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Additional Information

Sludge management modeling to enhance P-recovery as struvite in wastewater treatment plants

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Abstract

Interest in phosphorus (P) recovery and reuse has increased in recent years as supplies of P are declining. After use, most of the P remains in wastewater, making Wastewater Treatment Plants (WWTPs) a vital part of P recycling. In this work, a new sludge management operation was studied by modeling in order to recover P in the form of struvite and minimize operating problems due to uncontrolled P precipitation in WWTPs. During the study, intensive analytical campaigns were carried out on the water and sludge lines. The results identified the anaerobic digester as a “hot spot” of uncontrolled P precipitation (9.5 gP/kg sludge) and highlighted possible operating problems due to the accumulation of precipitates. A new sludge line management strategy was simulated therefore using DESASS© software, consisting of the elutriation of the mixed sludge in the mixing chamber, to reduce uncontrolled P precipitation and to obtain a P-rich stream (primary thickener supernatant) to be used in a crystallization process. The key operating parameters were found to be: the elutriation flow from the mixing chamber to the primary thickener, the digestion flow and the sludge blanket height of the primary thickener, with optimized values between 70-80 m³/d, 90-100 m³/d and 1.4-1.5 m, respectively. Under these operating conditions, the preliminary results showed that P concentration in the primary thickener overflow significantly increased (from 38 to 100 mg PO₄-P/L), which shows that this stream is suitable for use in a subsequent crystallization reactor to recover P in the form of struvite.

Keywords

Nutrient recovery; sludge treatment; crystallization; uncontrolled precipitation; urban WWTP

1. INTRODUCTION

The demand for Phosphorus (P), a non-renewable material essential to life, is on the increase and recent studies have shown that the production rate of economically available phosphate reserves will peak between 2030 and 2040, after which demand will exceed supply (Cordell *et al.*, 2009). In addition, phosphate discharges into the environment will have to be controlled, due to problems such as eutrophication. Wastewater Treatment Plants (WWTPs) thus play an important role, as they are one of the main routes of non-diffuse P losses. Moreover, P recovery from municipal wastewater now presents an opportunity to generate local supplies of P fertilizers (Bradford-Hartke *et al.*, 2015). Sustainable P management should therefore focus on its final recovery from wastewater. In this regard, the Swiss government recently approved (01.01.2016) a new regulation which imposed obligatory P recovery and recycling in the form of inorganic products from all sewage sludge and slaughterhouse waste, which should serve as an example to other countries.

In WWTPs with Enhanced Biological Phosphorus Removal (EBPR), phosphates and other ions (i.e. magnesium and potassium) are removed from wastewater and accumulated inside the polyphosphate accumulating bacteria (PAO) as internal granules of polyphosphate (Poly-P). The fate of the phosphate in EBPR processes is thus to be transferred from the water line to the sludge line. Sludge stabilization in large WWTPs is usually carried out by anaerobic digestion, during which Poly-P is released into the liquid phase, which notably raises P, magnesium and potassium concentrations. Ammonium and other metal cation concentrations also increase significantly, due to the organic matter degradation that takes place inside the digester. The increased concentrations of dissolved components and the high pH achieved during anaerobic digestion raise the P precipitation potential in this stage of the treatment system (Ohlinger *et al.*, 1998).

The uncontrolled precipitation of struvite (MgNH₄PO₄·6H₂O) onto pipe walls and equipment surfaces of anaerobic digestion and post-digestion processes has been frequently reported (Parsons and Doyle, 2004; Barat *et al.*, 2009a). Precipitation problems lead to higher sludge management costs (Neethling

and Benish, 2004) and reduce the potential P that can be recovered in the WWTPs. These precipitation problems, along with struvite's potential as a fertilizer, have led wastewater companies and research groups to study P recovery from wastewater as struvite.

P recovery technologies from flows with dissolved P (e.g., WWTP effluents, digester supernatants) via precipitation or crystallization as struvite or calcium phosphates produces more clean and crop-available materials than technologies that recover P from sewage sludge ash (SSA). However, the P recovery rates (< 25% relative to the WWTP input) are relatively low compared with those obtained in the SSA processes (~40–50% relative to the WWTP input) (Egle *et al.*, 2016).

The product thus obtained from dissolved P streams can be used as an effective slow-release fertilizer in agriculture (de-Bashan *et al.*, 2004; Egle *et al.*, 2016) and can be sold at a profit. Using struvite as a fertilizer not only involves its recovery, but also the reuse of nutrients, thereby promoting sustainable WWTP management. However, although struvite crystallization has been widely studied on the laboratory scale (Battistoni *et al.*, 2000; Pastor *et al.*, 2008; Martí *et al.*, 2010; Lahav *et al.*, 2013), its full-scale application is still limited in Europe, and only a few WWTPs in Germany, Denmark, The United Kingdom and The Netherlands have as yet put this technology into practice (Desmidt *et al.*, 2015). These full-scale applications are mainly focused on P recovery in the dewatering stream after anaerobic digestion, which reduces the potential P recovery, since an important amount of P is lost inside the anaerobic digesters and post-digestion systems due to uncontrolled precipitation.

