

Sludge reduction via biodegradation of the endogenous residue (X_E): experimental verification and modeling

Cheikh Fall, Ericka L. Millan-Lagunas, Carlos Lopez-Vazquez, Christine Maria Hooijmans and Yves Comeau

ABSTRACT

The feasibility of sludge reduction via the X_E biodegradation process was explored both experimentally and through modeling, where the main focus was on determining the value of the b_E parameter (first order degradation of X_E) from a continuous process. Two activated sludge (AS) systems (30 L) were operated in parallel with synthetic wastewater during 16 months: a conventional activated sludge (CAS) system and a modified low-sludge production activated sludge (LSP-AS) process equipped with a side-stream digester unit (DU). First, the long term data of the CAS reactor (1 year) were used to calibrate the ASM model and to estimate the heterotrophic decay constant of the cultivated sludge ($b_H = 0.29 \text{ d}^{-1}$, death-regeneration basis). Second, pre-simulations were performed to design the LSP-AS system and to estimate the DU volume required (40 L), to avoid X_E accumulation in the process. Third, the LSP-AS process was built, put in operation and monitored for more than 9 months. This allowed assessment of the actual behavior of the quasi-complete solids retention system. Once calibrated, the modified AS model estimated the value of the b_E parameter to be in the range of $0.003\text{--}0.006 \text{ d}^{-1}$, satisfactorily describing the overall sludge yield reduction of up to 49% observed in the experiments.

Key words | activated sludge modeling, endogenous products, sludge minimization

Cheikh Fall (corresponding author)
Ericka L. Millan-Lagunas
 Universidad Autonoma del Estado de Mexico
 (UAEM),
 Apdo postal 367,
 Toluca C.P. 50091,
 Mexico
 E-mail: c-fa-ll@hotmail.com

Carlos Lopez-Vazquez
Christine Maria Hooijmans
 UNESCO-IHE,
 Westvest 7,
 Delft 2611 AX,
 The Netherlands

Yves Comeau
 Polytechnique Montréal,
 P.O. Box 6079, Station Centre-Ville,
 Montréal, Québec,
 Canada H3C 3A7

INTRODUCTION

There is a continuing interest in developing activated sludge (AS) processes that produce lower amounts of solids residuals. An accepted strategy consists of inserting a digester into the return activated sludge (RAS) line of the treatment plants (Saby *et al.* 2003; Labelle *et al.* 2015). Different mechanisms have been proposed to explain the reduced sludge yield (such as metabolic uncoupling, lysis and cryptic growth, biological floc destruction, and predation), whereas other authors have proposed the biodegradability of the endogenous residue (X_E) as the dominant mechanism (Park *et al.* 2006; Ramdani *et al.* 2012), conventionally assumed to be non-biodegradable matter in AS models (Henze *et al.* 2000).

Previously, it was suggested that X_E could be biodegraded further, being a first-order kinetic reaction with a decay rate constant b_E . The latter hypothesis was featured as an option in recent versions of BioWin (Envirosim 2014). Few authors provided an estimate of the b_E parameter (from batch studies), being typically 0.007 d^{-1} . b_E was found

somewhere between 0.005 and 0.012 d^{-1} under anaerobic and full or intermittent aeration conditions in digesters (Park *et al.* 2006; Ramdani *et al.* 2012). By carrying out and modeling seven sludge batch digestion tests in different environments, Martínez-García *et al.* (2016) provided an estimation of b_E between 0.001 and 0.005 d^{-1} , depending on the redox conditions and operational patterns (aerobic, anaerobic, hypoxic and different intermittent aeration versions). However, other authors indicate that long solid retention time (SRT) and starvation conditions in side-stream reactors do not promote the degradation of a specific sludge fraction (Habermacher *et al.* 2015).

Due to the previous contradictory findings and considering that b_E has never been determined from a continuous process type, there is a need for more evidence about sludge minimization potential via X_E biodegradation, and to increase our understanding of the magnitude and relevance of such a process rate. This is essential when

modeling is used to evaluate the feasibility, or to justify the residence time of side-stream reactors, in the design of sludge-minimization processes based on the principle of X_E degradability (Spérandio *et al.* 2013; Fall *et al.* 2015).

This paper describes a conventional activated sludge system (CAS, in duplicate) and one modified low-sludge production activated sludge (LSP-AS) process designed, built, operated and monitored for a long time in the laboratory (16 months). The main interests of the present study were: first, demonstrate the sustainability of a quasi-complete solids retention system; second, utilize a model to simulate its behavior; third, carry out long-term measurements to calibrate the model and provide a robust estimation of the b_E parameter, from a continuous treatment system.

