Desalination and Water Treatment
www.deswater.com
doi:10.5004/dwt.2017.20468

68 (2017) 319–329
March

Optimising a novel SBR configuration for enhanced biological phosphorus removal and recovery (EBPR^2)

Juan A. Baeza*, Javier Guerrero, Albert Guisasola

GENOCOV - Departament d'Enginyeria Química, Biològica i Ambiental. Escola d'Enginyeria. Univ Autonoma Barcelona, 08193, Bellaterra (Barcelona), Spain, Tel. 34 935811587, Fax 34 935812013, email: juanantonio.baeza@uab.cat (J.A. Baeza) Tel. 34 935814798, email: javi.guerrero.camacho@gmail.com (J. Guerrero), Tel. 34 935811879, email: albert.guisasola@uab.cat (A. Guisasola)

Received 4 April 2016; Accepted 27 December 2016

ABSTRACT

This work proposes a new SBR configuration to recover P from the water line: enhanced biological phosphorus removal and recovery (EBPR^2). The main objective is evaluating its feasibility using modelling techniques in view of its optimization. The new EBPR^2 configuration adds an anaerobic settling phase to the classical anaerobic/aerobic sequence to obtain an anaerobic/settling/aerobic/settling cycle. Part of the anaerobic supernatant with high P content is extracted from the SBR and a chemical P-precipitation unit will be in charge of recovering it. The optimal operation is obtained for an anaerobic supernatant extraction of 4.3% of the total volume per cycle. The system is stable and accomplishing COD, N and P discharge limits for any VFA/Total COD ratio in the influent and for sludge retention time higher than 4 d. More than 60% of the P in the influent can be recovered. Lower COD is required than in the classical configuration. The system works with similar amount of PAO but with lower polyphosphate content, which provides a more resilient configuration. In addition, solids are wasted after the anaerobic phase with three times the internal PHA content compared to the classical aerobic purge, improving the chances to recover and valorise this bioplastic.

Keywords: EBPR; PAO; Recovery; Struvite; PHA; Phosphate; Polyphosphate

1. Introduction

One of the new challenges of our society is to move the focus of wastewater treatment from nutrient removal to nutrient recovery. In this sense, P is a paradigmatic element since it has many useful applications but, according to its current extraction rate, P sources are going to be limited in this century. Anthropogenic wastes contain 3 MtP/y, which stand for 20% of the global P needs. P is starting to be recovered in wastewater treatment plants (WWTP) as struvite ($NH_4MgPO_4 \cdot 6H_2O$) from the supernatant of anaerobic digestion of waste sludge. However, alternatives must be found to increase P-recovery performance while lowering the plant energetic needs. Recently, some works are focusing in studying enhanced biological phosphorus removal (EBPR) process combined with P-recovery from the main water line using anaerobic stripping [1–6], although stability or performance problems have been observed. EBPR, which is based on the enrichment of the WWTP microbial community in polyphosphate accumulating organisms (PAO), is a logical option for P-removal, since it is the most sustainable technology to meet P discharge limits. However, its combination with P-recovery would give additional advantages as decreasing the undesired precipitation of struvite usually found in anaerobic digesters. Precipitation of P after the anaerobic zone has been described previously, for example in the BCFS configuration (biological-chemical phosphorus and nitrogen removal) [7,8] which, based on the UCT configuration, already described the benefits of combining the EBPR process with P precipitation. This technology is

---

*Corresponding author.

Presented at EuroMed 2015: Desalination for Clean Water and Energy Palermo, Italy, 10–14 May 2015. Organized by the European Desalination Society.

designed to work under continuous mode and it is currently used in some full-scale WWTP.

Kodera et al. [3] proposed a two-step process with a first COD removal reactor followed by a modified trickling filter to remove and concentrate P. The trickling filter worked in three phases: a first aerobic continuous with P-uptake from the treated wastewater (12 h), the second anaerobic batch (4 h) for P-release and a final draining phase (5 min) to extract the concentrated P-stream. The system required a stream with high VFA concentration (up to 2000 mgCOD/L) to enhance P-release during the anaerobic batch stripping phase in addition to the effluent treated for P-removal during the aerobic phase. Zou et al. [5] proposed a continuous configuration for biological nutrient removal and induced crystallization (BNR-IC) with a sequence anaerobic tank, settling, part of the supernatant to the IC column for P-recovery, aerobic tank, settling, anoxic tank, post-aeration tank and a final settler. Lv et al. [2] studied the effect of anaerobic P stripping in a conventional anaerobic/aerobic SBR displaying excellent EBPR performance. Once every three SBR cycles, after a settling period at the end of the anaerobic stage, 5 L of supernatant with high P content were removed for chemical P precipitation. The system operated initially with good P-removal, although PAO activity decreased progressively, and after 80 d resulted in unrecoverable deterioration of EBPR.

Acevedo et al. [1] proposed a similar strategy with removal of the supernatant of the anaerobic phase, but with a lower frequency of one or three cycles per week. When using three extractions per week, the influent composition was the same, but when performing a single extraction per week, an extra amount of VFA was used to induce a strong P-extraction with higher P concentration. The operation with one extraction per week operated satisfactory during 5 weeks, with P-recoveries up to 81%, but a progressive decrease in PAO activity was observed, and hence long-term stability of this approach was not demonstrated. Valverde-Pérez et al. [4] studied a new configuration (enhanced biological phosphorus removal and recovery system, referred to as EBP2R) for P and N recovery as a stream that could be used as medium for green microalgae cultivation. Their model-based study is based on diverting part of the effluent from the anaerobic reactor of an anaerobic + aerobic continuous configuration to obtain an enriched P-stream and the treatment of the main stream to obtain an enriched N-stream. The authors modelled the system to calculate the best operational conditions and demonstrated that the process could be stable. Finally, Zou et al. [6] also presented another process of EBPR combined with phosphorus recovery (EBPR-PR), for COD, N and P removal and P recovery from domestic wastewater. It was composed of an anaerobic/anoxic tank and a P-recovery column with two zones (crystallization reaction and settling). Excellent nutrient removal and P-recovery as hydroxyapatite was achieved, demonstrating that crystallization recovery of phosphorus greatly enhanced EBPR efficiency, especially when a proper fraction of anaerobic supernatant was treated by the P-recovery column.

Considering the increased interest in using PAO capability to concentrate P in enriched streams, we evaluated an alternative configuration for SBRs called enhanced biological phosphorus removal and recovery (EBPR^2) to make classical EBPR compatible with P-recovery in the water line. SBR configuration was selected because it has been widely applied in P removal studies with high enrichment of PAO [9–12]. The purpose of EBPR^2 SBR configuration is treating municipal-like wastewater while recovering as much P as possible in a concentrated stream. It consists of an SBR configuration with an anaerobic/settling/aerobic/settling cycle, obtaining at the end of the anaerobic phase a much higher concentration of P than in a continuous system and without adding external organic matter. Some part of the supernatant obtained after the an aerobic settling with high P content is extracted from the SBR. A chemical P-crystallization or precipitation unit will be in charge of recovering the P in this water as metal salt or as struvite with the addition of Mg(II) and a slight pH increase. This side P recovery in our configuration would eliminate the need of a purge of aerobic sludge and thus we also propose an anaerobic sludge purge, where sludge would have the highest concentration of PHA, which could be valorised as bioplastic after a proper extraction phase.