In this context, the LIFE+ PHORWater project proposes the first WWTP integral management model to enhance P recovery. A significant novelty of this study compared to others is that the methodology proposed tries to boost the relatively low P recovery rates in technologies using flows with dissolved P and to reduce the uncontrolled P precipitation in anaerobic digestion and post-digestion processes.

The study project was carried out in the Calahorra WWTP (La Rioja, Spain) and involved simulation of a novel sludge management operation designed to enhance P-recovery in the form of struvite and to minimize operating problems from uncontrolled P precipitation. Intensive analytical campaigns were carried out on the water and sludge lines of the Calahorra WWTP to calibrate the BNMR2 model (Barat *et al.*, 2013) implemented with DESASS© software (Ferrer *et al.*, 2008) to simulate a new sludge line management strategy and determine the optimal operating conditions.

2. MATERIALS AND METHODS

2.1. Calahorra WWTP

Calahorra WWTP has a treatment capacity of 23000 m³/d. The water line operates for biological nitrogen and phosphorous removal (A2/O configuration) following preliminary treatment and primary settling. The total reactor volume is 15255 m³ divided into anaerobic, anoxic and aerobic zones. Primary sludge and waste activated sludge (WAS) are concentrated in a gravity thickener and two rotary dynamic thickeners, respectively. Once thickened, both sludges are mixed before being anaerobically digested in a thermophilic digester with SCABA agitator. The digested sludge is stored in a secondary digester and finally dewatered by centrifugation. The effluents from centrifuges and sludge thickeners are recycled to the water line. The layout of the WWTP is sketched in Figure 1, in which the sampling points are numbered.

2.2. Analytical methods

Total solids (TS), total volatile solids (TVS), suspended solids (SS), volatile suspended solids (VSS), total and soluble Chemical Oxygen Demand (COD_{tot}, COD_{sol}) and total and soluble P (P_{tot}, P_{sol}) were measured in accordance with the Standard Methods (APHA, 2012). Total and soluble nitrogen (N_{tot}, N_{sol}) were measured by the standard kits (Merck, Darmstadt, Germany, 100613). Volatile fatty acid concentrations (VFA) were measured by the 5-point titration method (Moosbrugger *et al.*, 1992). Total and soluble calcium (Ca_{tot}, Ca_{sol}), magnesium (Mg_{tot}, Mg_{sol}) and potassium (K_{tot}, K_{sol}) were analyzed by Atomic Absorption Spectrometry (AAS) (ICE 3000 SERIE S, Thermo Scientifics, Franklin, EEUU). Ammonium (NH₄-N), nitrate (NO₃-N) and phosphate (PO₄-P) concentrations were determined by Standard Methods (APHA, 2012) in a Smartchem 200 automatic analyzer (Westco Scientific Instruments). The presence of Polyphosphate Accumulating Organisms (PAO) and Glycogen Accumulating Organisms (GAO) was assessed by the Fluorescence *in situ* Hybridisation (FISH) technique. Cell hybridization was performed as described in Amann *et al.* (1990).

2.3. Simulation method

The mathematical model used in the present study was the BNRM2 (Barat *et al.*, 2013) implemented in DESASS© software (Ferrer *et al.*, 2008). The BNRM2 is a general model, which includes all the components and transformations needed to reproduce the main biological, physical and chemical processes that take place in a WWTP.

Initially, the Calahorra WWTP model was dynamically calibrated using the experimental data obtained in the analytical campaign (see 3.2.1). The calibration method consisted of tuning the different model parameters in order to minimize the error between the experimental and simulated values. After calibration, the model was used to simulate and optimize the new sludge handling configuration proposed in this paper (see 3.2.2.).

3. RESULTS AND DISCUSSION

3.1. Evaluation of P precipitation and potential P-recovery

Table 1 shows the average values and standard deviations of the main parameters analyzed in the water and sludge lines during the analytical campaigns carried out under normal WWTP operation during four months. During this period, five sampling campaigns were carried out to obtain accurate information on the plant's performance. Special attention was paid to spacing out the sampling campaigns to coincide with the 20-day hydraulic retention time in the anaerobic digester.

The samples were collected in the winter months, since the EBPR process showed a historically worse performance at low temperatures. However, as can be observed in Table 1, the water line worked adequately in terms of obtaining good P removal efficiency, with values of around 80%. These analytical results were confirmed by the FISH technique, which showed the presence of PAO ($9\% \pm 2$) and low GAO ($3\% \pm 1$) (Glycogen Accumulating Organisms) populations in the biological reactor. Other full-scale wastewater treatment plants performing enhanced biological phosphorus removal have shown similar percentages for PAO and GAO population than the ones obtained in this study (Lanham *et al.*, 2013).