METHODS

The processes were operated in semi-continuous mode as sequencing batch reactors (30 L), modeled as continuous aerobic systems. Two flowsheets were considered, a conventional activated sludge (CAS, Figure 1(a)) and a modified LSP-AS process (Figure 1(b), RB + 2 settlers + 1 digester unit, DU). For simplicity in the laboratory, the wastage was from the mixed liquor; however, in practice, the WAS and the feed of the digester could be taken from the underflow of the main settler. For the simulations as well as for the experiments, an acetate-based synthetic wastewater was used. So, the sludge had only two main fractions, the heterotrophic biomass, X_H and its endogenous residue, X_E . In similar conditions, the autotrophic fraction (X_A) was estimated by Ramdani *et al.* (2010) to be less than 2% of the total biomass, so this component was negligible in term of chemical oxygen demand (COD). The hydraulic residence time (HRT) of both systems was 1.5 d. The SRT (in the aeration tank) was 15 d for the CAS, against 300 d approximately for the LSP-AS system (quasi-complete solids retention). The COD of the inflow was 500 mg/L (641 mg/L sodium acetate), and the

COD/N/P ratio was approximately 100/4/2. NH_4Cl and KH_2PO_4 were added for the total P and N needs. The operation cycle of the sequencing batch reactors (SBRs) included an anaerobic phase of 1 h after the feed, followed by an aerobic phase for the rest of the day. The non-aerated selector function was used as a strategy to overcome some bulking problems that had initially appeared.

Pre-simulations were carried out with ASM1-Aquasim and BioWin to design the LSP-AS process, determining the digester volume required for avoiding the accumulation of X_E in the system. The CAS system was operated and monitored for more than 180 days. One CAS system continued for another 180 days, the other CAS system was made into a LSP-AS system by adding a DU, and continued for 270 days. The steady state model of the CAS system was calibrated to estimate the heterotrophic decay constant (b_H) of the cultivated sludge. Later, the b_H value was verified through batch tests. For the design of the LSP-AS system, the mathematical models (ASM1 in Aquasim or the Biowin general model) were extended, considering that X_E biodegrades in the digester with a first-order rate constant of 0.007 d^{-1} in the digester (typical b_E value from the literature) (Park *et al.* 2006; Ramdani *et al.* 2012).

The systems were monitored for temperature (T), pH, oxidation-reduction potential (ORP), dissolved oxygen (DO), oxygen uptake rate (OUR), volatile and total suspended solids (VSS and TSS), chemical oxygen demand (COD), sludge volume index (SVI), N and P, in accordance with *Standard Methods* (APHA 2005). Strict attention was devoted to obtain representative samples from the tanks and the effluents (homogenizing, decanting, measuring volumes, compensation for evaporation, etc.). This allowed observation of the actual behavior of the systems. At the beginning, the two SBRs (RA and RB) were operated as duplicates of the CAS parent system. Later, the DU was filled with a seed of concentrated mixed liquor (ML) and interconnected with the RB reactor to provide the LSP-AS system. The DU tank was intermittently mixed (closed-loop pumping, 15 min per hour) and aerated

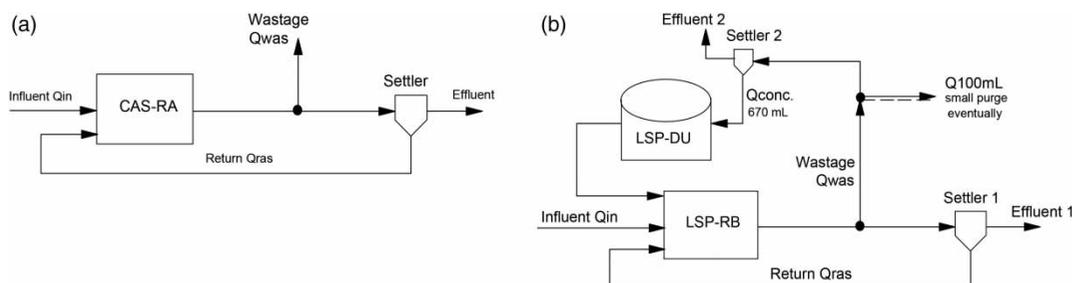


Figure 1 | Flow sheets of the parent CAS system (a) and of the modified LSP-AS process (b).

(5 min/3 h ON/OFF), as suggested by a previous study (Martínez-García et al. 2016). The latter authors determined that the intermittent aeration cycle of 5 min/3 h ON/OFF was one of the best conditions for degrading the endogenous residues.

The model of the modified system was calibrated under steady-state as well as under dynamic conditions (the latter case was based on the solids build up profiles), to provide an estimation of the actual b_E parameter. Cumulative graphics of the produced biomass versus the consumed substrate were setup to estimate the observed yield (Y_{obs}) of each system, and to estimate the overall percentage of sludge reduction.

RESULTS

Long-term behavior of the CAS systems

The variation of the mixed liquor suspended solids (MLSS) concentrations in the systems during the last 450 days is shown in Figure 2 (from October 2014 to the end of January 2016). At the beginning, both RA and RB were operated as CAS, reaching similar average MLSS levels. After 180 days (from April 2015), RB was connected to a digester and operated as a modified AS system for sludge reduction (LSP-AS system). RA remained as the reference CAS system, maintaining the same trend and plateau level. In contrast, the solids increased more and more in the modified LSP-AS system (reactor B and DU), all along the following 270 days of operation.

