Minimisation of Sequencing Batch Reactor Volume by Optimisation of the Hydraulic and Solids Retention Time

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Abstract
In this work, we attempted to minimise the sequencing batch reactor (SBR) volume through optimising the hydraulic retention time (HRT) and solids retention time (SRT). In order to minimise the required volume of the SBR, the HRT and SRT have to be set to their minimum. This study therefore was aimed at determining to what extent HRT and SRT can be decreased for a given wastewater and for an effluent quality target. In order to maintain relatively constant feed composition, a synthetic wastewater composed of 1g/l glucose was used throughout this study. An experiment of nine different SBR runs (HRT in the range of 0.5 – 4 days; SRT in the range of 1 – 65.3 days; organic load rate (OLR) in the range of 0.27 – 2.14 g COD/l/day) was carried on the glucose wastewater. The process achieved a successful operation in terms of glucose removal (> 98%) with an OLR of 2.14 g COD/l/day (HRT of 0.5 days) at 2.5 days SRT, which is higher than most of the reported values in the literature for aerobic activated sludge. The process however failed at lower SRTs, achieving only 5 and 20 % glucose removal for 1 and 1.7 days SRT respectively. The optimum HRT and SRT for this process were 0.5 and 2.5 days respectively. The oxygen consumption and sludge production rates were calculated for all the runs and the results showed that aeration requirements increased and sludge production rate decreased with increase in the SRT. The strategy of reducing the HRT by decreasing the SRT can potentially lead to even lower reactor volumes and higher values of the OLR.

Keywords
Sequencing batch reactor (SBR); hydraulic retention time (HRT); solids retention time (SRT); organic load rate (OLR); optimization

INTRODUCTION

Sequencing batch reactor (SBR) is a variant of the activated sludge system characterised with intermitted flow operation (Von Sperling, 2007). It is designed to treat a wide range of industrial and domestic wastewaters by combining all the traditional activated sludge treatment processes, namely, biological reaction and secondary clarification, in a single vessel using a time controlled sequence rather than separated units as in the case of conventional continuous-flow processes (Artan and Orhon, 2005, Wang et al., 2010). The SBR process is a cyclic operation characterised with sequence of phases (fill, react, settle, withdrawal and idle) during the cycle, each lasting for predetermined time duration (Dionisi et al., 2001, Wilderer et al., 2001). Amongst the major advantages of this process is that the treatment phases can be rearranged or omitted and the duration of each phase can be altered depending on the influent dynamics, treatment requirements and the overall design goals (Von Sperling, 2007; Ni et al., 2009). This intrinsic flexibility in “tailoring” a treatment cycle pattern has made the process viable and implemented in full-scale plants worldwide (Mittal, 2006). The main operating parameters associated with the SBR process are the hydraulic retention time (HRT), solids retention time (SRT), length of treatment phases and the number of cycles per day (Dionisi et al., 2001, Artan and Orhon, 2005).

The SRT in a typical activated sludge process is generally in the range of 10 – 20 days (Johns, 1995) and it is well known that the SRT is the single most important parameter for the design and operation of the activated sludge process because it affects the reactor volume, oxygen requirements, sludge production and effluent quality (Artan and Orhon, 2005). This range of values (10 – 20 days) is evidently high, resulting in the generation of a considerable amount of aged sludge with low degradability and poor energy recovery in an anaerobic digester (AD); requiring long HRT; requiring large reactor volume and footprint; and ultimately high capital investments and high energy demands (Ge et al., 2013). One promising alternative in making the process more sustainable and cost effective is operating with short SRT and HRT.

Reducing the HRT will minimise the SBR volume and footprint, thereby reducing capital and investment costs. For a given wastewater at a certain flow rate and composition, reducing the HRT corresponds to increasing the volumetric organic load rate (OLR). However, the HRT can only be reduced to an extent because, for a fixed SRT, reducing the HRT will cause an increase in the biomass concentration, with a decrease in the settling rate and increase in the aeration requirements per unit of reactor volume (Dionisi, in press). Therefore, decreasing the HRT while keeping the SRT fixed can potentially cause the process to fail. However, these potential problems caused by low HRT can be counterbalanced by appropriate manipulation of the SRT. Indeed, the SRT affects the amount of biomass in the reactor and the oxygen consumption. In particular, by reducing the SRT, at a fixed HRT, the biomass concentration in the reactor and the oxygen consumption both decrease. However, reducing the SRT can potentially compromise the effluent quality. From these considerations, it is evident that, in order to minimise the reactor volume the HRT and SRT need to be optimised simultaneously (Ge et al., 2013). While reducing the HRT, the SRT needs also to be reduced, in order to achieve a process that requires the minimum reactor volume, while still having acceptable values of the biomass concentration and oxygen requirements and satisfying the effluent quality requirements. The question is: which are the optimum values of the HRT and SRT for a given wastewater? This study addresses this question with an experimental investigation of the behaviour of lab-scale SBRs operated in a range of HRT, SRT and OLR values with a synthetic wastewater at a fixed composition.