From the experimental data obtained on phosphorus, magnesium, potassium and calcium, mass balances were applied in the mixing chamber and the anaerobic digester following the method proposed in Martí *et al.* (2008a), according to which the organic content of P, K, Mg, and Ca per 100 mg of TVS of mixed sludge (primary+WAS) was estimated as: 1.4 mg of P, 0.3 mg of Mg, 1.4 mg of K and 0.2 mg of Ca, taking into account the proportion of primary and WAS sludge in the experimental period (i.e. 45 and 55%, respectively). The mass balance results in the mixing chamber and anaerobic digester are shown in Table 2.

The potassium mass balance in the mixing chamber pointed to a high potassium release due to Poly-P degradation (K_{PAOrel}) which was also reflected in the Mg_{PAOrel} and P_{PAOrel} in this unit. Under the conditions achieved in the mixing chamber (anaerobic conditions, WAS with PAO bacteria replenished with Poly-P, and presence of VFA from the thickened primary sludge) a significant amount of Poly-P stored by the PAO was degraded to supply the energy requirements associated with polyhydroxyalkanoate accumulation. These results indicate that Poly-P degradation took place mainly in the mixing chamber before the anaerobic digester.

The results also revealed high P precipitation, mainly in the anaerobic digester, in which 38.6 kgP/d, or 81% of available P precipitated (i.e. influent + total release during anaerobic digestion). In addition, a high magnesium precipitation of 11.9 kg/d (90%) and a relatively high calcium precipitation of 11.4 kg/d (65%) were calculated. Both the increase in the concentrations of dissolved components and the high pH achieved (7.9) raised the P precipitation potential in this stage of the sludge treatment line, which means that operating problems related to the accumulation of these precipitates inside pipes and equipment could be expected. The significant amount of Mg precipitated suggests the possible formation of struvite as a solid in the anaerobic digester. Considering struvite as the main magnesium precipitate, the amount of phosphate precipitated as struvite was estimated to be 39%. The mass balances in the mixing chamber also indicated that P and Mg were being precipitated in this unit. However, these precipitation processes were less significant in the mixing chamber, due to its lower pH content (6.3). Indeed, the highest soluble P concentration in the sludge line was measured in this unit (163.2 ± 34.7 mg PO_4 -P/L).

Table 3 shows the assessment of lost P and the P available for recovery in the current sludge line configuration. The results were based on the average mass flow rate of sludge fed to the mixing chamber during the experimental period (4057 kgTS/d; data provided by Calahorra WWTP). As stated above, the main P loss point is in the anaerobic digester (9.5 gP/kg sludge) due to the high precipitation, also in the mixing chamber, where a low P precipitation was estimated. P is also lost in the dewatering system, since part of the soluble P remains in the dewatered sludge.

Three supernatant streams contain available P that could be recovered as struvite in a crystallization process: these are the primary thickener supernatant (Sampling Point (SP) 7), the WAS thickening supernatant (SP 8), and the centrate from the digested sludge dewatering (SP 12).

As Table 1 shows, the P concentration in the WAS thickening supernatant was quite low, which indicates that this stream is not a good candidate for a further crystallization step, although it was considered in the P availability assessment.

Table 3 shows that the Potential P-recovery (%), which represents the phosphorus that could be recovered in a crystallization process in relation to the maximum phosphorus available in the sludge treatment system, is 14%. Of the total P entering the WWTP, only 9% could be recovered, so that a new sludge management alternative was evaluated to increase the potential P-recovery in the rejected liquors.

3.2. Optimal sludge line management to maximize P recovery

Most of the systems that have been developed to recover P as struvite from WWTPs (NuReSys, Struvia, Crystallactor, Ostara, etc.) treat the anaerobic digester supernatants, resulting in sludge dewatering (Desmidt *et al.*, 2015). However, as shown in this study, at this point of the sludge line, most of the available P is lost mainly due to precipitation in the sludge treatment line (anaerobic digester, centrifuges, pipes, pumps, etc.). It was therefore necessary to develop new sludge management alternatives to reduce this uncontrolled precipitation and to maximize the P available for further recovery.

The P released in the digester is the result of organic matter degradation (P in the organic matter represents 58% of the P_{tot} loaded in the sludge treatment line) and Poly-P hydrolysis (the P in Poly-P represents 42% of the P_{tot} loaded in the sludge treatment line). The organic matter degradation process that takes place in the anaerobic digester is a consequence of sludge stabilization and cannot be reduced to minimize P precipitation. However, the P released from the Poly-P in the digester can be reduced by enhancing its release and separation before digestion. The optimal sludge handling configuration proposed is therefore based on the reduction of the phosphate load to anaerobic digestion, to maximize the release and further separation of P before digestion.