The main objective of this work was to evaluate the feasibility of the biological system of this novel configuration using modelling techniques in view of its optimization. Specifically, the long term evolution of the system under different volume extraction, the applicability of the system depending on the wastewater composition regarding COD fractionation and the effect of SRT were studied. Moreover, the performance was compared when the purge was performed at the end of the anaerobic or aerobic phase. Finally, the feasibility to reduce COD requirements for P-removal was evaluated.

2. Materials and methods

Two 10 L SBRs were simulated with the cycle configurations detailed in Table 1. The conventional EBPR configuration used as a reference consisted of a 6 h cycle including feeding (5 min), anaerobic phase (115 min), aerobic phase (210 min) and purge + settling + decanting (30 min). The retrofitted EBPR^2 configuration cycle (Fig. 1) was also 6 h long but with feeding (5 min), anaerobic phase (85 min), purge + settling + partial decanting (30 min), aerobic phase (210 min) and settling + decanting (30 min). The volume extracted in the partial decanting was in general 0.5 L, but different extraction volumes were also tested.

The kinetic model used was an extension of ASM2d [13] with nitrite included as another state variable. The process kinetics, stoichiometry and parameter values can be found in a previous work [14]. DO concentration dynamics was also modelled including its control using a proportional controller, with a set point of 3 mgO$_2$/L during the aerobic phases. All the simulations were performed with Matlab® and the differential equations of the system balances were solved with *ode15s* function, a variable order method recommended for stiff systems.

The SBR conventional operation was simulated in different phases considering 22 state variables: 10 soluble compounds, 11 particulate compounds and volume as an additional state variable. The conventional EBPR cycles started with a feeding phase at constant influent flow rate under anaerobic conditions, followed by the

Table 1
Comparison of the conventional EBPR vs. new EBPR^2 SBR cycle configurations

Conventional EBPR SBR		New EBPR^2 SBR	
Phase	Duration (min)	Phase	Duration (min)
Feeding	5	Feeding	5
Anaerobic	115	Anaerobic	85
Aerobic	210	Purge + Settling + Partial decanting	30
Purge + Settling + Decanting	30	Aerobic	210
Total	360	Settling + Decanting	30
		Total	360

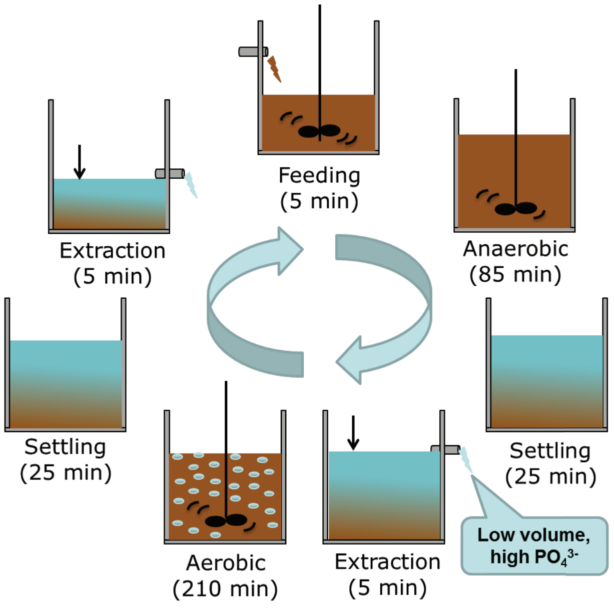

Fig. 1. SBR EBPR^2 configuration.

rest of anaerobic phase without feeding. The DO control was activated at the beginning of the aerobic phase. Just after the aerobic operation, the required volume of sludge purge was extracted to obtain the desired SRT. Finally, ideal sedimentation was considered, the treated effluent was discharged and the increased concentration of particulate compounds in the SBR was calculated according to the final volume after extraction. These final concentrations and volume were used as starting point for the subsequent SBR cycle. The new EBPR^2 configuration (Fig. 1) was simulated using a similar procedure, but with the purge implemented just after the anaerobic phase and an additional ideal settling phase and extraction of water after the anaerobic purge.

All the results presented were obtained under stable operation with 100 d of simulation (400 cycles) with the same operational conditions except for explicitly detailed changes. Fig. 2 shows an example of long term simulation and the results considered under stable operation for the last cycle.

The conventional feeding composition was 300 mgCOD/L as VFA, 20 mgN–NH_4^+/L, 1 mgN–NO_3^-/L, 9 mgP–PO_4^{3-}/L, 20 mgS_I/L, 20 mgS_{Alk}/L, 25 mgX_I/L, 20 mgX_H/ L, 1 mgX_{PAO}/L, 1 mgX_{AOB}/L and 1 mgX_{NOB}/L, considering zero the rest of components. However, other compositions were also tested for studying the effect of VFA/COD ratio and influent VFA concentration. SRT was maintained at 15 d except in simulations for evaluating its effect.

Mathematical optimization of anaerobic extraction volume and SRT was performed using the Matlab function *fminbnd*, which finds a minimum of a single-variable function on fixed interval using golden section search and parabolic interpolation algorithm.

3. Results and discussion

3.1. Comparison of EBPR^2 performance to a typical EBPR SBR configuration

First of all, the soluble and particulate compounds profiles obtained in the simulation of a conventional cycle configuration (i.e. anaerobic/aerobic sequence) are compared to the new profiles obtained using the EBPR^2 configuration with extraction of anaerobic supernatant. Fig. 3 shows the conventional EBPR cycle obtained under stable SBR operation after a simulation period of 100 d. The system operated with a high anaerobic P-release linked to VFA (S_A) uptake and a slight increase of ammonium concentration due to some biomass lysis. During the aerobic phase, DO increased and was maintained around 3 mgDO/L by the proportional controller. Complete P-uptake and total ammonium oxidation to nitrate was obtained during this phase. Nitrite accumulation was observed (up to 2 mgN–NO_2^-/L), but it was oxidised and finally only nitrate around 6 mgN–NO_3^-/L was released in the effluent.