Furthermore, the metabolism of the biomass in the CAS systems was characterized through the kinetics of the 24 h SBR cycle (COD, OUR, N and P, versus time, Figure 3). The shaded zones in Figure 3 represent the anaerobic phase (first 1.5 h) of the SBR cycles, which was followed by an aerobic period during the remaining time (un-shaded area). In the left figure, the COD was followed in both

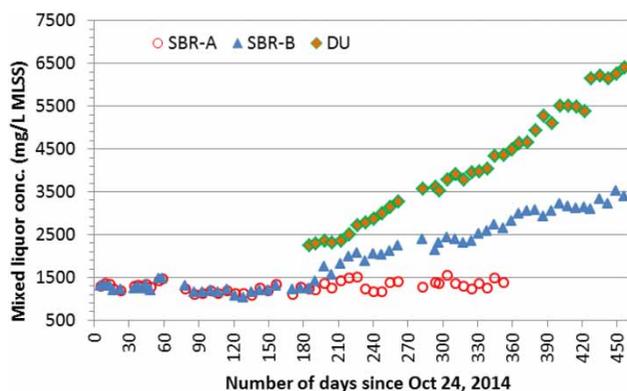


Figure 2 | Mixed liquor concentration in SBR-A (as CAS), SBR-B (as CAS, and then as LSP-AS) and the DU.

zones, while the OUR makes sense only for the aerated phase. In the right figure, different symbols were used to differentiate between the NO_2 consumed (denitrification) and the nitrates produced (nitrification), as well as for the ammonia in the anaerobic, versus in the aerated steps.

Minimal COD uptake (20%) occurred during the anaerobic phase (first 1.5 h), followed by fast aerobic storage of the remaining substrate (300 mg/L COD in 30–45 min) with very high O_2 consumption rate (SOUR of $90 \text{ mg O}_2 \text{ g VSS}^{-1} \text{ h}^{-1}$). The stored polymers (X_{Sto}) were used later for aerobic growth, until the fifth to seventh hour. Depletion of the N and X_{Sto} reserves was followed by a step of endogenous respiration (SOUR of $3 \text{ mg O}_2 \text{ g VSS}^{-1} \text{ h}^{-1}$) for the rest of the 24 h cycle. Due to high pH in the system (8.8), 43% of the added ammonia volatilized, against 43% nitrified and 14% assimilated. At least 4 mg N- NH_4 /L remained in the systems at the end of the exogenous phases, which demonstrated that NH_4 limitation did not occur. The dominant microorganism species could have certain capabilities to store COD intracellularly, being probably glycogen accumulating organisms on the marginal COD taken up anaerobically or simply some ordinary heterotrophic biomass (OHOs) as described with ASM3. In contrast, as shown in Figure 3 (right), there was not any evidence of anaerobic release and aerobic over-storage of the phosphorus, (probably because the P content in the influent was low), which excluded the dominance of the P accumulating organisms.

Calibration of the SBR-CAS model (conventional activated sludge)

In steady state conditions, when the influent characteristics, the yield of the biomass and the SRT of the process are known, the heterotrophic decay constant (b_H) is the parameter that determines the quantity of sludge in the reactors. This is accepted in many wastewater treatment plants (WWTPs) modeling protocols (Hulsbeek et al. 2002; Fall et al. 2011). So, to calibrate the CAS model, different values of b_H were assessed, searching to match the measured average MLCOD in the aeration tanks (1,440 mg/L, 15 d SRT). Four scenarios were studied, the results of which are shown on Table 1. In all the scenarios, the following parameters were fixed: Y_H to 0.67 (heterotrophic yield); f_{CV} and f_{VT} , respectively, to 1.35 and 0.86, as measured (COD/VSS and VSS/TSS ratios of the biomass). Additionally, the removal efficiency of the point-settler model was calibrated (settler E of 98.0 to 98.5%) to fit the measured average VSS concentration in the effluent (25 mg/L).

Scenarios 1 and 2 utilized the same initial b_H value (default of 0.62 d^{-1} , death-regeneration process). These

