Early detection of struvite formation in wastewater treatment plants

Kazi Parvez Fattah PhD

Assistant Professor, Department of Civil Engineering, American University of Sharjah, Sharjah, United Arab Emirates

Farah Laj Chowdhury MASc, PEng, CAPM

Adjunct Faculty, University of Sharjah, Sharjah, United Arab Emirates

Wastewater treatment plants operating anaerobic digestion of their sludge often have to encounter phosphate-based formations that clog piping, valves and pumps that reduce the efficiency of the treatment plant. In addition to treatment process problems, these formations require significant costs for their removal or to have the clogged piping replaced. Among the many possible phosphate-based precipitates, struvite is the most common. In most instances, the formation and build-up of struvite within the treatment stream goes unnoticed until a critical stage is reached where the only option is replacement of the clogged pipes and valves. However, the early detection of struvite formation through regular monitoring of the parameters that influence struvite build-up can reduce the problems. This paper presents procedures and results obtained to detect struvite formation potential in a secondary wastewater treatment plant in Canada. Based on supersaturation values, it was found that there was a high probability of struvite formation around the sampling points. High nutrient looping for both nitrogen (20%) and phosphorus (48%) were calculated at the treatment plant.

Notation

IAP ionic activity product

K_{sp}^{eq} equilibrium solubility product

{ } brackets activity of the ions in moles per litre

Introduction

It is well known that a number of wastewater treatment plants all over the world, especially those using anaerobic digestion of its sludge, encounter nutrient-related problems. Among the most common problems is the formation of struvite (magnesium ammonium phosphate hexahydrate (MAP), struvite ($MgNH_4PO_4 \cdot 6H_2O$)) (Fattah, 2012; Marti *et al.*, 2008; Uysal *et al.*, 2010). One of the principal reasons for struvite formation is high concentrations of nutrients, principally phosphate and ammonium, in areas post anaerobic digesters. Struvite formations foul and encrust the sludge return lines, pumps and valves. Methods to remove the struvite formations are usually time consuming, labour intensive and costly. Often, the only solution is to replace the clogged piping. The formation and growth of ‘uncontrolled’ struvite increases operational (e.g., pumping), maintenance costs (e.g., example, for removing struvite and/or replacement of piping and valves) and reduces the plant’s hydraulic capacity by reducing the diameter of the piping. One way of staying ahead of this uncontrolled struvite growth is through analysing and monitoring struvite formation potential before process equipment is encrusted with struvite. Although a problem when left unchecked and untreated, controlled production of struvite in a sidestream process (Fattah *et al.*, 2012; Hutnik *et al.*, 2013) has the potential to be

economically beneficial to treatment plants since the maintenance costs decrease and extra revenue can be generated from the commercial trade of the struvite crystals. It is worth mentioning that struvite can be used as fertiliser (Turker and Celen, 2007). Thus, having knowledge of parameters that influence struvite precipitation is vital from both operational and economic points of view.

The early detection of struvite formation potential requires a complete study to benchmark conditions related to struvite formation. This benchmarking is important because future studies can then be compared with it to determine if conditions are getting worse or not. It is also important to carry out regular monitoring of some of the factors (e.g., concentration of phosphate, ammonium and magnesium) that control struvite precipitation, because if the conditions are right, struvite can encrust the whole pipe section within a few days. It is also vital to remember that wastewater treatment plants are all different in some way or the other because of the characteristics of the influent wastewater, the processes used and how they are operated and the chemicals that are used. Therefore, each treatment plant needs to carry out its own benchmarking study.

Another important aspect of the presence of phosphorus and nitrogen in the treatment stream is ‘nutrient looping’. In case of no nitrogen and phosphorus removal processes in the treatment stream, both struvite formation and nutrient looping may occur. Nutrient looping is the trapping of untreated nitrogen and phosphorus within the treatment plant. Nutrient looping occurs when the centrate or digested supernatant, which typically have high phosphorus and nitrogen

concentrations, is returned back to the headworks area for further treatment. Nutrient trapping hampers biological treatment processes and hence process efficiency is decreased (Sagberg *et al.*, 2006).

