

## Simulation of a novel strategy for improving a biological phosphorus removal system start-up

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### Abstract

This work analyses (by means of simulation) the effect of reducing the length of the aerobic phase in the start-up of an Enhanced Biological Phosphorus Removal (EBPR) process conducted in a sequencing batch reactor system. This new control strategy is based on finishing the aerobic phase when phosphorus is depleted from the medium. Two scenarios were simulated: one with fixed aerobic phase (usual EBPR operation) and the other with a variable aerobic phase length linked to phosphorus presence (novel strategy presented in this work). After thirty days of start-up simulation, the results revealed that the ratio of polyphosphate accumulating organisms to ordinary heterotrophic organisms was 90% higher than in the variable aerobic phase length scenario. According to the simulations performed in this work, this control strategy allowed achieving higher net phosphorus removal capacity.

**Keywords:** Aerobic phase length; Enhanced Biological Phosphorus Removal; Polyphosphate Accumulating Organisms; Sequencing Batch Reactor.

### 1. Introduction

Nowadays, a better understanding of the biological processes for the wastewater nutrient removal is necessary to increase their efficiency. Among them, enhanced biological phosphorus removal (EBPR) is widely accepted as one of the most economical and sustainable processes to remove phosphorus from wastewater, but at the same time, it is a complex process when compared to biological removal of organic matter (COD) or nitrogen. The EBPR process is based on the enrichment of activated sludge with polyphosphate accumulating organisms (PAO). Under anaerobic conditions, PAO take up organic substrates (preferably volatile fatty acids) and store them as poly-hydroxyalkanoates (PHA), while the degradation of intracellular glycogen provides reducing equivalents (Mino *et al.* 1987, Smolders *et al.*, 1995). The energy for this process is obtained partly from the glycogen degradation but mostly from the hydrolysis of the intracellular stored polyphosphate (polyP), resulting in an orthophosphate release into solution. In the subsequent aerobic phase, PAO take up excessive amounts of orthophosphate to recover the intracellular polyP levels by oxidising the stored PHA. Meanwhile they grow and replenish the glycogen pools using PHA as both carbon and energy sources (Smolders *et al.*, 1995). Net phosphorus removal is achieved by wasting sludge after the aerobic period when the biomass contains high levels of polyP.

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In most of the systems, the aerobic period is longer than the time required by PAO to uptake the orthophosphate from the medium. From the depletion of this orthophosphate until the end of the aerobic period, PAO are not favoured in front of the other organisms present in the biomass, such as ordinary heterotrophic organisms (OHO) and/or glycogen accumulating organisms (GAO). Hence, the rest of aerobic phase could be not necessary (it could even be detrimental) for PAO growth (Brdjanovic *et al.* 1998). The main purpose of this study is to test by simulation the improvement in the start-up of an EBPR system of modifying the operational sequencing batch reactor (SBR) conditions to favour PAO growth. The operational modification tested consists of controlling the length of the aerobic phase by avoiding periods with no orthophosphate in the medium. The proposal of this study consisted in analysing (by means of simulation) the effect of implementing this new control strategy in the start-up of an EBPR system. Hence, the state variables values obtained after thirty days of simulation with both systems (fixed and variable aerobic phase length linked to phosphorus presence) were compared. The reference kinetic model used for simulations was a modification of the widespread Activated Sludge Model 2d (ASM2d) (Henze *et al.* 2000).

## **Model description**

### Biological Model

The model for the description of the biological processes involved in both anaerobic and aerobic phases was a modification of the ASM2d. This modification consisted of omitting the autotrophic and physical precipitation processes and including the glycogen economy concept in the PAO processes. The contemplation of the glycogen as an important compound implied the inclusion of a new process (glycogen aerobic production) and some stoichiometric modifications as detailed in Guisasola *et al.* (2004). The ASM2d default parameters were used except for those related to the glycogen economy, taken from Pijuan *et al.* (2004). The OHO population was included as described in ASM2d because the competition between OHO and PAO had a strong influence on PAO dynamic behaviour. Moreover, if an EBPR system was started with typical wastewater treatment plant biomass, the ratio PAO to OHO would be very low. In short, the model involved 14 biological processes related to OHO and PAO and 11 state variables:  $S_A$  (fermentation products-acetate),  $S_F$  (readily biodegradable substrates),  $S_O$  (dissolved oxygen),  $S_P$  (orthophosphate),  $S_{CO_2}$  (dissolved carbon dioxide),  $X_{PAO}$  (PAO biomass),  $X_{PHA}$  (poly-hydroxyalcanoates),  $X_{GLY}$  (glycogen),  $X_{PP}$  (polyphosphate),  $X_H$  (OHO biomass),  $X_S$  (slowly biodegradable biomass) and  $X_I$  (inert organics).