Regarding the particulate compounds (Fig. 3B), the high decrease during the feeding phase is the dilution effect of the influent due to the increased volume (Fig. 3C) and the same total amount of biomass from the previous cycle. During the anaerobic phase, it is observed the decrease in the polyphosphate (PP) content and the increase of poly-hydroxyalkanoates (PHA) linked to S_A uptake by PAO. The opposite trend is observed for both variables during the aerobic phase: increase in PP due to phosphate uptake and decrease of PHA due to PAO growth. The final increase of particulate compounds is due to the settling process. In this typical SBR configuration, the purge is performed at the end of the aerobic phase, when PHA is minimum (139 mgCOD/L) and PP is maximum (232 mgPP/L), obtain-

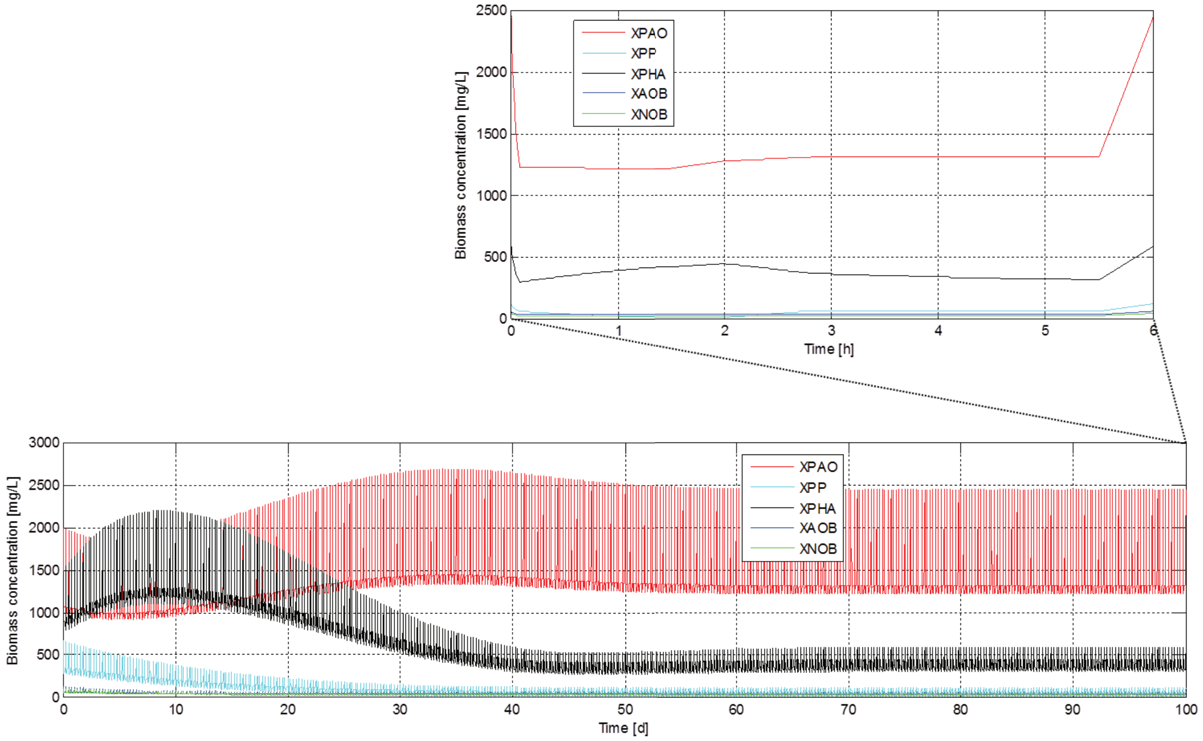

Fig. 2. Example of long term Matlab simulation of the $EBPR^2$ configuration for 400 consecutive cycles (bottom) and magnification of the last cycle (top).

ing the highest polyphosphate content of the biomass and hence achieving the highest P-removal.

Fig. 4 compares the profiles obtained under stable operation (100 days of simulation) with the $EBPR^2$ SBR configuration. In this simulation, the partial decanting after the anaerobic phase is only 5% of the reactor volume, which was determined as a proper operation as explained below. This configuration also provides complete P-removal, complete ammonium oxidation and approximately the same nitrate concentration in the effluent. The main difference in the soluble compounds is in the VFA concentration at the end of the anaerobic phase, which is $S_A = 14$ mg COD/L instead of the total consumption observed in the conventional configuration. This profile is a consequence of the depletion of PP at the end of the anaerobic phase, which limits VFA uptake. However, the system is able to accomplish total P-removal during the aerobic phase, due to the lower VFA requirements with this configuration, as will be discussed below. Nitrogen removal is similar to the previous case, except for the detection of a small amount of nitrite at the end of the cycle (< 0.5 mgN–NO_2^-/L).

The profiles of particulate compounds for the $EBPR^2$ SBR configuration are shown in Fig. 4B. PHA concentration in the biomass throughout the cycle is much higher (PHA> 300 mgCOD/L) than in the conventional configuration. In particular, at the end of the anaerobic phase, where the sludge is purged in this configuration, PHA is 435 mgCOD/L, which is three times higher than the sludge purged in the conventional configuration. Hence, it would provide a higher capacity to produce PHA and a decrease in oxygen requirements in the subsequent aerobic phase due to the higher COD content of the biomass purged. There is no need to purge the biomass at the end of the aerobic phase, because most part of P is removed with the anaerobic extraction: 5% of the reactor volume extracted at the end of the anaerobic phase contains 63% of P in the influent. It is a way to concentrate P in the influent and hence it highly enhances the possibility of P recovery by precipitation: P concentration in the extracted anaerobic water is 57 mgP–PO_4^{3-}/L compared to 9 mgP–PO_4^{3-}/L in the influent. Moreover, PAO biomass works with much lower PP content, reaching only 62 mg PP/L at the end of the aerobic phase. As the PAO biomass concentration is similar in both cases, it implies that PAO are able to uptake much more P and hence they are prepared to face unexpected disturbances of higher P concentration in the influent.

3.2. Effect of volume of anaerobic extraction

To make a deeper evaluation of the $EBPR^2$configuration, the effect of different volumes of anaerobic extraction was simulated. The initial conditions for all these tests were obtained simulating the conventional operation for 100 d. Extraction volumes in the range 0.05–2 L/cycle were tested. For each case, stable operation was obtained after 100 d of simulation with each specific extraction volume. Fig. 5 presents the concentration of the main compounds of interest obtained for the last simulated cycle at the end of the anaerobic and aerobic phases. Soluble compounds at the end of the aerobic cycle (Fig. 5C) are not much affected with the different volume extractions as very similar con-