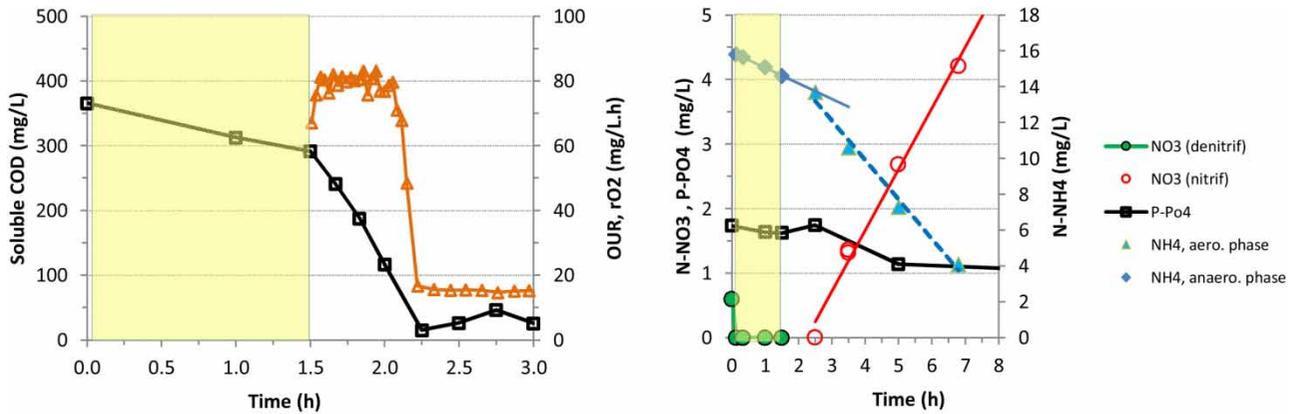


Figure 3 | COD and OUR time profiles (left); nitrogen and phosphorus profiles (right) during the 24 h cycle of the SBRs.

Table 1 | Calibration of the CAS model

Scenario #	Adjusted parameters		Model predictions			Model $r_{O_2\text{-endo}}$ ($\text{mg L}^{-1} \text{h}^{-1}$)
	Settler E (%)	b_H (d^{-1})	MLCOD (mg COD/L)	X_H	X_E	
1	100	0.62	1,250	650	570	
2	98.0	0.62	1,060	620	420	
3	98.6	0.26	1,520	1,150	355	
4	98.5	0.29	1,450	1,070	360	5.1
Measured values (average) →			$1,440 \pm 125$	-	-	4.0 ± 1.2
			-			

cases were compared to show the significant MLCOD differences (approximately 200 mg/L) that may result in the predictions, while taking into account versus not, the solids lost through the effluent. So, knowledge of the amount of entrained solids will be very important during calibration.

Scenario 3 showed the need to significantly decrease the heterotrophic decay constant (b_H , from 0.62 to 0.26 d^{-1} at least), to be able to significantly increase the predicted MLCOD concentration (from 1,060 to 1,520 mg/L COD). A better match of the measured MLCOD (1,440 mg/L) was achieved with a slightly higher b_H value (0.29 d^{-1} , scenario 4 in Aquasim; 0.27 d^{-1} in BioWin). Additional independent cross-check was provided by the endogenous oxygen uptake rate ($r_{O_2\text{-endo}}$, Table 1). Thus, the SBR-CAS model was correctly calibrated.

Batch tests to validate the b_H value

The b_H value estimated from calibration (0.27–0.29 d^{-1}) was much lower than the default in ASM1 (0.62 d^{-1}),

suggesting the need to carry out a verification to confirm the data. Knowing the value of b_H in the experiments is a prerequisite to be able to identify and extract the value of the b_E parameter (X_E degradation) subsequently, using the data of the LSP-AS process. Figure 4 shows the data of a batch digestion test performed to determine the b_H constant value. The OUR (also noted as r_{O_2}) and the COD data series from the batch test were separately, as well as simultaneously, fitted with the simplified ASM1 model (decay of X_H and nitrification). The simultaneous fit must be based on the relative values, normalized with the initial values at $t=0$ (i.e. the ratios COD (t)/COD initial and r_{O_2} (t)/ r_{O_2} initial); this is because the order of magnitude of the COD (thousands of mg/L) is much higher than for the r_{O_2} (<20 mg/L h) (Fall *et al.* 2014). The identifiability of the parameters was better in the simultaneous fit. Nitrification occurred in the batch tests and was reflected by a pH drop from 9 to less than 5 at the end of the test, and by the high concentration of nitrate detected at day 45 (202 mg N/L). To calculate the total COD from the model ($=X_H + X_E$), the autotrophic biomass (X_A) was neglected; in contrast, the OUR due to nitrification was taken into account in the model used to fit the endogenous respirograms. The average b_H values from the simultaneous fits were $0.101 \pm 0.008 \text{ d}^{-1}$ in the experiment performed in June 2015, against $0.089 \pm 0.004 \text{ d}^{-1}$ in February 2015 (results not shown). These are endogenous-respiration based values which can be translated in the death-regeneration average b_H value of 0.26 d^{-1} . In conclusion, the independent batch test performed confirmed the low decay rate constant of the cultivated model-sludge, in accordance with the calibration results of the SBR-CAS model.

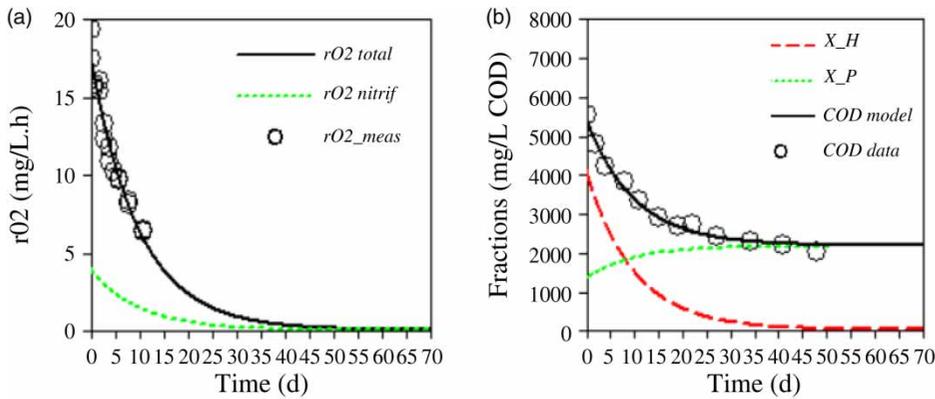


Figure 4 | Simultaneous fit of the OUR (a) and the COD data (b) to estimate the b_H from batch test.