With this aim, the Calahorra WWTP was simulated on the BNRM2 Model (Barat *et al.*, 2013) implemented with DESASS© software (Ferrer *et al.*, 2008) using the experimental data obtained in the analytical campaign.

3.2.1. Model Calibration

The BNRM2 model was calibrated fitting the simulated results with the experimental results of the whole WWTP including the water line and the sludge line. The model was able to accurately reproduce the biological processes in the water line simulation (see Figure S1): nitrification in the aerobic zone, denitrification in the anoxic zone and P release and uptake during the anaerobic and aerobic zone, respectively. As can be seen in Figure S2a, the model was able to predict the COD, SS, P (total, soluble and PO_4 -P), nitrogen (total, soluble, NH_4 -N, NO_3 -N) and total and soluble Ca, K and Mg concentrations in the effluent of the water line.

On the other hand, as one of the key aspects of the new configuration relies on sludge management, the sludge line was simulated to accurately reproduce its current performance, especially with regard to the primary settler, gravity thickener and mixing chamber, as will be described below. As can be seen in Figure S2b, the model was able to reproduce the physical and biological processes that take place in the primary settler, gravity thickener and mixing chamber. Among them, the hydrolysis processes involved in COD and SS fate in the mixing chamber and the primary thickener were well reproduced in the simulation using a hydrolysis rate value of $3.0 d^{-1}$. The important fermentation process that occurs in the gravity thickener should also be noted, which raises VFA from 285 mgCOD/L (primary settler) to 946 mgCOD/L (thickened sludge). This was responsible for the considerable phosphate release in the mixing

chamber (300.7 mg PO₄-P/L) associated with the VFA uptake by PAOs. The whole wastewater treatment plant was fitted with the default values of the model parameters proposed in the BNRM2, with the exception of some parameters related to the biological phosphorus removal processes. The decay rate of PAO (b_{PAO}), polyhydroxyalkanoates (b_{PHA}) and polyphosphate (b_{PP}) was reduced from the value proposed in the BNRM2 (0.2 d⁻¹ in Barat *et al.*, 2013) to 0.15 d⁻¹ in order to properly reproduce the processes related to biological P removal.

3.2.2. Optimization of sludge line management

After fitting the sludge line performance of the Calahorra WWTP with the experimental data, the proposed sludge management configuration (Figure 2) was simulated modifying the operating conditions in order to reduce the high P precipitation observed in the digester and to obtain an overflow stream with a high phosphate concentration suitable for use in a crystallization process. The simulations were based on the P extracted from the mixing chamber for the above-mentioned reasons. The simplicity of the sludge line modification and the minimal implementation costs were both crucial to deciding the best sludge line management. Previous studies (Martí *et al.*, 2008b; Barat *et al.*, 2009b) have shown that the mixing chamber combined with elutriation of mixed sludge in the primary thickener is an effective method of extracting high P concentrations before digestion. For this purpose, the mixed sludge is recirculated to the gravity thickener of the WWTP, in which the soluble compounds present in the mixed sludge (including phosphate) will be washed and extracted with the thickener supernatant. This P-rich stream (primary thickener supernatant) thus might be used in a crystallization process.

The operating parameters modified in the optimization process were the elutriation flow from the mixing chamber to the primary thickener and the digestion flow. The elutriation flow was varied from 25 to 390 m³/d and the digestion flow from 45 to 105 m³/d. These ranges were selected in accordance with the capacity of the pumps available at the WWTP. Figure 3 shows the phosphate concentration and the SS concentration in the primary thickener supernatant (Figure 3a and b, respectively) and the SS concentration in the thickened sludge (Figure 3c) simulated within the aforementioned flow ranges. As can be seen in Figure 3a, the higher the elutriation flow and the lower the digestion flow, the higher the P concentration in the thickener supernatant, thus increasing the potential P-recovery. However, these elutriation and digestion flows are limited by the thickener capacity to retain solids and by the solids concentration in the thickened sludge that enters the anaerobic digester. The SS concentration in the supernatant of the primary thickener is a good indicator of the sludge blanket height. When the SS concentration sharply increases indicates that the sludge blanket height achieves its maximum value losing solids with the effluent. As can be seen in Figure 3b, high elutriation flows (above 250 m³/d) combined with low digestion flows (below 55 m³/d) raises the sludge blanket to the final overload of the primary thickener. As previously indicated, the thickened sludge solids concentration is another bottleneck in the proposed system. This concentration has a limit related to the maximum solids concentration at which the digester agitation system is able to work. As Figure 3c shows, the solids concentration in the thickened sludge increases drastically when the digestion flow decreases. Therefore, although low digestion flows increase the phosphate concentration in the gravity thickener effluent (see Figure 3a), this digestion flow should be limited according to the digester mixing capacity (i.e, maximum 25 g SS/L at Calahorra WWTP). Thus, the digestion flow should not decrease below 70 m³/d to prevent thickened sludge solids concentration higher than 50 g SS/L (considering that the average SS reduction in the Calahorra digester is around 50%). At this digestion flow the elutriation flow should not exceed 150 m³/d to avoid SS in the thickener supernatant above 1000 mg SS/L.