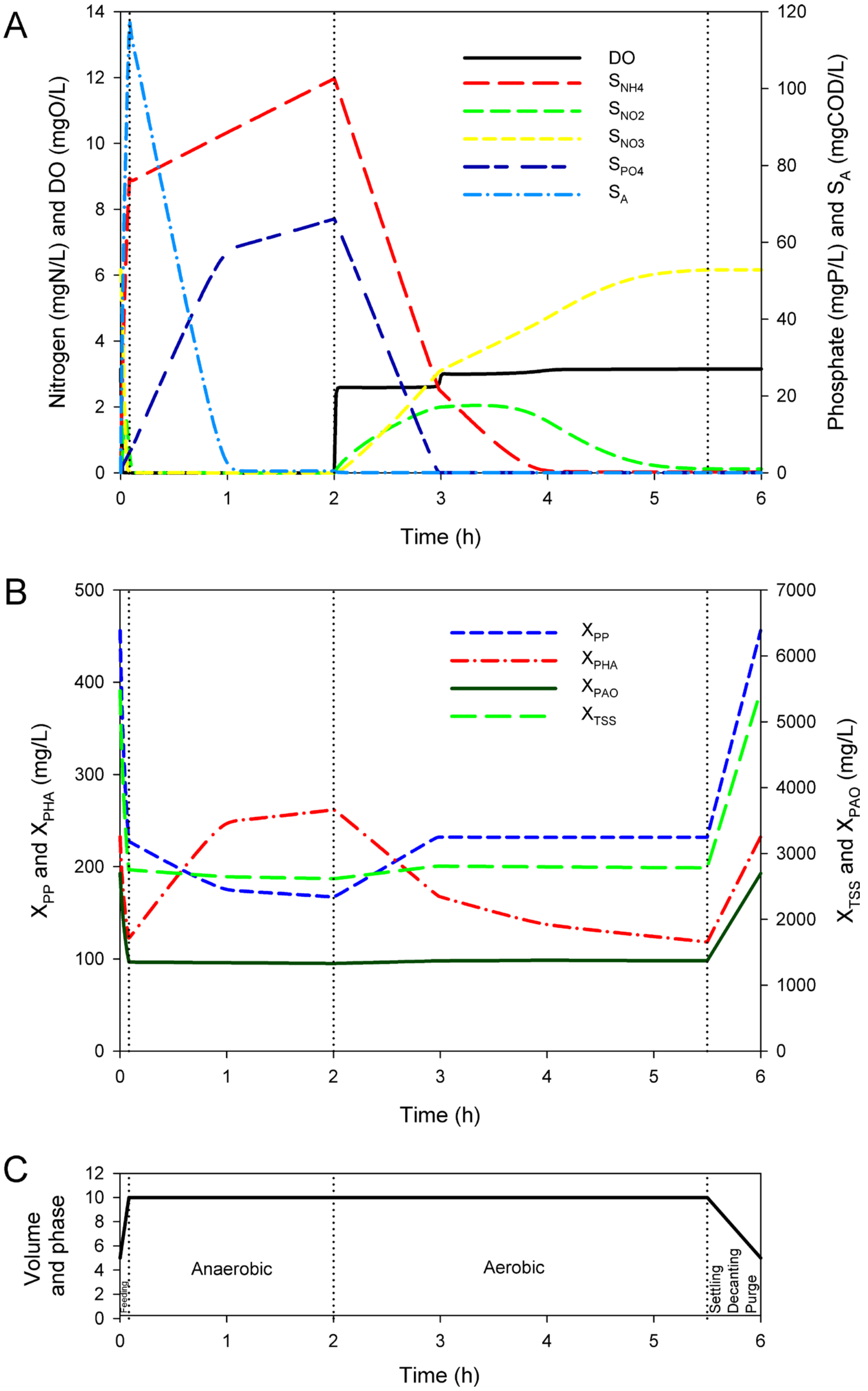

Fig. 3. Evolution of main soluble compounds (A), particulate compounds (B) and volume (C) during a conventional EBPR cycle with stable SBR operation.

centrations are obtained for each compound represented, independently of the extracted volume. P is always completely removed, while most of nitrogen in the effluent is in the form of nitrate. Nitrate concentration around 5–6 mgN–NO_3^-/L is due to the cycle configuration with a final aerobic reaction, although it would be lower than typical legal TN limits of 10 mgN/L. Hence, the proposed system would be able to remove nutrients independently of the volume extracted in the range 0.5–20%. However, the concentration of soluble compounds at the end of the anaerobic phase (Fig. 5A) shows how phosphate is greatly affected. When the anaerobic volume extracted is lower than 0.5 L, a maximum concentration around 61 mg P–PO_4^{3-}/L is obtained. Extraction volumes higher than 0.5 L (i.e. 5% of the total

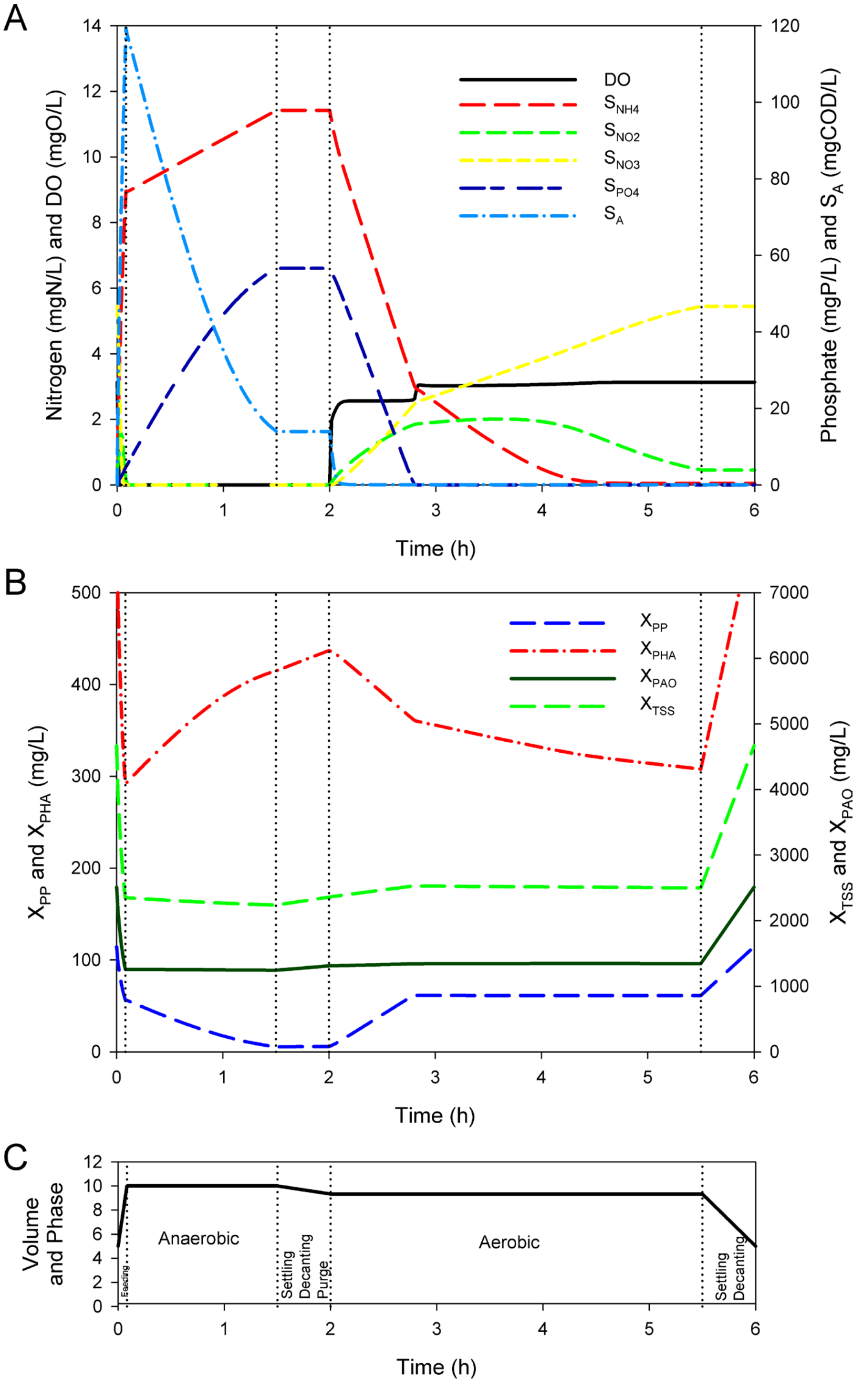

Fig. 4. Evolution of main soluble compounds (A), particulate compounds (B) and volume (C) during an SBR cycle using the novel EBPR^2 configuration with anaerobic water extraction and purge after the anaerobic phase.

volume) decreased phosphate concentration, hindering its chances to be recovered by chemical precipitation.