METHODS

Wastewater and inoculum

The wastewater used as the SBR feed was a synthetic wastewater prepared from analytical grade glucose with a concentration of 1 g/l. Nutrients in a form of mineral solution was added to the wastewater before feeding to the reactors. The composition of the mineral solution is reported in Table 1. Soil from Craibstone, Aberdeen was use as inoculum in this study. The soil was screened and homogenised in standard soil test sieves (0.6 mm) and then stored in containers at room conditions. Detailed microbial characterization of the soil is presented in Bartram et al. (2014).

Experimental design and SBR Operation

An experiment of nine different SBR runs (HRT in the range of 0.5 – 4 days; SRT in the range of 1 – 65.3 days; OLR in the range of 0.27 – 2.14 g COD/l/day) was carried out on the synthetic wastewater in a lab scale sequencing batch reactor. Locally constructed cylindrical glass vessels with a working volume of 1L were used as reactors. The reactor was operated sequentially with 4 cycles per day and a cycle time of 6 hours to treat the wastewater at room conditions. The SRT in each run was set by the sludge withdrawal rate. Table 2 shows the reactor operating conditions for all the runs. Two VELP SP 311 peristaltic pumps (Italy) were used to fill and empty the reactors during fill and effluent withdrawal phases every cycle respectively. Mixing was carried out using magnetic bars with the aid of a Stuart CD162 magnetic stirrer (UK). Fine air bubbles were supplied to the reactor through an air diffuser from an Interpet Airvolution AV Air Pump (UK). A programmable 220 – 250 V Energenie Four Socket Power Management System (UK) was used to control the length of the phases for each cycle during the treatment. Each run was stopped after the reactor reached steady state (i.e. after relatively stable values of the biomass and substrate concentrations were maintained for at least a week) and enough data was collected.

Table 1. Composition of mineral solution used in the experiments. 50 ml of mineral solution was added per litre of the wastewater.

Substance	Concentration
NH_4Cl	16 g/l
K_2HPO_4	70 g/l
NaH_2PO_4	48 g/l
CH_4N_2S (Thiourea)	0.4 g/l

Sampling and analysis was done three times every week to measure the reactor performance in terms of effluent and sludge qualities. Effluent quality was monitored at the end of a cycle by measuring effluent soluble chemical oxygen demand (COD), total carbohydrates, and volatile suspended solids (VSS) while sludge quality was monitored at the end of react phase by measuring the VSS in the well-mixed reactor. Sludge withdrawal from the well-mixed reactor was done manually on a daily basis at the end of react phase. The pH and temperature were monitored throughout the experiments. The operating conditions and set-up for all runs were identical, except listed otherwise in Table 2.

Table 2. Operational characteristics of the SBR for each run.

Run	HRT (days)	OLR $(\frac{g\ COD}{l.day})$	Sludge Withdrawal Rate (ml/day)	Length of the Phases (min)				Volume Fed Per Day (ml/day)
				Fill (aerated)	React	Settle	Effluent Withdrawal	
1	4	0.27	250	2	300	58	2	250
2	4	0.27	90	2	300	58	2	250
3	4	0.27	35	2	300	58	2	250
4	4	0.27	18	2	300	58	2	250
5	4	0.27	0	2	300	58	2	250
6	1	1.07	1000	5	300	55	5	1000
7	1	1.07	350	5	300	55	5	1000
8	1	1.07	0	5	300	55	5	1000
9	0.5	2.14	100	10	295	55	10	2000

The sequential phases adopted for each run were: fill (aerated fill), react, sludge withdrawal, settle and effluent withdrawal. The reactors were started up by inoculating 5 g of well-sieved soil with 1 L of wastewater in the reactor. The cycle was initiated with the settle phase, followed by effluent withdrawal. Then the first feed was added and reactor operation continued according to the programmed cycle pattern. A small amount of solids in the reactor inevitably leaves the system with the effluent after the settle phase, thus the actual SRT in the reactor is calculated from the concentrations of solids in the well-mixed reactor and in the effluent as shown in equation 1 below.

$$SRT = \frac{V \cdot X}{Q_w \cdot X + Q_{eff} \cdot X_{eff}} \qquad (1)$$

Where V is the working volume of reactor (ml) and Q is the daily influent flowrate (ml /day), X is the solids concentration in the well-mixed reactor, Q_W and Q_{eff} are the daily sludge and effluent withdrawal volumes respectively and X_{eff} is the solids concentration in the effluent.