Among the important factors influencing supersaturation ratio (SSR) in wastewater treatment plants are the ions that form struvite, namely, phosphate, ammonium and magnesium (Fattah *et al.*, 2012; Pastor *et al.*, 2008). In addition to the ions, pH, temperature and conductivity of the water matrix influence struvite formation potential (Ali and Schneider, 2008; Fattah *et al.*, 2012). SSR is often used in the wastewater treatment industry as an indication of struvite formation potential and is calculated by Equations 1 and 2. When SSR is greater than one, there is a good probability that struvite will form (Galbraith and Schneider, 2009). However, it does not necessarily mean that the struvite will stick together at $SSR = 1$ to form significant clogging in pipes. The agglomeration and sticking to the piping depend on other hydrodynamic factors such as mixing condition, distribution of the flow and presence and concentration of other impurities (Doyle and Parsons, 2002; Hutnik *et al.*, 2013).

$$1. \quad SSR = IAP / K_{sp}^{eq}$$

$$2. \quad IAP = Mg^{+2}NH_4^{+}PO_4^{-3}$$

The secondary wastewater treatment plant studied uses trickling filters for organic removal and anaerobic digestion of the sludge. The digested sludge is centrifuged, and the resulting centrate is then temporarily collected in a centrate sump. From the centrate sump, the centrate is returned and mixed with the primary clarifier effluent. This return of the centrate has been defined in this study as the looping in the treatment plant. The treatment plant has reported recurrent issues of uncontrolled struvite formation in the piping

system between the digester and the centrifuge (Figure 1). It was reported that the valves operating downstream of the digesters were also clogged with struvite. However, no regular monitoring of the factors that affect struvite formation was performed, and therefore, the management of the treatment plant was in the dark regarding future struvite formation potential.

This study was carried out to investigate the status of the struvite formation potential at a wastewater treatment plant in Canada. The struvite formation potential was identified in terms of SSR at the sampling points. Data from the current period were compared with a benchmarking study carried out 2 years earlier to investigate possible trends in the parameters monitored. The purpose of this exercise was to evaluate potential changes in the phosphate, ammonium and magnesium concentrations that may indicate potential changes in the problems related to the formation of struvite.

Materials and methods

SSR was used as an indication of the possibility of struvite formation at the sampling locations in the treatment stream over two study periods. Wastewater samples were tested in the treatment plant laboratory, and the resulting data were used to evaluate the struvite formation potential by running a struvite formation program coded in Matlab (Fattah, 2010). The sampling periods have been designated as period A (benchmarking study) and period B, with the latter being more recent. The parameters that are used to calculate SSR were measured every week over a period of 2 months regularly to investigate the difference in the readings at two different locations of the treatment stream. The sampling locations were, namely, (a) the centrate formed after centrifuging of the sludge and (b) the centrate sump. The reason for sampling at the sump was to investigate the possible struvite precipitation at this location due to prevalent lower temperatures as it is located underground but outdoors. Each of the samples was centrifuged at

Figure 1. Struvite formations in the pipes between the digesters and the centrifuge

4000 RPM for 10 min to reduce the solids content. The resulting supernatant was then filtered using 0.45 µm filter paper prior to analytical measurements. All parameters and conditions were measured according to APHA *et al.* (2005).

Results and discussion

Influent characteristics

The characteristics of the influents with respect to the three struvite-contributing ions during the two study periods are given in Table 1. The results show that there was no significant difference in the concentrations of the three major ions. Although there was no significant change in the average concentration of orthophosphate (OP) (0.8 mgP/L), based on the total influent flow, there was an overall reduction of 35% in the mass of OP entering the treatment plant. In terms of struvite precipitation potential, this reduction is desired. However, it was found that the average magnesium concentration increased over the two periods. Of more concern is that all the maximum concentrations in period B were higher than the concentrations in period A. Of major concern is that magnesium was substantially (26%) higher in period B than the average value in period A. The magnesium concentration change is important because typically magnesium is the limiting ion for struvite formation in wastewater treatment plants and sudden increase in the magnesium concentration can increase struvite formation potential rapidly.

Comparison of magnesium concentration

Centrate

The centrate average magnesium (Mg) concentrations over the sampling period were 10.6 and 6.4 mg/L for periods A and B, respectively. On an average, it has been noticed that there is a 40% decrease in the magnesium concentration over the two sampling periods. With no significant change in the influent magnesium concentration over the two sampling periods (Table 1), it is reasonable to infer that the lowering of magnesium concentration is due to the possibility of struvite formation upstream of the centrifuge. This hypothesis is validated by the fact that increased struvite formations were discovered in the circulation line to the centrifuge (Figure 1). Although not prominent, a closer look at the data points in Figure 2 shows a faint pattern in the magnesium concentrations in

Figure 2. Centrate magnesium concentrations during the two sampling periods

the centrate. Peaks in data are followed by valleys. This cycle helps in explaining the struvite formation hypothesis – increase in magnesium (peak) increases the SSR, causing struvite to form, which subsequently lowers the magnesium concentration (valley). However, it is necessary to monitor the centrate magnesium concentration over a wider range/longer period to fully validate the hypothesis.