On the other hand, much higher changes are observed in the biomass composition. Extraction volumes higher than 0.5 L have a negative impact on PAO concentration, leading to an almost equivalent increase of ordinary heterotrophic organisms (OHO). PAO limitation by PP is the responsible of this trend, as observed in Fig. 4 and Fig. 5B. The excessive anaerobic extraction of P does not allow recovering the PP reserves under aerobic conditions (Fig. 5D), and hence PAO are out-competed by OHO because PAO are not able to store all the available VFA as PHA during the anaerobic phase and it is oxidised under aerobic conditions by OHO. Another interesting trend is the maximum PHA concentra-

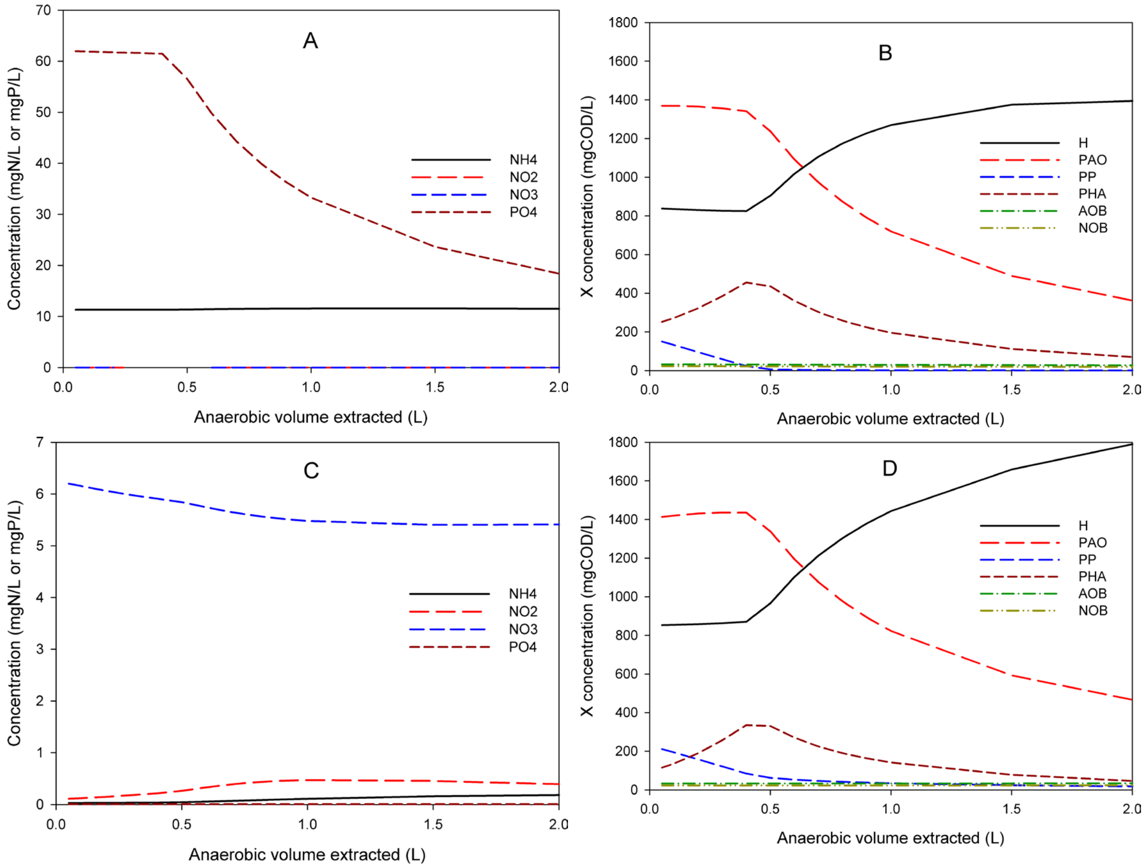

Fig. 5. Effect of anaerobic volume extraction on the EBPR^2 SBR performance under stable operation. (A, B): concentrations at the end of the anaerobic phase. (C, D): concentrations at the end of the aerobic phase. (A, C): N and P soluble compounds. (B, D): heterotrophic (H), PAO, AOB and NOB biomass concentration and internal PAO reserves of PHA and PP.

tion observed at the end of the anaerobic phase around 0.5 L of extraction per cycle (Fig. 5B). At lower extraction volumes, PAO are not limited by P and hence can oxidise its PHA reserves linked to P-uptake. At higher extraction volumes, the PAO concentration decreases due to the limitation by P and hence PHA concentration decreases accordingly.

These simulations may explain the instability observed in previous experimental works with higher extraction volumes [1,2], probably due to the excessive PP depletion. Removal of 5 L of supernatant in a single cycle destabilizes the system because PAO are not able to uptake VFA under anaerobic conditions in the next cycle, favouring OHO consuming COD under aerobic conditions. PAO are highly disfavoured because if there is no VFA storage as PHA they have limited ability for P-uptake in the aerobic phase. The repetition of these limiting conditions for PAO would finally lead to its washout.

3.3. Optimization of volume of anaerobic extraction

Different criteria can be used for optimising the volume of water to be extracted after the anaerobic settling. Phosphate concentration should be as high as possible to allow the implementation of P-recovery by chemical precipitation. Considering the results shown in Fig. 5A and 5D, the optimization of the extracted volume in our case study should be restricted to values lower than 0.5 L per cycle to have the maximum phosphate concentration and to avoid limitation of PAO growth.

The best extracted volume can be selected based on the criterion of maximum production of PHA, which can be calculated by multiplying the volume of anaerobic purge by the PHA concentration at the end of the anaerobic phase. Maximizing this criterion, the optimum extracted volume in a cycle is 0.434 L. It results in a PHA production of 79 mg COD/cycle, which represents a 5.3% of the COD contained in the wastewater fed to the SBR. This extraction of 4.34% of the reactor volume (8.68% of the influent flow) would provide the maximum production of PHA at SRT = 15 d, but also allows recovering 59% of the influent P as a concentrated stream, with 60.9 mgP–PO_4^{3-}/L, i.e. an enrichment of 6.8 times the influent concentration. For comparison purposes, when the extracted volume was increased to 0.5 L, the amount of PHA produced decreased to 72 mg COD/cycle (4.8% of initial C OD) and the phosphate that could be recovered increased up to 62.7%, although at a lower concentration of 56.4 mgP–PO_4^{3-}/L.