According to the simulation results, the proposed sludge configuration was implemented and tested in manually mode for three months at the following conditions: digestion flow between 90 and 100 m³/d and elutriation flow between 70 and 80 m³/d. In these conditions the average P concentration in the thickener supernatant was 100 mg PO₄-P/L, reaching P concentration peaks of up to 132 mg PO₄-P/L. The sludge blanket level remained between 1.4 and 1.5 m (lower than 50% of the thickener depth) and the SS concentration in the thickener supernatant was lower than 850 mg SS/L. As can be seen in Figure 3a, the P concentration measured in the thickener supernatant was lower than the one expected in the model simulations (around 160 mg PO₄-P/L). These discrepancies are attributed to the lower biological P removal efficiencies in the water line during this period (EBPR_{efficiency} = 76%) than the ones obtained during the analytical campaign used for model calibration (EBPR_{efficiency} = 80%). This reduction in the P removal efficiencies reduces the P available in the sludge line and thus its potential recovery. The development of an algorithm to control the elutriation process would improve the operation leading to higher P concentrations in the thickener supernatant as predicted in the simulations. Nonetheless, the proposed sludge configuration provides a P-rich stream, suitable for use in a further crystallization

reactor to enhance P-recovery as struvite, and reduces the P concentration entering the digestion system minimizing thus the uncontrolled precipitation problems.

CONCLUSIONS

The sludge management operation of a WWTP was simulated to enhance P-recovery as struvite and to minimize any operating problems due to uncontrolled P precipitation. The simplicity of the sludge line modification and the minimal implementation costs were both crucial to determining the best simulated sludge line management system. In conventional operations, only 14% of P would be available for recovery in a subsequent crystallization process (9% of total P entering the WWTP). The simulated sludge management operation aimed at maximizing the potential recovery of P as struvite by elutriation in the gravity thickener of the mixed sludge contained in the mixing chamber. The elutriation flow from the mixing chamber to the primary thickener, the digestion flow and the sludge blanket height of the primary thickener were the key operating parameters and the optimized values were between 70-80 m³/d, 90-100 m³/d and 1.4-1.5 m, respectively. The preliminary results of the WWTP's new configuration show that the primary thickener overflow has become a P-rich stream (100 mg PO₄-P/L) suitable for use in a crystallization reactor to obtain enhanced P-recovery in the form of struvite. As a consequence the amount of P entering the digestion units has been decreased which will reduce the uncontrolled P precipitation in the WWTP.

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Table 1 Average and standard deviations of flow rates, TS, TVS, pH and PO₄-P, Ca_{sol}, Mg_{sol} and K_{sol} concentrations in the sampling points of Calahorra WWTP (See Figure 1) (*calculated by mass balance; ** Total suspended solids (SS) and volatile suspended solids (VSS) are determined in streams 0, 1 and 2). n.a.: not available;