Extension of the CAS model to design the LSP-AS process

The parent CAS system was extended with a DU and was reconfigured as an LSP-AS process (Figure 1(b)), a complete solids-retention system. The calibrated b_H value (0.29 d^{-1} in Aquasim-ASM1 vs 0.27 d^{-1} in BioWin) of the CAS-SBR was used in the extended model, along with the f_{CV} and f_{VT} of the model-sludge (1.35 and 0.86), and the acetate-based aerobic yield of 0.67 d^{-1} (Y_H , as in ASM1). Simulations were performed to determine the optimum digester volume and HRT, while assuming a first-order constant of 0.007 d^{-1} (b_E) for the degradation of the endogenous residues (BioWin and Aquasim-ASM1). The results of the simulation are given in Table 2, showing the expected quantities of solids (COD, TSS, VSS, X_H , X_E) in the reactor and in the digester, for three different DU volumes (V_{DU}). The first scenario in Table 2 ($V_{DU} = 10 \text{ L}$) corresponds to the 15 d HRT, suggested in the literature as design criteria for the on line RAS-digesters (Johnson et al. 2008). The TSS concentrations would be too high in this case (5,650 mg/L).

Both the 40 L and the 60 L DU allow reduction of the MLSS concentrations in the aeration tank to less than

3,000 mg/L, which lies within the typical range for AS systems. The performance of the 40 and 60 L scenarios were not too different, which suggested selecting the smaller volume. The active X_H concentration in the mixed liquor of the selected LSP-AS scenario (1,180 mg/L COD) is expected to belong to the same range as for the CAS system (1,070 mg/L), which means no big change for the aeration needs. The predicted X_H level in the digester (550 mg/L) is also low, reflected in low endogenous oxygen consumption, a high VSS reduction (46%) and a high level of stabilization. The model predicted an acceptable, but almost twice higher MLSS level in the aeration tank of the modified AS process (2,470 mg/L), compared to the CAS system (1,260 mg/L MLSS). In practice, this will need a larger clarifier area. Under 60 days' HRT, the theoretical X_E removal efficiency of the DU will be 30%, while its solids content will be around 4,000 mg/L TSS. Based on all these results, the digester was built with a 40 L volume and put in operation together with the SBR-B, to match the experimental setup for the LSP-AS process (layout of Figure 1(b)). In practice, the DU volume can be reduced further by configuring the tank as continuous stirred tank reactors (CSTRs) series and/or by thickening the

Table 2 | Expected solids concentrations in different scenarios of the LSP-AS system

V_{DU}	Settler E (%)	Mixed liquor concentrations (mg/L)				Solids concentrations in the digester (mg/L)			
		MLSS	MLCOD	X_H COD	X_E COD	TSS	X_H COD	X_E COD	%VSS rem
10 L	99.7%	5,650	6,600	1,340	5,240	14,150	1,800	14,650	16%
40 L	99.3%	2,470	2,870	1,180	1,670	3,960	550	4,040	46%
^a	99.2%	2,270	2,630	–	–	3,340	–	–	–
60 L	99.1%	2,060	2,390	1,150	1,220	2,660	370	2,700	56%

^aIn scenario 40 L*, a small volume of mixed liquor was daily wasted from the reactor (100 mL).

sludge influent (e.g. feeding from the underflow of settler 1). Also, while implementing the system in the laboratory a small wastage flow to the LSP-AS system was made. 100 mL were wasted from the 2 L mixed liquors extracted daily from the SBR reactor (scenario 40 L* in Table 2), to avoid the eventual build-up of precipitates from the trace inorganic chemicals (P, Fe, Ca, Mg) included in the synthetic wastewater.

Behavior of the LSP-AS process during its operation

As shown in Figure 2, from the moment that the RB was interconnected to a digester and operated as a modified AS system, the solids increased more and more in the modified LSP-AS system (reactor B and DU), during the following 270 days of operation. In different occasions, it happened that punctually (for 3–5 consecutive weeks), the data showed an apparent tendency to plateau, which seemed to indicate that steady state was reached. A steady state calibration was performed at each of those events, using different b_E values depending on the apparent MLSS steady state levels. Through continuous monitoring, it was observed that, in reality, a true and definitive steady state was never reached. However, the increasing trend of the solids was relatively slow, allowing the modified system to operate conveniently (below 3,500 mg/L MLSS) for a long period, with the DU volume provided. The situation of the LSP-AS system at the end of the experiments is depicted in Table 3, giving the average of the last four weekly measurements, for RB and for the DU.