When the objective was only PHA production without P recovery, the system could be further optimised modifying other operational conditions as SRT. This optimization was tested by stablishing a fixed volume of anaerobic extraction of 0.434 L and maximizing the PHA production using SRT as the only modified operational parameter. This optimization led to SRT = 8.0 d, producing 119 mgCOD/cycle of PHA (7.9% of COD recovering), but at the expense of a reduced recovery of P (only 41.8%) and at lower phosphate concentration of 43.3 mgP–PO_4^{3-}/L.

An important remark is that the optimized results obtained in this section are site-specific, and hence must be optimized using the specific plant conditions of influent composition and other operational parameters. The optimisation presented shows the complexity of selecting the different operational parameters and its variability depending on several conflicting criteria. A multi-criteria optimisation methodology is recommended in these cases because it enables a more extensive evaluation of different alternatives where none of the criterion is conditional to the other [15].

3.4. Recovery of P as struvite in the extracted anaerobic effluent

Wastewater potential for struvite formation depends on the concentrations of phosphate, ammonium and magnesium and the pH. Mg(II) in wastewater is usually present in a lower concentration than that required for the precipitation of struvite. Hence, recovering P via precipitation from the extracted anaerobic water as struvite usually requires Mg(II) dosage and a slight pH increase. Struvite solubility product is pK_{ps} = 13.26 [16], and then the maximum concentration of chemical species Mg^{2+}, NH_4^+ and PO_4^{3-} that can be present in a solution in equilibrium is $K_{ps} = 10^{-13.26} = C_{Mg^{2+}} \cdot C_{NH^{4+}} \cdot C_{PO_4^{3-}}$. Considering this equation and the acid-base equilibrium constants for ammonium and phosphate, the amount of struvite that could be precipitated and, thus, the percentage of P recovered were calculated for different scenarios.

Taking as a reference the effluent anaerobic wastewater obtained operating at SRT = 15 d and extracting 0.5 L, the concentration of phosphate and ammonium were 56.4 mgP–PO_4^{3-}/L and 11.4 mgN–NH_4^+/L. Then, considering these two concentrations, only the pH and the concentration of Mg(II) must be fixed for the calculation of struvite precipitation. pH was fixed at a reasonable value of 9.5 that could be achieved with aeration for CO_2 stripping and a final adjustment with base addition. For a low Mg(II) concentration of 10 mg/L, 16% of P in the anaerobic wastewater could be recovered as struvite. The percentage of P recovery increases to 41% when this Mg(II) concentration is increased up to 50 mg/L. This theoretical recovery is not very high because ammonium concentration is low in this wastewater (11.4 mgN/L), being the limiting factor for the precipitation. Then, it seems logical to increase this concentration by using other ammonium-reach streams as reject water resulting from the anaerobic digestion of sludge. If ammonium concentration is increased up to 50 mgN–NH_4^+/L and Mg(II) is also 50 mg/L, the percentage of P recovered as struvite increases up to 92%, which makes it much more profitable.

An adequate optimization of this P-recovery percentage is needed for each specific wastewater. Other factors as volume exchange ratio (V_{ER}) for the SBR configuration can also help to increase this percentage. For example, increasing from the current V_{ER} = 50% to 75% would increase ammonium concentration from 11.4 to 16.5 mgN–NH_4^+/L. Hence, it is shown that further process optimization of the cycle configuration for increasing P-recovery is possible.

3.5. Effect of the ratio VFA/Total COD in the influent

The effect of the ratio of VFA with respect to the total COD in the wastewater was studied to evaluate the capacity to treat influents with different COD fractionation. For these simulations, the part of COD that was not VFA was considered as 40% of fermentable COD (S_F) and 60% of biodegradable particulate COD (X_S). Fig. 6 shows that the EBPR² system provides good effluent quality for any VFA/COD ratio. PAO are more favoured at higher ratios, but there is always enough PAO concentration to achieve complete P-removal. As expected, higher PHA content is observed at higher VFA/COD ratios. Therefore, the model predicts that, independently of the fractionation of the COD in the wastewater, the combination of the biological removal in the reactor with the extraction of the supernatant is able to obtain an effluent with lower than 0.1 mgP–PO_4^{3-}/L and hence total P-removal.

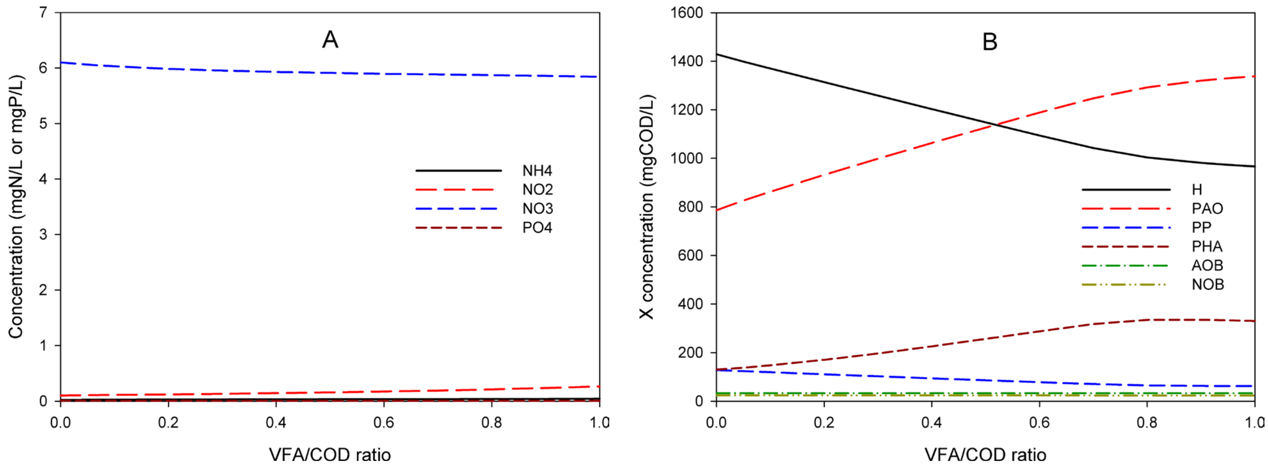

Fig. 6. Effect of the fraction of VFA in the influent with respect to total COD (VFA/COD ratio) on the EBPR² SBR performance under stable operation. Concentrations at the end of the aerobic phase. (A): N and P soluble compounds. (B): heterotrophic (H), PAO, AOB and NOB biomass concentration and internal PAO reserves of PHA and PP.

3.6. Effect of SRT on EBPR^2 performance

SRT was also evaluated because in the previous simulations it was demonstrated as an operational parameter with high impact (Fig. 7). The simulation results with the typical influent support that a SRT of 4 d or higher allows to obtain a very good nutrient removal. Surprisingly, even with a low amount of PAO, lower than 200 mg X_{PAO}/L, the system is able to obtain total P removal. The higher nutrient concentration is nitrate, but it is always lower than 6.0 mg TN/L i.e., below the allowed discharge limits. Regarding the effect of SRT on biomass composition, it produces important changes, with increasing PAO content at higher SRT. Higher PAO concentration implies a higher capacity to face increased P concentration in the influent and hence high SRT would be recommended to ensure stability. Finally, the maximum PHA content of the biomass is obtained at SRT of 10 d or higher, although to obtain the maximum PHA productivity, the volume of purge at each SRT should be also considered. In this case, with a volume of 0.5 L extracted at the end of the anaerobic phase, the higher productivity of PHA (96 mgCOD/cycle) is obtained for SRT = 8 d.