Sampling point	Stream type	Flow rate (m ³ /d)	pH	TS mg/L	TVS %	P _{tot} mg/L	PO ₄ -P mg/L	Ca _{sol} mg/L	Mg _{sol} mg/L	K _{sol} mg/L
0	water	13310 ±2178	7,6 ±0,1	269** ±23	76** ±6	7.0 ±1.5	4.5 ±1.7	131.5 ±14.7	26.4 ±0.9	27.4 ±0.6
1	water	13871 ±1983	7,4 ±0,1	129** ±2	65** ±2	5.9 ±0.9	4.2 ±1.3	122.8 ±16.6	25.5 ±0.6	28 ±1.8
2	water	13281 ±1975	7.2 ±0.1	8** ±2	75** ±1	1.4 ±0.6	0.9 ±0.8	123.7 ±25	24.8 ±0.7	22 ±0.7
3	sludge	94 ±21	6.6 ±0.6	24808 ±7067	81 ±2	149.6 ±27.4	35.2 ±13.6	169.7 ±47.4	32.2 ±1.8	54.9 ±13.6
4	sludge	434 ±40	n.a.	5788 ±274	72 ±2	161.6 ±70.9	0.5 ±0.1	107.9 ±15.1	22.4 ±1.3	24.6 ±1.5
5	sludge	52 ±12	6.2 ±0.6	37027 ±5023	81 ±2	221.5 ±74.8	60.2 ±15.4	186.5 ±33.3	43.9 ±14	76.2 ±27.2
6	sludge	37* n.a.	n.a.	65495 ±5197	88 ±9	n.a.	1.3 ±0.1	98.5 ±14.6	24.4 ±2	25.4 ±6.5
7	side stream	42* n.a.	n.a.	1288 ±583	82 ±1	52.5 ±16.9	37.8 ±13.3	160.1 ±20.4	34.9 ±6	56.9 ±17.3
8	side stream	398* n.a.	n.a.	n.a.	n.a.	n.a.	1.3 ±0.1	98.5 ±14.6	24.4 ±2	25.4 ±6.5
9	sludge	89 ±10	6.3 ±0.2	42676 ±4719	83 ±1	534.4 ±125.5	163.2 ±34.7	159.8 ±10	56.1 ±9.1	166.7 ±67.3
10	sludge	89* n.a.	7.9 ±0.2	25341 ±925	70 ±3	486.2 ±33.8	99.2 ±21.9	69.9 ±5.2	15 ±7.5	316.6 ±76.5
11	sludge	89* n.a.	7.7 ±0.1	25040 ±1082	69 ±3	476.1 ±24.4	87.5 ±23.9	70.5 ±13.9	14.6 ±4.8	322.1 ±54.3
12	side stream	80* n.a.	7.9 ±0.1	716 ±387	60 ±6	118.2 ±33.4	84.6 ±32.5	63.3 ±12.1	12.2 ±2.6	283.6 ±33.3

Table 2 K, P, Mg and Ca mass balances in the mixing chamber and the anaerobic digester (subindex are defined as follows: ORGrel: release due to organic matter degradation, PAOrel: release from Poly-P hydrolysis, TOTrel: total release, prec: precipitated).

		Mixing chamber	Anaerobic digester
Potassium mass balance			
K _{TOTrel}	kg/d	9.8	13.3
K _{ORGrel}	kg/d	1.9	9.2
K _{PAOrel}	kg/d	7.9	4.1
Phosphorus mass balance			
P _{PAOrel}	kg/d	22.4	11.6
P _{ORGrel}	kg/d	4.4	21.3
P _{TOTrel}	kg/d	26.8	32.9
P _{prec}	kg/d	15.5	38.6
Magnesium mass balance			
Mg _{PAOrel}	kg/d	6.3	3.3
Mg _{ORGrel}	kg/d	1.0	4.9
Mg _{TOTrel}	kg/d	7.4	8.2
Mg _{prec}	kg/d	5.6	11.9
Calcium mass balance			
Ca _{ORGrel}	kg/d	0.7	3.5
Ca _{prec}	kg/d	0	11.4

Table 3 Potential P-recovery assessment in the current sludge line configuration.

Phosphorus loss (gP/kg sludge):	
Precipitation in the digester	9.5
Precipitation in the mixing chamber	3.8
Dewatered sludge	0.2
Total P lost	13.5
Phosphorus available (gP/kg sludge):	
Primary sludge overflow	0.4
WAS liquor	0.1
Dewatering centrate	1.7
Total P available	2.2
Potential P-recovery (%)	14.0