At the end of the experiments (January 2016), the average concentrations in the aeration tank (Table 3, 3,370 mg TSS/L and 3,790 mg COD/L) were higher than the pre-simulated values (Table 2, respectively 2,470 mg TSS/L and 2,870 mg COD/L). In the DU, the currently measured concentrations were 6,250 mg TSS/L and 7,130 mg COD/L (Table 3), compared to the pre-simulated values of 4,150 mg TSS/L and 4,800 mg COD/L. Based on these differences, it appeared necessary to readjust the value of the b_E parameter in the model. This was even more necessary, because the

pre-simulation model did not include all the actual operational data (e.g. the small wastage flow and the correct f_{CV} and f_{VT} ratios).

Other behavioral data of interest were the temperature (around 20 °C), the pH, the endogenous oxygen consumption rate ($r_{O_2\text{-endo}}$) of RA and of the DU, as well as the ORP and the DO time-profiles of the digester. The pH was 0.6 units lower in the digester, compared to the aeration tank. The endogenous oxygen consumption rate, at the end of the SBR daily cycle was around 4 mg $O_2 L^{-1} h^{-1}$ in RA and in the DU. This confirmed that the residual COD_s detected in the reactors were non-biodegradable compounds, probably from lysis. The OUR data were used to cross-check the calibration of the b_E parameter, matching the O_2 consumption as well as the solids concentrations in the reactors. The DO and the ORP in the digester were routinely monitored (each for 2 weeks), following the 3-h cycles of intermittent aeration (5 min/3 h ON/OFF). Figure 5 provides a typical example of the ORP and of the DO profiles in the digester.

The conditions in the DU alternated between very reductive anaerobic environment (ORP of –350 mV and DO of 0 mg/L), to micro-aerobic conditions (ORP of –150 to –30 mV, and DO of about 2 mg/L). The obtained ORP profile was similar to the one shown by Troiani et al. (2011), except for the durations in the lower versus in the higher sides. The digester environment was in the range of –150 to –30 mV for 30 min, against 2.5 h in the interval of –150 to –350 mV. After 5 min of aeration, the DO reaches 2 mg/L and the medium stays aerobic for 20 to 25 min more. The environment becomes anaerobic for the remaining 2.5 h. These are the actual conditions in the DU by which X_E will eventually get biodegraded.

Also, the ammonium (NH_4), nitrites (NO_2) and nitrates (NO_3) concentrations were almost 0 mg/L in the DU. The color of the sludge in the digester did not change to black, suggesting that the 5 min/3 h on/off aeration was inhibiting the growth of strict anaerobic microorganisms such as methanogens. Accumulation of nitrates (or ammonia) did not occur, contrary to what is expected in strict aerobic conditions (or in anaerobic digesters, respectively, for NH_4).

Table 3 | Current average characteristics in the LSP-AS system during the last 28 days

Reactors	TSS (mg/L)	COD_T (mg/L)	COD_s (mg/L)	pH (–)	T (°C)	f_{VT} –	f_{CV} –
Mixed liquor (RB)	3,370 ± 120	3,790 ± 80	25 ± 5	9.0 ± 0.1	19.5 ± 0.6	0.84 ± 0.01	1.33 ± 0.07
Digester (DU)	6,250 ± 110	7,130 ± 200	22 ± 2	8.3 ± 0.2	19.4 ± 0.9	0.82 ± 0.0	1.39 ± 0.02

TSS, total suspended solids; COD_T and COD_s , total and soluble COD; $r_{O_2\text{-endo}}$, endogenous respiration rate (at the end of the SBR cycle, 24 h after feeding). f_{VT} = g VSS/g TSS; f_{CV} = g COD/g VSS.

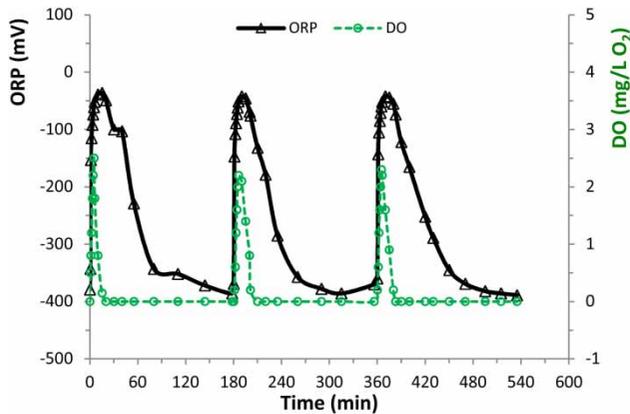


Figure 5 | Variation of the ORP and of the DO in the digester (3-h aeration cycles).

The absence of N chemical species in the sludge is a very interesting fact with respect to the potential removal mechanisms, and considering the traditional problem of high N-loads from sludge handling facilities. Among several potential causes that need further insight, there are Anammox processes, simultaneous nitrification–denitrification, NH_3 stripping and cryptic reuse of the ammonia produced by lysis.