3.7. Effect of COD requirements

The feasibility to reduce COD requirements for P-removal was also studied comparing simulations with the conventional EBPR cycle and the EBPR^2 configuration. VFA was tested as sole carbon source in the range 50–400 mg COD/L (Fig. 8). VFA requirements in EBPR^2 were lower, obtaining a P concentration of 0.7 mg P–PO$_4^{3-}$/L with VFA concentration in the influent of 150 mg COD/L. However, P concentration was 3.2 mg P–PO$_4^{3-}$/L for the same COD in the conventional SBR configuration, and VFA concentration around 200 mg COD/L was required to achieve complete P-removal. This decrease of COD requirements is caused by part of P being removed via the anaerobic water extraction. It is only an effect of the new SBR configuration, because all the model simulations use the same stoichiometric coefficients and model parameters. Regarding VFA concentration effect on biomass, a limiting trend is observed in EBPR^2 for VFA above 300 mg COD/L. This is due to polyphosphate limitation that does not allow to consume anaerobically all the VFA and then OHO are favoured consuming the excess under aerobic conditions. This limitation is not observed in the conventional configuration and higher PAO concentrations can be achieved. In any case, this is not a problem for the EBPR^2 configuration because total P-uptake is always obtained.

3.8. Comparison to previous configurations

EBPR^2 configuration allows the removal of COD, N and P, while recovering more than 60% of the P in the influent. Lower COD is required than in the classical EBPR SBR configuration. The system also allows obtaining a similar amount of PAO but with lower PP content, characteristics that provide a more stable configuration able to face increases of P in the influent.

EBPR^2 has higher stability than other configurations proposed where less frequent extraction was used, although with an excessive volume of anaerobic extraction, which led to process failure due to EBPR deterioration [1,2]. The results of our study show that extractions volumes higher than 5% per cycle disfavour PAO activity. In addition, compared to previous works [e.g., 1,3], there is no requirement of a VFA enriched stream for P-release in EBPR^2, although at the expense of a lower increase in P concentration.

While the configurations in the literature aiming at P-recovery demonstrate the possibility of obtaining a P-enriched stream, some of them do not achieve an effluent below the conventional discharge limit of 1 mgP–PO$_4^{3-}$/L[3] or its purpose is not obtaining an effluent to be discharged, as the work of Valverde-Pérez et al. [4], with the objective of transforming the influent in medium for green algae cultivation.

The comparison with other continuous configurations shows that the biological process can be implemented in a single reactor instead of multiple reactors and settlers [5] or separation phases [4]. As an important drawback for continuous operation, the enriched P-stream achieves lower P-concentration than in SBR configurations, where the length of the anaerobic phase can be adjusted to increase this value if enough COD is available in the influent.

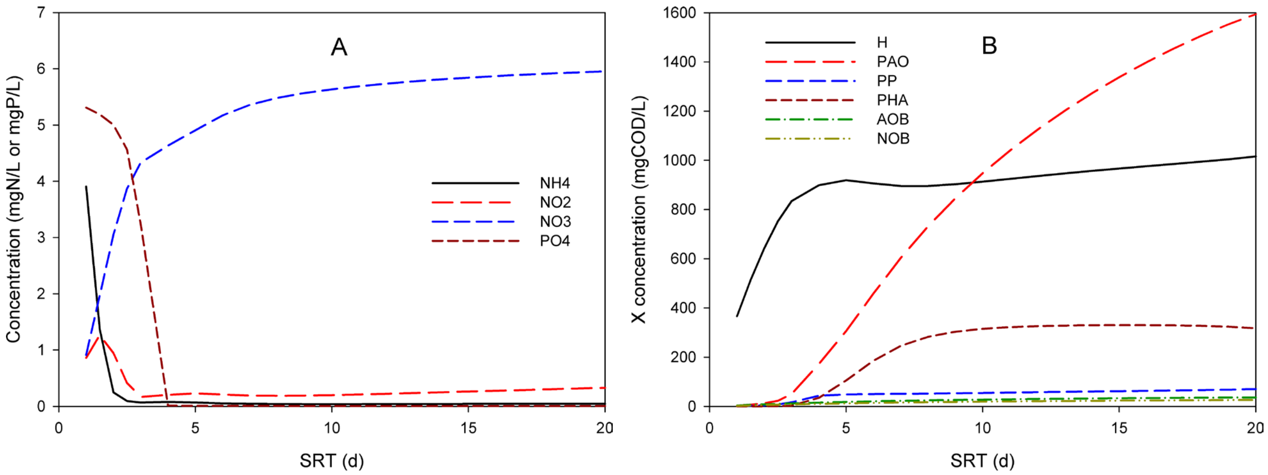

Fig. 7. Effect of SRT on the EBPR^2 SBR performance under stable operation. Concentrations at the end of the aerobic phase. (A): N and P soluble compounds. (B): heterotrophic (H), PAO, AOB and NOB biomass concentration and internal PAO reserves of PHA and PP.

