

## Plant-wide Modelling of N and P Removal with Aerobic and Anoxic-Aerobic Digestion of Waste Sludge

Ikumi, DS.\*, Vogts, M.\*\*, Ekama GA. and Brouckaert, CJ.\*\*\*

\* Water Research Group, Dept. of Civil Eng., Univ of Cape Town, Rondebosch, 7701, South Africa.

\*\* Royal Haskoning DHV, Pietermaritzburg, South Africa

\*\*\* Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal, Durban 4041, South Africa.

**Keywords:** Anoxic-aerobic digestion; Mathematical modelling; Mineral precipitation

### Summary of key findings

When waste activated sludge (WAS) from biological nutrient removal (BNR) activated sludge (AS) systems is thickened to 3-6% TSS and then digested (aerobic or anaerobic), a high proportion of Nitrogen (N) and phosphorus (P) is released to the bulk liquid resulting in high concentrations of ammonia and orthophosphate up to several hundred mg/l (without denitrification or P precipitation) (Vogts *et al.*, 2014). To avoid the complexity of N removal from digested sludge dewatering liquor, Vogts *et al.* (2014) investigates N removal by nitrification and denitrification and P removal by P precipitation in anoxic-aerobic digestion (AAD) of P rich BNR system WAS. The plant-wide experimental set up for this investigation (i.e., a UCT process BNR system connected to continuous anoxic-aerobic digesters) was simulated, using the three phase (aqueous-gas-solid) plant wide model of Ikumi *et al.* (2014), as part of the model evaluation process. In the AAD, the P accumulating organisms (PAOs) do not grow but undergo endogenous respiration, releasing their stored polyphosphate (PP) as magnesium (Mg), calcium (Ca), potassium (K) and orthophosphate (OP). This PP release, with endogenous respiration in the AAD, occurs gradually with PAO death, and not rapidly as observed in AD systems (Harding *et al.*, 2009; Ikumi, 2011). This released PP results in high concentrations of P and cations in the aqueous phase of the mixed liquor, resulting in formation of struvite ( $MgNH_4PO_4$ ). Initially, it was expected that K-struvite ( $MgKPO_4$ ) would form, due to projected nitrification (hence low  $NH_4$ ) AAD systems. However, K-struvite did not precipitate due to its low solubility product, and it being known to precipitate at high pHs (about 10, Wilsenach *et al.* 2007; Taylor *et al.* 1963).

### Background and relevance

The complexities of adding phosphorus (P) into wastewater treatment plant (WWTP) mathematical models included their extension from 2 phase (aqueous –gas) to 3 phase (aqueous – gas –solid) and consequently, a well-represented link between the weak acid/base systems and bioprocesses (including the interphase transfers) for pH prediction. Moreover, to afford a material mass and charge balance framework for these models, the capability to distinguish and track the various P components (polyphosphate (PP), orthophosphate (OP), organically bound P (OrgP) and P precipitates) and knowledge of weak acid base conditions (from measurements of OP, ammonia, pH, alkalinity, volatile fatty acids (VFA) and ionic strength) was essential.

Despite the energy savings offered from using anaerobic digesters (ADs) in sludge treatment, some WWTPs have adopted anoxic-aerobic digesters (AADs) for waste activated sludge (WAS) treatment to avoid the high level of technical competence required for AD operation and to encourage further nutrient removal (nitrification and P precipitation). Similar to ADs, the AAD of P-rich WAS raises research questions, regarding the impact of biomass P and PP on the 3 phase (aqueous-gas-solid) mixed weak acid base chemistry of AAD systems (i.e., (i) are the P and metal ( $Mg^{2+}$ ,  $K^+$ ,  $Ca^{2+}$ ) content of PP released rapidly from PAOs as noticed in AD or gradually with PAO endogenous respiration? And (ii) Are their concentrations, once released in the aqueous medium, sufficient for formation of mineral precipitates?). The study by Vogts *et al.* (2014) addresses these aspects, and this paper uses their findings towards validation of the three phase plant-wide model (PWM\_SA) (the simulated experimental setup is described below).