### SBR cycle modelling

This biological model was integrated in the simulation of a whole SBR cycle. Each cycle could be divided in five sequential phases: feeding of the wastewater, anaerobic, aerobic, settling and extraction of the treated wastewater. Biological reactions were been considered in the anaerobic and aerobic phases.

*Feed phase:* This phase was simulated as an instantaneous process. The influent flow was 5 litre and contained COD (as acetate), phosphorus and enough essential micronutrients for microbial growth so that no limitations occurred in the reactor.

*Anaerobic phase:* This phase was characterised by a constant length of two hours and an oxygen setpoint of zero mg O<sub>2</sub>/L.

*Aerobic phase:* The oxygen set point value in this phase was set to 8 mg O<sub>2</sub>/L to avoid any oxygen limitation. The length of this phase was fixed to 3 hours or was variable depending on whether there was P-strategy control or not.

*Settling and extraction phases:* These two phases lasted a total of one hour and were considered together for model simplification. The concentrations of the state variables at the end of the cycle were calculated with mass balances according to the waste and the total volume extracted (5 L).

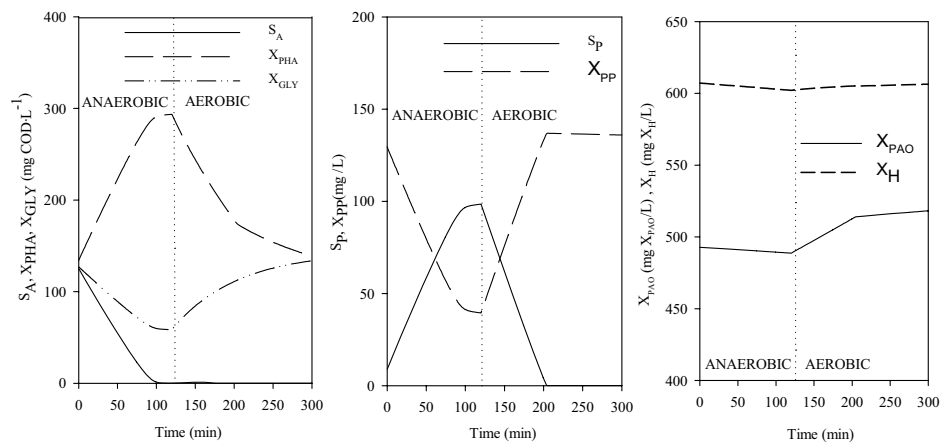
#### Simulation tools

The modelling software used was MATLAB 6.5 (The MathWorks, Natick, MA). The differential equations were solved using the function *ode15s*. This solver is particularly indicated for stiff systems.

### **Simulation results**

#### One cycle simulation

The profiles of the main compounds along one period of anaerobic + aerobic phases (with fixed aerobic length) are depicted in Figure 1. In the anaerobic phase, acetate ( $S_A$ ) is taken up and stored into PHA linked to glycogen degradation (Fig 1a). The energy necessary for this process is mostly obtained from polyP hydrolysis which results in orthophosphate release (Fig 1b). Finally, neither the PAO nor the OHO ( $X_H$ ) are able to grow on this phase, and the lysis process cause a decay in both biomasses (Fig 1c). On the other hand, in the aerobic phase the PAO use the previously stored PHA to restore its internal glycogen pools (Fig 1a), to uptake orthophosphate from the media in terms of polyP (Fig 1b), to grow (Fig 1c) and, finally, it is oxidised for maintenance purposes. However, PAO are only able to grow with orthophosphate in the media. PAO growth decreases sharply when the orthophosphate is totally depleted (~200 min) (Fig. 1c).



*Figure 1 – Profiles of the main compounds along the anaerobic phase (120 min) and the aerobic phase (180 min) of a typical EBPR cycle.*

Hence, the time period between orthophosphate depletion and the aerobic phase end becomes a waste of time and energy according to our objective of enriching the SBR population with PAO. In the cycle depicted on Fig. 1, the last aerobic 100 minutes in the media could have been removed without any negative effect to PAO population.