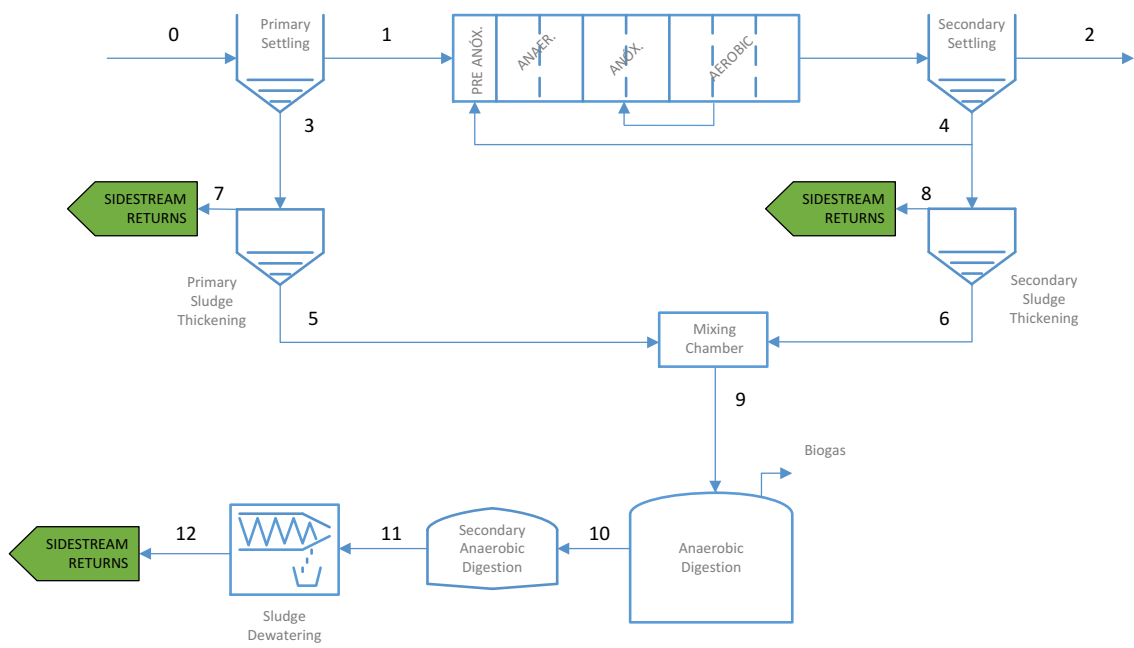


Figure 1 Layout of Calahorra WWTP (sample points numbered).

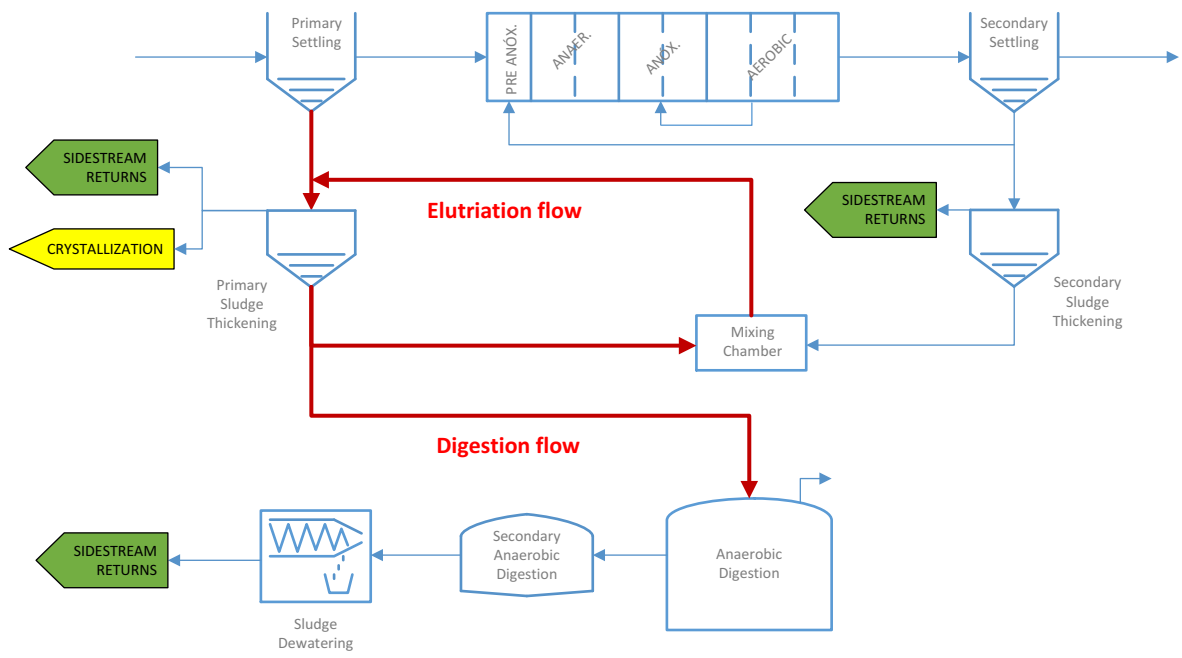
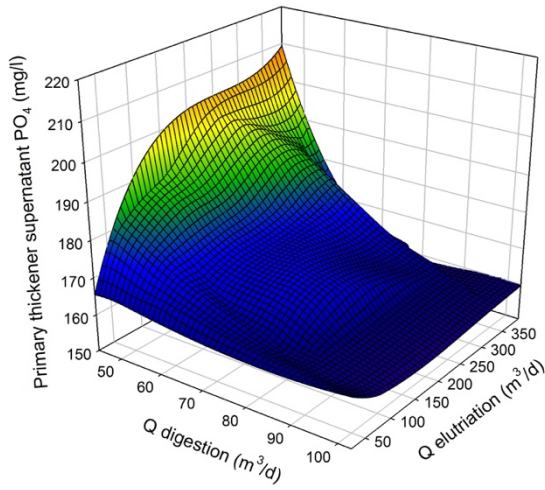
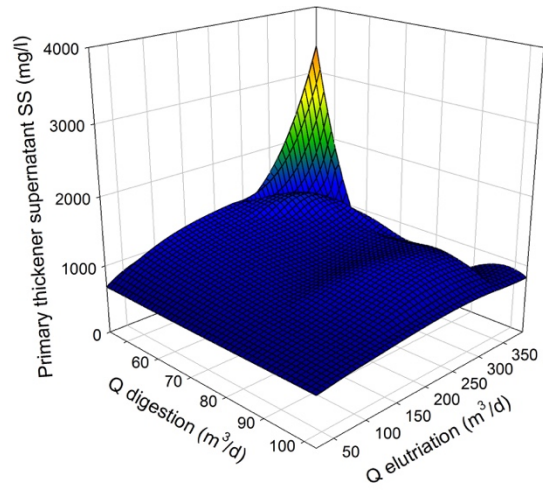