Centrate sump

The centrate sump magnesium concentration varied from a high of 12 mg/L to a low of 1.5 mg/L in period B, with an average of 7.5 mg/L. In comparison, the average magnesium concentration during period A was 9.4 mg/L, but varied between 10.5 and 7.5 mg/L. The wide range of magnesium values during period B is noteworthy. This can be related to the magnesium concentrations in the centrate and is discussed in detail later in this paper. The range of values for the two periods is illustrated in Figure 3.

Comparison of ammonium-nitrogen concentration

Centrate

The average centrate ammonium-nitrogen (NH₄-N) concentrations over the sampling periods were 1499 and 1344 mg/L for periods A and B, respectively. The centrate ammonium concentration in period B was consistently lower than the values obtained in period A, as illustrated in Figure 4. The sudden change in the ammonium concentration, from 1440 mg N/L on a particular day (sample 15) to 1120 mg N/L the next day, occurred on the same day phosphate concentration decreased (from 214 to 206 mg/L), the magnesium concentration decreased from 7.12 to 4.62 mg/L, and the pH increased from 7.6 to 7.7. This reiterates the importance of a regular monitoring system in place to notice these sudden changes. If a sampling day shows possible precipitate formation, precautionary measures can then be taken to immediately reduce the potential of the precipitate accumulating in problem areas.

Centrate sump

The average centrate sump ammonium-nitrogen (NH₄-N) concentrations over the sampling period were 1075 and 1083 mg/L

	Total magnesium: mg/L		Ammonium: mg N/L		OP: mg P/L	
	Period A	Period B	Period A	Period B	Period A	Period B
Average	2.5	2.7	20	21.9	2.2	1.4
Minimum	2.1	2.3	16	12.6	1.8	0.5
Maximum	2.8	3.4	26	27.9	2.5	2.9

Table 1. Influent characteristics at the wastewater treatment plant for the two study periods

Figure 3. Centrate sump magnesium concentrations during the two sampling periods

for periods A and B, respectively. Figure 5 illustrates the centrate sump ammonium-nitrogen concentrations during the two sampling periods. Except for 1 d, there are not many variations between the two periods. However, if examined closely, a pattern similar to those found with magnesium concentrations seems to emerge – high values (1200 mg/L) followed by low values (1000 mg/L) on a regular basis. Two possible scenarios can cause this. First, the variation in the treatment occurring in the treatment plant, and second, some ammonium-precipitates are forming. However, it was not possible to determine which of the possible scenarios was occurring without further investigation.

Comparison of OP concentration

Centrifuge feed

For OP, an additional sample was taken in both the periods in the line connecting the digester and the centrifuge due to observed problems in the pipeline. The average OP concentrations over the

Figure 4. Centrate ammonium-nitrogen concentrations during the two sampling periods

Figure 5. Centrate sump ammonia concentrations during the two sampling periods

sampling period were 458 and 213.5 mgP/L for periods A and B, respectively. The average decrease in phosphate concentrations over the two periods was 53%. There is significant difference between the OP concentrations between the two periods (Figure 6). One reason for this large difference can be attributed to the fact that samples were taken from different locations (due to change in the sampling ports) during the two sampling periods, but within the same pipeline. Period A samples were taken in the upstream section in the digester sludge storage tank (DSST), while period B samples were taken from the downstream section of the pipeline connecting the DSST and the centrifuge. Although the choice of the sampling point during period B is not ideal for comparison with those from period A, this graph helps explain an important observation made by the operators at the plant. Increasing hydraulic pressure on the circulation line to the centrifuges, possibly due to reduction in pipe diameter, was reported at the wastewater treatment plant. There were some valves in the line that were not closing. It was

Figure 6. Centrifuge feed OP concentrations during the two sampling periods

hypothesised that phosphate precipitate formation resulted in the reduction of pipe size. Thus, it is possible that the lowering of the centrate feed phosphate is due to the formation of phosphate precipitates. The condition within the sample line is discussed in later sections.