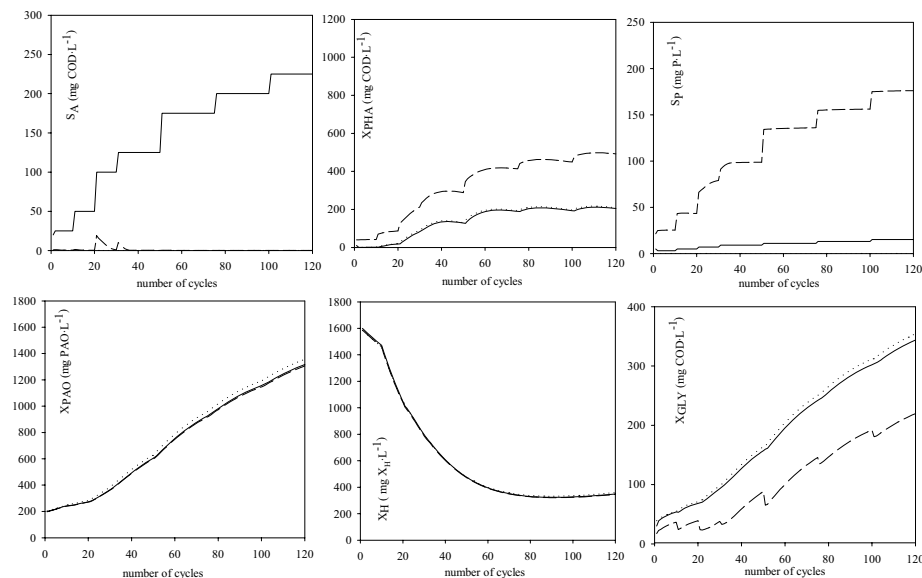
The main goal of this study consisted of analysing the effect of implementing a new control strategy based on reducing the aerobic phase so that the periods without orthophosphate (when PAO growth is very slow) do not occur. This new strategy (P-strategy control) was implemented to simulate EBPR system start-up and to monitor the evolution of the main compounds involved. The results obtained with and without control strategy were compared. The initial values used for both simulations are shown in Table 1.

*Table 1 – Initial values for dynamic simulation*

Parameter	Initial value	Parameter	Initial value
Biomass (mg SSV/L)	4000	$X_{GLY}$ (mg COD/L)	30
$X_{PAO}$ (mg $X_{PAO}$ /L)	200	$X_S$ (mg COD/L)	0
$X_H$ (mg COD/L)	1600	$X_{PP}$ (mg P/L)	20
$X_{PHA}$ (mg COD/L)	10	$X_I$ (mg COD/L)	0

#### Simulation without control (fixed aerobic phase length)

Each cycle lasted 6 hours, so 120 cycles were placed in 30 days. The profiles of the main compounds along the 30-days simulation without control are depicted in Figure 2. The influent COD and P concentrations were increased along with the PAO growth. At the beginning of the start-up, the influent COD and P were set to a very low value because of the low initial PAO fraction in the biomass. It was necessary to ensure that all the COD is taken up in the anaerobic phase for a proper PAO growth in the aerobic phase. However, the steady-state PAO value reached if the initial influent conditions were kept would have been very low. Then, an adequate feed pattern was designed in terms of COD and P according to the PAO growth theoretically observed.



*Figure 2 –Start-up period without control (6-hour cycle). Anaerobic phase initial (solid), aerobic phase initial (dashed) and aerobic phase end (dash-dotted).*

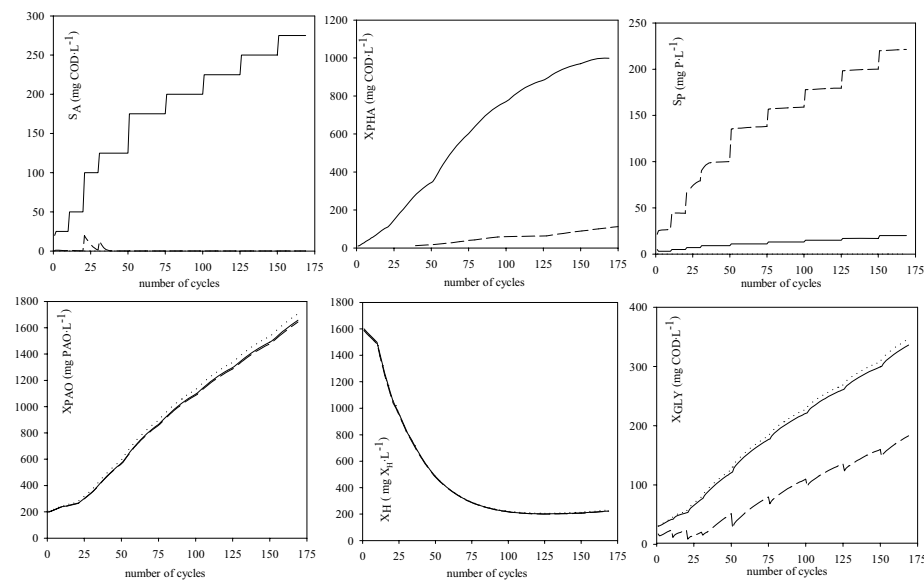
The OHO population ( $X_H$ ) hit a low during the start-up period (Fig.2) because they could only grow on COD under aerobic conditions and the only COD present was due

to the hydrolysis and fermentation processes (a very low COD value). On the contrary, PAO rose considerably, because they grew on the previously stored  $X_{PHA}$ . Hence, the start-up process with fixed aerobic phase length could be successful (but also can be optimized). In the next section, this efficiency in PAO growth is compared with a system with variable aerobic phase length depending on P concentration.