The experimental set up for this investigation comprised a membrane (MBR) University of Cape Town (UCT) nitrification denitrification enhanced biological P removal (NDEBPR)

system treating settled WW, from the Mitchells Plain wastewater treatment plant (WWTP) in Cape Town, with anoxic/aerobic digestion (AAD) of its WAS in two intermittently aerated (3h air on, 3h air off) aerobic digesters, AAD1 fed concentrated WAS (2x, 20gTSS/l) and AAD2 fed dilute WAS (1/3, 3.3gTSS/l), both operated at 20 days sludge age. These two AADs were operated over 21 months with 4 time periods, each with different dosing chemicals and two different aeration patterns to (i) observe the effect of pH on nitrification and P precipitation, (ii) the effect of different cations on P precipitation, (iii) the build-up of nitrate under fully aerobic conditions and (iv) to monitor the biomass digestion rate via the oxygen utilisation rate (OUR) decrease and nitrate increase (Vogts *et al.*, 2014). To ensure that the parent NDEBPR WAS was P rich, (i) 200 mgCOD/l of acetate (and also about 40 mgP/l of potassium dihydrogen phosphate ( $\text{KH}_2\text{PO}_4$ )) was dosed to the settled WW fed to the UCT system for enhanced growth of PP accumulating organisms (PAOs) and (ii) a reasonably short sludge age of 10 days was maintained (to ensure presence of active biomass in the WAS) by wasting the sludge directly from the aerobic reactor, which was also concentrated (~10gTSS/l) due to membranes (Ramphao *et al.*, 2005). Moreover, to observe P release rate and extent of aerobic mineral precipitation, the P rich WAS and AAD1 effluent sludge was batch aerobically digested (AerD) at low and high TSS. Experimental results from this set up are presented in more detail by Vogts *et al.* (2014).

A three phase plant wide model (PWM\_SA, Ikumi *et al.*, 2014) was developed for simulating the biological processes to track and predict the output of materials (COD, carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), magnesium (Mg), potassium (K) and calcium (Ca)) along the unit processes of a NDEBPR WWTP. It comprises three sub-models, integrated for simulation of the entire WWTP under various configurations ((i) NDEBPR AS system linked to (ii) an AD or an (iii) anoxic-aerobic digestion (AAD) for WAS stabilisation). The two sub-model components used to simulate the above experimental set up include:

1. The ionic speciation model (Brouckaert *et al.*, 2010). This model includes pairing of ionic components and inter-phase transfers of component species. Table 1 gives an example of a set of equilibrium and mass balance equations used in the ionic speciation subroutine.
2. The ASM2-3P model: This is the Activated Sludge Model No. 2 (ASM2, Henze *et al.*, 1995), modified to include the ionic speciation model (Brouckaert *et al.*, 2010), the Inorganic Settleable Solids (ISS) model of Ekama and Wentzel (2004) and including multiple mineral precipitation according to Musvoto *et al.* (2000a,b).

## Results

The figures 1.1 and 1.2 below show a part of the progressive validation of the ASM2-3P model, through comparison of some model simulation results to data generated from the experimental investigation by Vogts *et al.* (2014).

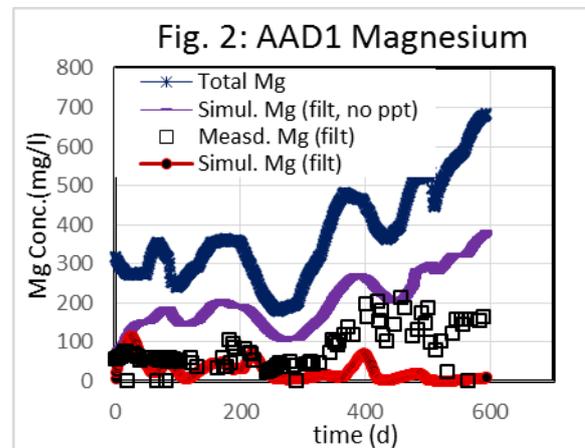
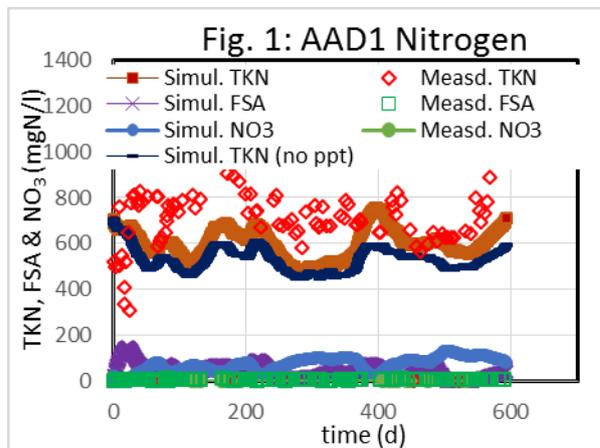
## Discussion