Centrate

The average OP concentrations over the sampling period were 195 and 208 mgP/L for periods A and B, respectively (Figure 7). There has been a slight increase (6.6%) in the average concentration of OP in the centrate from study A to study B. However, as illustrated in Figure 7, there is a large variability in the concentrations; there were periods of higher OP (above 215 mgP/L) than the average of 208 mgP/L. Although the differences are small, the combination of OP increase, in addition to other struvite precipitation factors' increase (Mg, $\text{NH}_4\text{-N}$, pH) on a particular day, can bring about rapid struvite formation. Therefore, it is necessary to monitor all the factors simultaneously. Since there is no significant increase in the OP concentration in the influent, this increase (from 195 mgP/L in period A to 208 mgP/L in period B) indicates a possibility that over the last 2 years, phosphate has been accumulating at the wastewater treatment plant. In terms of struvite formation, this is a worrisome trend. It is also worthwhile to compare the phosphate concentration in the centrate with that in the centrifuge feed. It is expected that there would be negligible change in OP concentration brought about by centrifuging the digested sludge. However, although there was a 5 mg/L lowering of the average phosphate concentration, this relates to approximately 5.6 kg/d loss of phosphate. It is highly likely that some of this precipitate is accumulating within the centrifuge itself, or in the accompanying piping. The management of the wastewater treatment plant is in the processes of verifying this hypothesis.

Centrate sump

The average OP concentrations over the sampling period were 138 and 161 mgP/L for periods A and B, respectively (Figure 8). As

Figure 7. Centrate OP concentrations during the two sampling periods

Figure 8. Centrate sump OP concentrations during the two sampling periods

expected (since the centrate concentrations are higher), there was an increase of 17% in the centrate sump OP concentrations in period B compared with period A. With no significant increase in influent OP and only 6.6% increase in the centrate OP, it is reasonable to hypothesise that OP is being accumulated in the centrate sump.

Centrifuge feed line struvite formation potential

During period A, an SSR of 2.2 was calculated for a particular day in the centrifuge feed. It was then suggested that although the struvite formation potential was relatively high ($\text{SSR} = 2.2$), the small struvite crystals formed would be carried over with the sludge. However, recent observations suggest that the crystals did form and accumulated in the circulation line to the centrifuge. This suggests that the struvite, and/or other phosphate precipitates, has a preference to stick to the pipes rather than be carried over with the sludge all the time. The actual mechanism of accumulation in the pipes as opposed to 'flow-through' is yet to be accurately determined. It is important to note the difference in temperatures between the two periods (Table 2), as lowering of temperature enhances struvite formation. One of the major findings from the results obtained during the two periods is the observation of the high drop in the temperature of the sludge between the digester (DSST at an average temperature of 51°C during period A) and the centrifuge feed (at an average temperature of 39°C determined during period B). With no significant changes in the process operations during the two sampling periods, this decrease in temperature is of great importance as temperature has a large influence on the SSR (Fattah, 2010). For example, if the temperature during period A was 39°C instead of 51°C, then the SSR would have been 3.02, which is sufficient to cause instantaneous precipitation of struvite. It is also interesting to note the lowering of SSR during period B brought about by the decrease in phosphate and ammonia. Given that theoretically no phosphate is removed in the treatment plant, rather the phosphate gets recycled over and over again within the treatment system, a lowering in the

	pH	Temp: °C	OP: mg/L	Ammonium-nitrogen: mg/L	SSR
Period B	7.4	39	214	1421	1.12
Period A	7.4	51	458	1783	2.20

Table 2. Centrifuge feed parameters between two study periods

phosphate concentration indicates that some form of phosphate removal process has taken place. Given that the SSR (with respect to struvite) is high, formation of this precipitate is likely a driver that contributed to phosphate concentration lowering.

SSR in the treatment plant

The SSRs in the two sampling locations during period B are shown in Figure 9. It was observed that there were days when the SSR was above unity, indicating that formation of struvite is possible. It is also interesting to note the ‘peaks and valleys’ nature of the graphs. This shows the importance of continuous monitoring of factors that determine struvite formation potential. By having the ability to determine struvite formation potential in real time, operators can control the factors on which struvite formation depends (such as pH and temperature).

Nutrient looping

During anaerobic digestion, phosphates that accumulate in the sludge are released, thereby increasing the soluble fraction of phosphate. When this treated sample is centrifuged, the centrate formed contains high levels of soluble phosphate – one of the key ingredients of struvite formation. At the wastewater treatment plant, this centrate is rerouted back to the primary effluent (PE) channel. The consequence of this routing is that the phosphate present in the raw influent is never fully removed and the net concentration of phosphate within the treatment cycle increases. During period B, this return represented as much as 48% of the plant’s influent phosphate load, as shown in Table 3. The average ammonium-nitrogen concentration of the centrate that is returned to the PE channel was 1083 mg/L, which is approximately 20% of the influent ammonium mass load.

