg²⁺, NH₄-N and PO₄³⁻-P also improves the PO₄³⁻-P removal efficiency [33].

The struvite crystallization, struvite purification and dissolution are three separate processes. The main focus is on struvite crystallization (works in continuous mode) whereas purification and dissolution are auxiliary processes which can be carried out separately (once in a month or twice in six months). Struvite dissolution can also be done without purification depending on the utility and can be used for making alternative source of PO₄³⁻-P and Mg for further struvite formation in the crystallization reactor. The electrolytically dissolved struvite can be collected and stored in a container, and pumped into the crystallization reactor along with the influent feeding. An additional source of Mg can be added to match the stoichiometric conditions of struvite formation. Thus keeping the main purpose of our experiment (i.e. struvite crystallization) in mind, if we could easily and economically dissolve struvite by electrolysis, we could use the dissolved solution as an alternative source of Mg and PO₄³⁻-P for struvite formation.

3.5. Economic evaluation of the dissolution process

Under the optimum conditions obtained (7 V, 0.06% and RT 1.5 h), about 50 mg of PO₄³⁻-P was dissolved in the 1 L of solution. Based on these results, an economic analysis for making 1 m³ dissolved struvite solution from the electrolysis reactor was carried out and compared to the cost of using pure chemicals of PO₄³⁻-P

and Mg in the same quantity. In this assessment chemicals used and energy consumed were considered. The prices of chemical used and energy consumed are shown in Table 4. It is calculated that the total chemical cost and energy is 11.34 USD/m³ when dissolved struvite was recycled for crystallization, whereas the cost by using pure chemicals is 32.40 USD/m³. The results of economic analysis indicate that the average cost could be decreased to about 1/3rd and thus greatly lower the cost of the struvite precipitation. He et al. [5] reported that about 44% of the chemical costs were reduced by recycling struvite for three cycles. Huang et al. [7,31] also reported that 48.7% and 59% of struvite precipitation cost was decreased by using a struvite recycle technology, respectively.

4. Conclusions

In the present study, operating parameters to achieve electrolytically struvite dissolution were determined and effectiveness of the reutilization of the dissolved struvite as Mg and PO₄ source was also investigated. From the obtained results, following conclusions can be drawn.

1. The struvite dissolution was enhanced with increased NaCl concentration and electric voltage level, however from the study 0.06% NaCl and 7 V could be considered as optimum.
2. RT of 1.5 h was found to be suitable for PO₄³⁻-P dissolution and complete removal of NH₄⁺ from struvite. PO₄³⁻-P dissolution increased with increase of initial struvite amount, but a plateau occurred after 1.25 g/L, suggesting 1.25 g/L of struvite to be suitable.
3. Recovery of P and N removal from swine wastewater was significantly enhanced with the recycle of electrolytically dissolved struvite (*p* < 0.01) and the efficiencies were proportional to the recycle ratio.
4. Therefore, electrolysis could be a practical approach for struvite dissolution and recycling of the dissolved struvite as Mg²⁺ and PO₄³⁻-P source would be a good strategy to enhance struvite crystallization.

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