Observed yield and sludge reduction in the systems

The cumulative biomass production (VSS) was plotted against the cumulative COD mass removed in each system (Figure 6). The first two parallel lines correspond to the data of the SBRs operated as CAS systems (duplicates). In the upper part of the figure, the bifurcation represents the

cumulative curve for the modified system (LSP-AS). The observed yields (Y_{obs}) given by the slopes of the linear regressions were 0.27 ± 0.01 for the parent CAS systems, against 0.14 g VSS/g COD for the modified process (0.31 versus 0.17 g TSS/g COD). The corresponding sludge mass reduction is 49%, which is in the commonly claimed range for Cannibal and OSA systems (Saby et al. 2003; Johnson et al. 2008).

Examples of Y_{obs} values reported recently in the literature are 0.18 g TSS/g COD in the study of an OSA process (30% sludge reduction, Zhou et al. 2015) and 0.14 g TSS/g COD at a full-scale Cannibal facility (Labelle et al. 2015). The yield of a conventional AS was reported to be 0.33 g TSS/g COD for the reference system (Wu et al. 2013) compared to 0.19 g TSS/g COD for their OSA version, which is very similar to the results of the present study.

As calculated from the pre-simulation results, the expected yields were estimated to be 0.30 and 0.08 g TSS/g COD (73% sludge reduction) for the parent CAS system and for the designed LSP-AS system (for a b_E of 0.007 d^{-1}), respectively. The actual values obtained from the cumulative graphics (Figure 6) were 0.31 versus 0.17 g TSS/g COD (50% sludge reduction). For the CAS system, the pre-simulated (0.30) and the actual yield (0.31) were very similar. In contrast for the LSP-AS system, the actual Y_{obs} value is higher than the pre-simulated value with a b_E of 0.007 d^{-1} . This confirms that b_E in the LSP-AS system is lower than anticipated ($b_E < 0.007 \text{ d}^{-1}$). It must be noted that sludge production in CAS systems operated with real sewage is generally higher

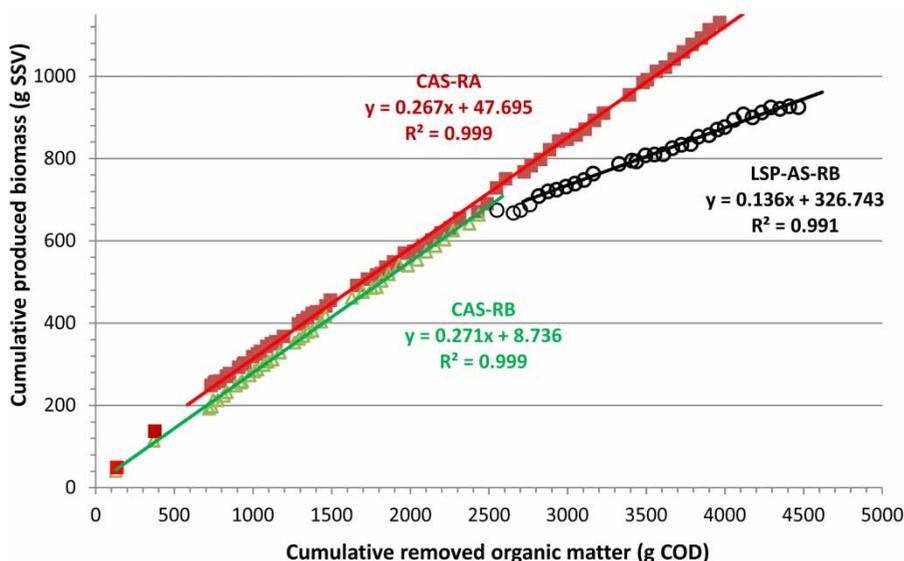


Figure 6 | Estimation of the observed yields in the CAS and LSP-AS systems.

(typically 0.4 gTSS/gCOD, Ginestet & Camacho 2007) than with synthetic wastewaters.

Calibration of the LSP-AS model to estimate the b_E parameter

Although the solids levels in the modified AS system were rising throughout the experiment, the process demonstrated a real ability to reduce the amount of sludge produced (by almost 50%). Also, despite their continuous increase, the final concentration of solids after 1 year of operation remained within typical conventional ranges (<3,500 and <10,000 mg TSS/L in the aeration tank and digester, respectively). The average concentrations during the last 28 days of operation are given in Table 3. Based on the relatively low standard deviations obtained (Table 3), it may be observed that the increasing trends were very slow. Amanatidou et al. (2015) showed a typical example of what would happen if the waste AS flow were closed. As anticipated in a simulation of Fall et al. (2015), even with a relatively high b_E value of 0.007 d^{-1} , an adequate side-stream digester volume is needed to avoid a steady state happening at high MLSS levels (18,000 mg/L in the study of Amanatidou).