Figure 9. SSRs in the two locations in study B

	Influent	Centrate return
Flow (MLD)	450	1.86
Phosphate conc.: mg/L	1.4	161
Total load: kg P/d	630	299
NH ₄ -N: mg/L	21.9	1083
NH ₄ -N load kg/d	9855	2015

Table 3. Nutrient looping in the treatment plant

Conclusion

Results indicated that although the average SSR was lower than that during period B, there were sampling days when the SSR values were higher than unity. This indicates that struvite formation might have taken place on those particular days when the SSR was high. It was observed that the concentrations of magnesium, nitrogen and phosphorus were lower for a few days after several days of high SSR. It can be concluded that the SSR was low enough for the days when the concentration of the three ions were low and it takes time for the SSR to increase above unity. The phosphate and ammonia-nitrogen concentrations were decreased substantially from the centrifuge to the centrate sump. The reduction of phosphate and ammonia-nitrogen from the waste stream may have contributed to the uncontrolled struvite formation inside the pipes. The phosphate load from the centrate sump to the PE channel was close to half of the plant’s influent phosphate load. For total Kjeldahl nitrogen (TKN), the return amount was approximately one fifth. This study showed how it is possible to detect the formation of struvite at an early stage so that remediation measures can be taken before the formations hamper process operations. This detection is vital to the smooth operation of a wastewater treatment plant. Results indicate the importance of regular monitoring of the parameters that influence struvite formation.

Acknowledgements

The authors would like to thank the management of the wastewater treatment plant for funding this study and testing all samples at their laboratory. A section of this article was presented at ICEPR’14 (<http://International-ASET.com>).

REFERENCES

- Ali MI and Schneider PA (2008) An approach of estimating struvite growth kinetic incorporating thermodynamic and solution chemistry, kinetic and process description. *Chemical Engineering Science* **63**(13): 3514–3525.
- APHA, AWWA and WPCF (2005) *Standard Methods for the Examination of Water and Wastewater*, 21st edn. American Public Health Association, Washington, DC, USA.
- Doyle J and Parsons SA (2002) Struvite formation, control and recovery. *Water Research* **36**(16): 3925–3940.
- Fattah KP (2010) *Development of Control Strategies for the Operation of a Struvite Crystallization Process*. Doctoral dissertation, The University of British Columbia, Vancouver, BC, Canada.

-
- Fattah KP (2012) Assessing struvite formation potential at wastewater treatment plants. *International Journal of Environmental Science and Development* **3**(6): 548–552.
- Fattah KP, Mavinic DS and Koch FA (2012) Influence of process parameters on the characteristics of struvite pellets. *Journal of Environmental Engineering, ASCE* **138**(12): 1200–1209.
- Galbraith SC and Schneider PA (2009) A review of struvite nucleation studies. In *International Conference on Nutrient Recovery from Wastewater Streams*. IWA Publishing, London, UK.
- Hutnik N, Kozik A, Mazieniczuk A et al. (2013) Phosphates (V) recovery from phosphorus mineral fertilizers industry wastewater by continuous struvite reaction crystallization process. *Water Research* **47**(11): 3635–3643.
- Marti N, Bouzas A, Seco A and Ferrer J (2008) Struvite precipitation assessment in anaerobic digestion processes. *Chemical Engineering Journal* **141**(1–3): 67–74.
- Pastor L, Marti N, Bouzas A and Seco A (2008) Sewage sludge management for phosphorus recovery as struvite in EBPR wastewater treatment plants. *Bioresource Technology* **99**(11): 4817–4824.
- Sagberg P, Ryrfors P and Berg KG (2006) 10 years of operation of an integrated nutrient removal treatment plant: ups and downs. Background and water treatment. *Water Science and Technology* **53**(12): 83–90.
- Turker M and Celen I (2007) Removal of ammonia as struvite from anaerobic digester effluents and recycling of magnesium and phosphate. *Bioresource Technology* **98**(8): 1529–1534.
- Uysal A, Yilmazel YD and Demirel GN (2010) The determination of fertilizer quality of the formed struvite from effluent of a sewage sludge anaerobic digester. *Journal of Hazardous Materials* **181**(1–3): 248–254.

WHAT DO YOU THINK?

To discuss this paper, please submit up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as a discussion in a future issue of the journal.