#### Simulation with P-strategy control (variable aerobic phase length)

The aerobic phase length was controlled using orthophosphate concentration as measured variable. When it became lower than 0.1 mg P/L, the aerobic phase stopped and the settling/extraction phase started.

The simulation performed using the P-strategy control showed that 120 cycles could be performed in only 513 hours due to the reductions in the aerobic phase length. It meant a reduction of 207 hours with respect to the 720 hours required to perform 120 cycles without control. Hence, 29 % of the start-up time was useless for PAO growth and as such could be omitted without any negative effect as shown in Figure 3, where the simulated profiles of the main compounds with the P-strategy control are depicted. The graphic displays the trends observed during 170 cycles which was the amount of cycles that could be placed in 30 days of start-up using the P-strategy control. In the same period of time, more cycles could be performed and, hence, the EBPR system start-up became more efficient, in terms of time required to reach the steady state as well as in terms of amount of flow that could be treated.



*Figure 3 –Start-up period with P-strategy control (variable length). Anaerobic phase initial (solid), aerobic phase initial (dashed) and aerobic phase end (dash-dotted).*

The values of the main state-variables after thirty days of simulation are shown on Table 2. The ratio of  $X_{PAO}/X_H$  obtained using the P-strategy control was improved to a great extent (~90%). Moreover, the values of  $X_{PHA}$  in the P-strategy control were much higher because the aerobic phase was severely reduced. PHA in the aerobic phase was used for growth, glycogen restoration, polyP storage and maintenance purposes. Once

the glycogen was totally restored and there was no orthophosphate in the media, the PAO growth became low and the levels of  $X_{PHA}$  were wasted in maintenance purposes.

*Table 2 – Values reached after thirty days of simulation with and without P control*

Compounds	NO CONTROL- 120 CYCLES- 720 HOURS			WITH CONTROL- 170 CYCLES- 710 HOURS		
	Start anaerobic	Start aerobic	End aerobic	Start anaerobic	Start aerobic	End aerobic
$S_A$ (mg COD/L)	175	0.1	0.0	175	0.1	0.0
$X_{PHA}$ (mg COD/L)	75	298	76	545	768	559
$X_{PAO}$ (mg $X_{PAO}$ /L)	1036	1028	1068	1197	1187	1229
$S_P$ (mg P/L)	13	138	0.0	13	142	0.1
$X_{PP}$ (mg P/L)	258	131	265	375	245	385
$X_H$ (mg COD/L)	275	273	283	168	166	172
$X_{GLY}$ (mg COD/L)	264	168	272	240	142	246
$X_{PAO}/X_H$ (g $X_{PAO}$ /g $X_H$ )	3.75	3.76	3.93	7.14	7.13	7.14

## CONCLUSIONS

The simulations performed in this work reveal that reducing the length of the aerobic phase in an EBPR system start-up so that the end of the aerobic phase coincides with the total depletion of phosphorus in the media:

- increases the start-up efficiency in terms of PAO presence in the final sludge
- allows achieving higher phosphorus removal capacity and higher PAO to OHO ratio.

## REFERENCES

- Brdjanovic D, Slamet A, van Loosdrecht MCM, Hooijmans CM, Alaerts GJ, Heijnen JJ. 1998. Impact of excessive aeration on biological phosphorus removal from wastewater. *Water Res* 32:200-208.
- Guisasola A, Pijuan M, Baeza JA, Carrera J, Casas C, Lafuente J. 2004. Aerobic phosphorus release linked to acetate uptake in bio-P sludge: process modelling using oxygen uptake rate. *Biotechnol Bioeng* 85: 722-733.
- Henze M, Gujer W, Mino T, Van Loosdrecht MCM. 2000. Activated Sludge Models ASM1, ASM2, ASM2d and ASM3: Scientific and Technical Report n°9. IWA Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment.
- Mino T, Arun V, Tsuzuki Y, Matsuo T. 1987. Effect of Phosphorus Accumulation on Acetate Metabolism in the Biological Phosphorus Removal. In *Advances in Water Pollution Control 4: Biological Phosphate Removal from Wastewaters*. R. Ramadori (Ed.) pp 27-38. Pergamon Press, Oxford, U.K.
- Pijuan M, Saunders AM, Guisasola A, Baeza JA, Casas C, Blackall LL. 2004. Enhanced biological phosphorus removal in a sequencing batch reactor using propionate as the sole carbon source. *Biotechnol Bioeng* 85:56-67.
- Smolders GJF, van der Meij J, van Loosdrecht MCM, Heijnen JJ. 1995. A structured metabolic model for anaerobic and aerobic stoichiometry and kinetics of the biological phosphorus removal process. *Biotechnol Bioeng* 47:277-87.