The ASM2-3P models the behaviour of the parent NDEBPR system well by predicting values close to experimental observation. This allowed for, within a plant-wide set-up, the model performance evaluation of the AADs treating WAS from the parent NDEBPR system. Experimental evidence (Vogts *et al.*, 2014) shows that the PAOs do not grow in the AAD, but undergo endogenous respiration and die, releasing their stored PP as magnesium (Mg), calcium (Ca), potassium (K) and orthophosphate (OP). Struvite ( $\text{MgNH}_4\text{PO}_4$ ) precipitation occurs when the concentration of Mg, ammonia and OP is high enough (i.e., super saturation) in the mixed liquor. If the ammonia is low (< 1mgN/l), due to nitrification, and pH is high, it was suspected that K-struvite ( $\text{MgKPO}_4$ ), Newberryite ( $\text{MgHPO}_4$ ) or magnesite  $\text{Mg}_2(\text{CO}_3)_2$  would form. However, although both nitrification and struvite formation cause a decreased effluent AAD ammonia, unfiltered TKN reduction only occurs with the nitrification (struvite would re-dissolve to form ammonia,  $\text{Mg}^{2+}$  and OP in a diluted sample). Hence,

with an established nitrification capacity (from FSA released with organics degradation), predicted low effluent ammonia without reduction in unfiltered TKN, indicates struvite formation. This was the case with AAD1 and corresponded well with the reduced Mg and OP that matched the model predicted values, with the struvite formation. This was expected, due to the predicted high concentrations of P and cations ( $Mg^{2+}$  and  $K^+$ ) present in the aqueous phase of the mixed liquor, after PP release and the rise in  $H_2CO_3^*$  alkalinity. However, MgKP did not precipitate due to its low solubility product, and it being known to precipitate at high pHs (about 10, Wilsenach *et al.* 2007; Taylor *et al.* 1963). In fact the  $K^+$  provides a good indicator of % PP released, to determine the relative quantity of P released from PP in order to calculate the quantity that may have precipitated. When the P is modelled to be released at the same rate as the biomass (PAO) endogenous respiration ( $b_G = 0.04/d$ ), the filtered effluent  $K^+$  is similar to that simulated. This means that the PP release in the AAD does not occur rapidly as noted in the AD (Harding *et al.*, 2009; Ikumi, 2011) but gradually, with the PAO death according to endogenous respiration.

**Table 1: Example for equilibrium and mass balance equations for ionic speciation**

Weak Acid Sub-System	*Aqueous Phase Equilibrium Equations	Mass Balance Equation
Ammonia	$[NH_3] = \frac{K_{NH_4} \cdot [NH_4^+]}{(H^+)}$ $[NH_4SO_4^-] = \frac{[SO_4^{2-}] [NH_4^+]}{K_{NH_4SO_4}}$	$NH_x = [NH_4^+] + [NH_3] + [NH_4SO_4^-]$
<p>*Where <math>(H^+)</math> is the hydrogen ion activity, <math>[X]</math> the molar concentrations of species X and <math>K_X</math> is the thermodynamic equilibrium constant for species X, adjusted for Debye Hückel effects to account for the activity of ions in low salinity water (Stumm and Morgan, 1996).</p>		



**Figures 1.1 and 1.2: Showing lowered effluent ammonia (without TKN reduction) that matched the model predicted values (Fig 1.1) and corresponding Mg reduction (Fig 1.2), indicating formation of struvite.**

## References

- Brouckaert C.J., Ikumi D.S. and Ekama G.A. (2010). *A 3-phase anaerobic digestion model*. In: Proceedings. 12th IWA Anaerobic Digestion Conference (AD12), Guadalajara, Mexico, 1-4 Nov, 2010.
- Henze M., Gujer W., Mino T., Matsuo T., Wentzel M.C. and Marais G.v.R. (1995). *Activated Sludge Model No.2 (ASM2)*. IWA Scientific and Technical Report No.3, IWA Publishing, London, U.K.
- Ikumi, D.S., Harding, T.H., Brouckaert, C.J. and Ekama, G.A. (2014b). Plant wide integrated biological, chemical and physical processes modelling of wastewater treatment plants in three phases (aqueous-gas-solid). Research Report W138, Department of Civil Engineering, University of Cape Town, Rondebosch, 7700, Western Cape, South Africa.
- Vogts M., Ikumi D.S., Ekama G.A. (2014). *The Removal of N and P In Aerobic and Anoxic-Aerobic Digestion of Waste Activated Sludge from Biological Nutrient Removal Systems*. Procs. WISA conference (034). Mpumalanga, South Africa, 25-29 May.