The objective of reaching only one stable and definitive plateau for the MLSS concentrations (true steady state) was not achieved, which makes the estimation of the endogenous residues' degradation constant (b_E) via steady state calibration less accurate. Based on the pre-simulations, a clear steady state plateau was expected to happen before 6 months of operation of the LSP-AS system. A first apparent MLSS plateau was observed between days 283 and 332, when the sludge was more compact. During the last 90 days (out of 270 days) of operation, the sludge was less

compact, and the solids concentrations suffered a slow but continuous increase. Consequently, less effluent volume and its entrained solids were removed daily from the process (13 L instead of 20 L, independently of the influent substrate mass that was maintained constant). This may have contributed to the slow increase of the MLSS concentrations in the reactors, together with some possible precipitates accumulation from the synthetic influent.

Model calibrations to estimate the b_E constant were carried out in two ways: first, by steady state calibration, considering the average solids levels in RA and DU during the last 4 weeks of operation; and, second, by dynamic calibration, utilizing the time-profiles of solids in the reactors RB and DU. Only the first method is reported in this paper. Steady state calibration of the b_E parameter was achieved by matching the currently available data (COD of the sludge and the endogenous OUR, of RB and of the DU) with the model. The heterotrophic decay constant measured in the CAS system (0.29 d^{-1} , Aquasim) was assumed to be also valid for the LSP-AS system (for the SBR and DU reactors). Batch tests that measure the decay rates in the environment of each reactor may be used to verify this latter hypothesis. If necessary, the model should be rearranged, to accommodate up to three different b_H values for the various reactor environments used in the study; this will increase the general applicability of the modeling strategy proposed.

Other known parameters that were used in the model are the f_{CV} and f_{VT} ratios in the LSP-AS system (1.37 and 0.82), and the mixed liquor wastage flow of 100 mL/d. The efficiency of the settlers was fixed between 99.2 to 98.5% to match the average 20 mg VSS/L actually measured in the effluent. For the steady state calibration, average data of the

Table 4 | Steady state calibration of the LSP-AS model while using a b_H of 0.29 d^{-1}

Scenario #	Adjusted parameters		Model predictions for the reactor (RB) and for the digester (DU)					
	Settler E (%)	b_E (d^{-1})	Part. COD (mg/L)		X_H (mg/L COD)		$r_{O_2 \text{ endo}}$ ($\text{mg L}^{-1} \text{ h}^{-1}$)	
			RB	DU	RB	DU	RB	DU
0	99.8	0	9,930	25,700	–	–	–	–
1	99.2	0.007	2,630	3,870	1,170	500	5.6	2.5
2	99.2	0.006	2,750	4,250	1,170	500	5.6	2.5
Measured values → (average of the first plateau)			2,630 ± 160	4,290 ± 90	–	–	4.3 ± 0.5	3.6 ± 0.7
3	99.5	0.003	3,750	7,200	1,200	500	5.6	2.5
Measured values → (Final average at end of the runs)			3,790 ± 80	7,130 ± 200	–	–	–	–

last 4 weeks were used (solids in the mixed liquor of RA and in the DU). The average values were obtained using two alternate sets of data: (a) data series from a first apparent MLSS plateau observed between days 283 and 332, when the sludge was more compact (the average solids concentrations in the reactors were $2,630 \pm 160$ mg COD/L in RB and $4,290 \pm 90$ mg COD/L in the DU); (b) data at the end of the experiments (less compact sludge, the final concentrations of which were reported in Table 3).

For the calibration, the value of b_E was adjusted until the model matched the measured sludge concentrations (Table 4). First, it must be noted that if b_E was zero, i.e. if the endogenous residue X_E was completely non-biodegradable (scenario 0 of Table 4), the build-up of the solids would be much higher (approximately 10,000 mg/L in RA and 25,000 mgCOD/L in the DU) than the final values that were reached during the experiment.

Second, as illustrated by the scenario 1, model predictions of COD with the default b_E value of 0.007 d^{-1} were very low in comparison to the measured values. The best fit of the COD in the reactor and in the DU (<5% error) was achieved with a b_E value of 0.006 d^{-1} , based on the first apparent MLSS plateau observed (scenario 2), versus 0.003 d^{-1} when the MLSS data at the end of the experiments are used (scenario 3). Also, in both of these ultimate two scenarios, the calibrated model adequately predicted the actual endogenous oxygen uptake rates (r_{O_2} measurements). Furthermore, as reported in Table 4, the sludge from the processes became very stabilized; at the end of the runs, the active fraction X_H represented 32% of the sludge in the aeration tank, against 7% in the digester. As a consequence, the higher MLSS concentrations in the LSP-AS aeration tank did not increase the oxygen needs; also, once discharged from the process, the sludge produced did not need further stabilization treatment.

CONCLUSION

Based on the results of this study, sludge minimization and its modeling via the process of X_E biodegradation could be achieved. Almost 50% mass-reduction was observed, which corresponded to a b_E value between 0.003 and 0.006 d^{-1} . The description of sludge reduction via the X_E biodegradation process provides a quantitative and convenient way for sizing side-stream digesters for sludge reduction, in contrast to empirical criteria (HRT) used in Cannibal and OSA systems.

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