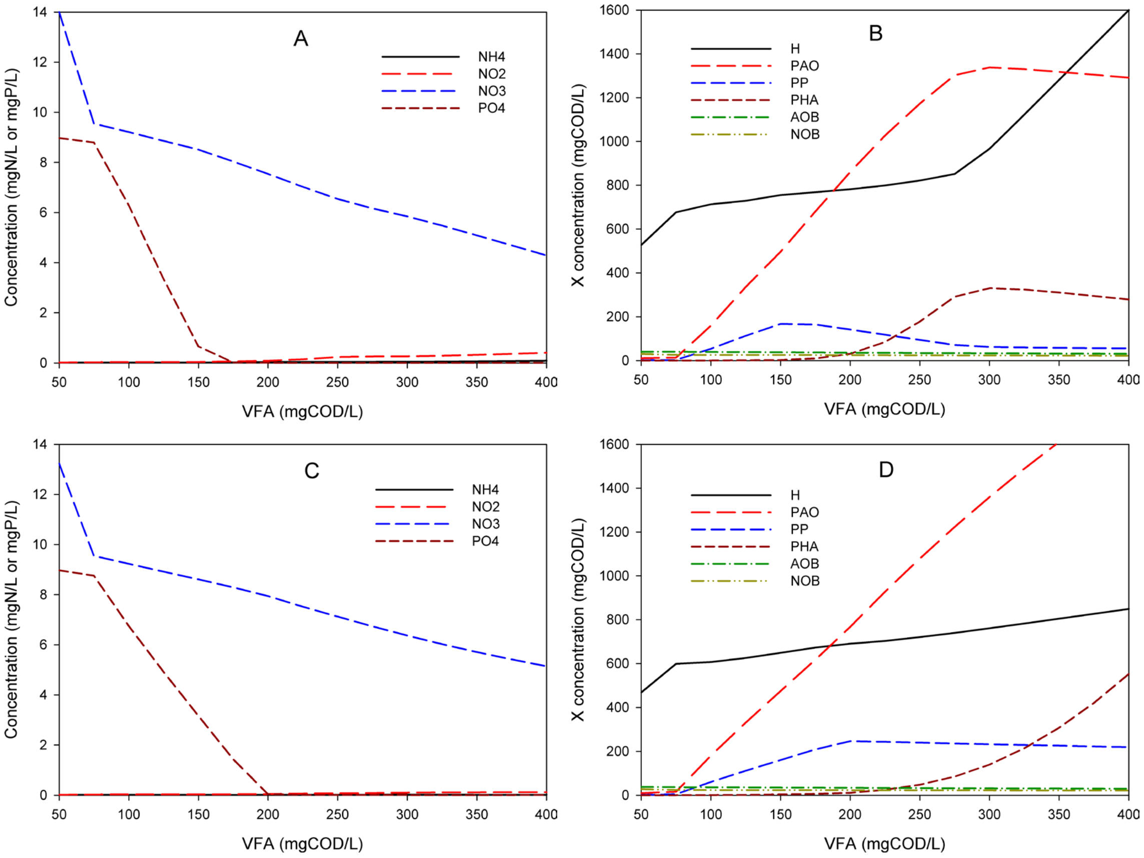

Fig. 8. Effect of influent VFA concentration on the EBPR^2 SBR performance(A, B) and the conventional SBR (C, D) under stable operation. Concentrations at the end of the aerobic phase. (A, C): N and P soluble compounds. (B, D): heterotrophic (H), PAO, AOB and NOB biomass concentration and internal PAO reserves of PHA and PP.

Further research is being currently developed in our research group to experimentally demonstrate that the anaerobic supernatant extraction with an optimised volume allows maintaining stable operation while obtaining a P-enriched stream.

4. Conclusions

EBPR^2 SBR configuration was evaluated by simulation with an ASM2d extended model as an alternative to integrate P-recovery in the main wastewater line. PAO were used to obtain a 6.8 fold increase of P concentration in an enriched stream, which increases the alternatives for P-recovery. Moreover, PHA production can be enhanced by sludge wastage at the end of the anaerobic phase maintaining good nutrient removal because P-removal does not depend on P content in the purged biomass. The stability of the system was demonstrated for a wide range of VFA/COD ratio and VFA concentration in the influent. It was also demonstrated that EBPR^2 has around 25% lower VFA requirements than the conventional configuration. The best anaerobic extraction volume for ensuring nutrient removal stability and higher PHA production in the system studied was 4.3% of the total volume per cycle (8.6% of the influent in a cycle). These results demonstrate the feasibility of P-recovery and PHA production in the main wastewater line using the new EBPR^2 SBR configuration, while guaranteeing PAO stability by selecting a proper anaerobic extraction volume.

Acknowledgements

This work was supported by the Spanish *Ministerio de Economía y Competitividad* (CTQ2014-60495-R) with funds from the *Fondo Europeo de Desarrollo Regional* (FEDER).The authors are members of the GENOCOV research group (Grup de Recerca Consolidat de la Generalitat de Catalunya, 2014 SGR 1255).

References

[1] B. Acevedo, C. Camiña, J.E. Corona, L. Borrás, R. Barat, The metabolic versatility of PAOs as an opportunity to obtain a highly P-enriched stream for further P-recovery, Chem. Eng. J. 270 (2015) 459–467.

[2] J.-H. Lv, L.-J. Yuan, X. Chen, L. Liu, D.-C. Luo, Phosphorus metabolism and population dynamics in a biological phosphate-removal system with simultaneous anaerobic phosphate stripping, Chemosphere, 117C (2014) 715–721.

[3] H. Kodera, M. Hatamoto, K. Abe, T. Kindaichi, N. Ozaki, A. Ohashi, Phosphate recovery as concentrated solution from treated wastewater by a PAO-enriched biofilm reactor, Water Res., 47 (2013) 2025–2032.

[4] B. Valverde-Pérez, E. Ramin, B.F. Smets, B.G. Plósz, EBP2R – An innovative enhanced biological nutrient recovery activated sludge system to produce growth medium for green microalgae cultivation, Water Res., 68 (2015) 821–830.

[5] H.M. Zou, X.W. Lu, T. Li, Effect of side-stream phosphorus recovery on biological phosphorus removal performance investigated by chemical and microbial analyses in a novel BNR-IC process, Water Sci. Technol., (2014) 1441–1447.

[6] H. Zou, Y. Wang, Phosphorus removal and recovery from domestic wastewater in a novel process of enhanced biological phosphorus removal coupled with crystallization, Biores. Technol., 211 (2016) 87–92.

[7] R. Barat, M.C.M. van Loosdrecht, Potential phosphorus recovery in a WWTP with the BCFS process: interactions with the biological process., Water Res., 40 (2006) 3507–3516.

[8] M.C.M. van Loosdrecht, F. Brandse, A. De Vries, Upgrading of waste water treatment processes for integrated nutrient removal-the BCFS® process, Water Sci. Technol., 37 (1998) 209–217.

[9] M. Pijuan, A.M. Saunders, A. Guisasola, J.A. Baeza, C. Casas, L.L. Blackall, Enhanced biological phosphorus removal in a sequencing batch reactor using propionate as the sole carbon source., Biotechnol. Bioeng. 85 (2004) 56–67.

[10] Y. Zhou, M. Pijuan, R.J. Zeng, H. Lu, Z. Yuan, Could polyphosphate-accumulating organisms (PAOs) be glycogen-accumulating organisms (GAOs)?, Water Res., 42 (2008) 2361–2368.

[11] C. Tayà, A. Guisasola, J.A. Baeza, Assessment of a bioaugmentation strategy with polyphosphate accumulating organisms in a nitrification/denitrification sequencing batch reactor., Biores. Technol., 102 (2011) 7678–7684.

[12] A. Oehmen, Z. Yuan, L.L. Blackall, J. Keller, Comparison of acetate and propionate uptake by polyphosphate accumulating organisms and glycogen accumulating organisms., Biotechnol. Bioeng., 91 (2005) 162–168.

[13] M. Henze, W. Gujer, T. Mino, M.C.M. van Loosdrecht, Activated sludge models ASM1, ASM2, ASM2d and ASM3: Scientific and technical report No. 9., IWA Publishing, London, 2000.

[14] J. Guerrero, A. Guisasola, J.A. Baeza, The nature of the carbon source rules the competition between PAO and denitrifiers in systems for simultaneous biological nitrogen and phosphorus removal., Water Res., 45 (2011) 4793–4802.

[15] J. Guerrero, A. Guisasola, J. Comas, I. Rodríguez-Roda, J.A. Baeza, Multi-criteria selection of optimum WWTP control setpoints based on microbiology-related failures, effluent quality and operating costs, Chem. Eng. J., 188 (2012) 23–29.

[16] K.N. Ohlinger, T.M. Young, E.D. Schroeder, Predicting Struvite Formation in Digestion, 32 (1998).