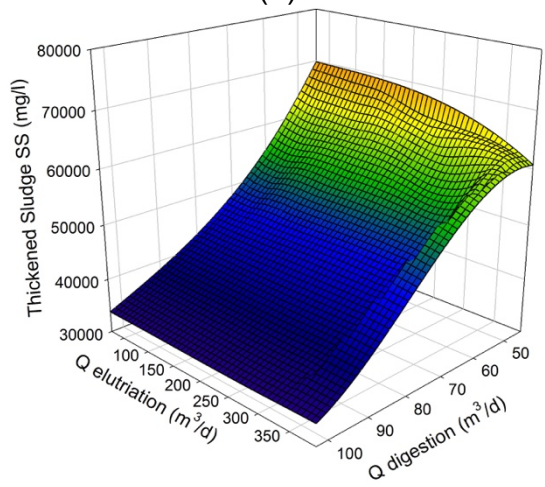
Figure 2 Proposed layout of Calahorra WWTP upgrade to implement a P-recovery system.



(a)



(b)



(c)

Figure 3 Simulation results of the proposed sludge line configuration (influent flow = 13310 m³/d). (a) Phosphate concentration in the thickener supernatant; (b) Total suspended solids in the primary thickener supernatant; (c) Total suspended solids in the thickened sludge.

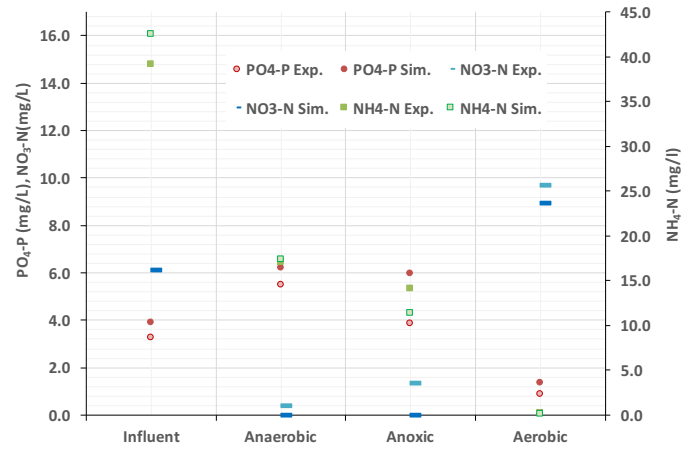
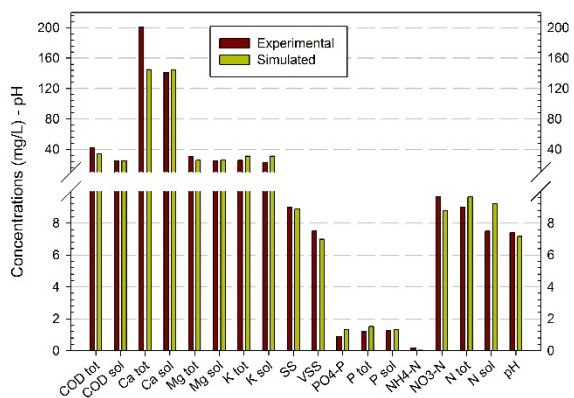
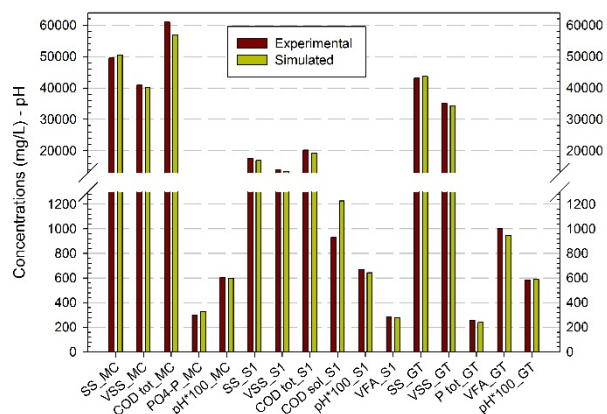


Figure S1. Experimental and simulated values obtained for ammonium, nitrate and phosphate throughout the biological reactor.



(a)



(b)

Figure S2. Experimental and simulated values of (a) Calahorra WWTP effluent composition (b) Primary settler (S1) gravity thickener (GT) and mixing chamber (MC) composition