Analytical method

Biomass concentration was measured as VSS and glucose concentration was measured both as COD and as total carbohydrates. The measurements and analysis of COD and VSS were carried out in accordance with Standard Methods (APHA, 1998) while the measurements and analysis of total carbohydrates was performed based on anthrone reagent method (Koehler, 1958). The reactor-effluent sample was filtered through a Millet syringe filter of 0.45µm pore size (Germany) prior to the COD and total carbohydrates analyses. A Spectroquant TR 620 thermoreactor (Germany) was used for heating the samples to the appropriate temperatures. A NOVA 60 photometer (Germany) was used to read the COD values and a Jenway 6314 spectrophotometer (UK) was used to measure the total carbohydrates at 620 nm. The dry weight VSS was determined using a Whatman 1822 – 047 Grade GF/C glass fibre filter paper of 1.2µm pore size (USA). The pH was measured using a Thermo Scientific Orion Versastar pH meter (USA).

RESULTS AND DISCUSSION

SBR Process performance

As mentioned in the Methods section, a mineral solution was added to the wastewater feed before treatment in the reactor. This was done in order to buffer the pH of the process to within a range of 6.5 – 7 and to also prevent any possible nutrient limitation. Traces of thiourea were also added in the mineral solution as reported in Table 1 to inhibit nitrification since this study is only focused on carbon removal.

Nine experiments (runs 1 – 9) were run at different HRTs and SRTs. The runs were grouped into two sets (HRT = 4 days and HRT ≤ 1 day) as shown in Figures 1 and 2. During the SBR runs, the sludge withdrawal rates (in Table 2) and the biomass concentrations in the well-mixed reactor and in the effluent were used to calculate the actual operating SRT using equation 1. As a result, the calculated SRT for each run was: Run 1 (4 days); Run 2 (8.7 days); Run 3 (16.3 days); Run 4 (27.3 days); Run 5 (65.3 days); Run 6 (1 day); Run 7 (1.7 days); Run 8 (38 days) and Run 9 (2.5 days). Figure 1 reports the performance for the first group of runs (1 - 5) from start-up to steady state in terms of substrate and biomass concentrations. These first five runs were carried out at OLR of 0.27 g COD/l/day, which is based on the 4 days HRT. The results in the Figure were in terms of COD in the effluent, total carbohydrates in the effluent, VSS in the well-mixed reactor (at the end react phase) and VSS in the effluent. A stable performance was observed virtually after 5 days from start-up for the COD and total carbohydrates. Glucose concentration in the effluent, measured as total carbohydrates, was done as an independent measurement from the COD to precisely quantify the glucose removal in the reactor. The figure clearly shows an agreement between the COD and the total carbohydrates analyses as 96 – 99 % of COD vs. 98 – 99 % of total carbohydrates were recorded in terms of glucose removal for runs 2, 3, 4 and 5. However, for run 1, glucose removal in terms of COD was 92 % and 98 % in terms of total carbohydrates. This is because the COD measurements accounts for residual by-products produced during metabolism especially for incomplete glucose degradation, which gives slightly higher values than the total carbohydrates.

The range of SRT (4 – 65.3 days) in this set of runs have very little effect on substrate removal as more than 96 % of glucose was removed after the first 5 days of inoculation. However, for the biomass in the well-mixed reactor, the concentration increased with the SRT and steady state was achieved even after just one solids retention time for each run. The biomass concentrations in the effluents were in the range of 100 – 132 mg/l. There wasn't any effluent withdrawal for Run 1 because the HRT was equal to the SRT. About 6 – 13 % of solids in the reactors were lost in the effluents for this set of runs indicating a good settling, judging from the high biomass concentrations in the reactor at the longer SRTs. The results in this first set of runs showed a near complete substrate removal of glucose (> 96%) with a SRT as short as 4 days, therefore the second set of runs was carried out a shorter HRTs and SRTs of 4 days.

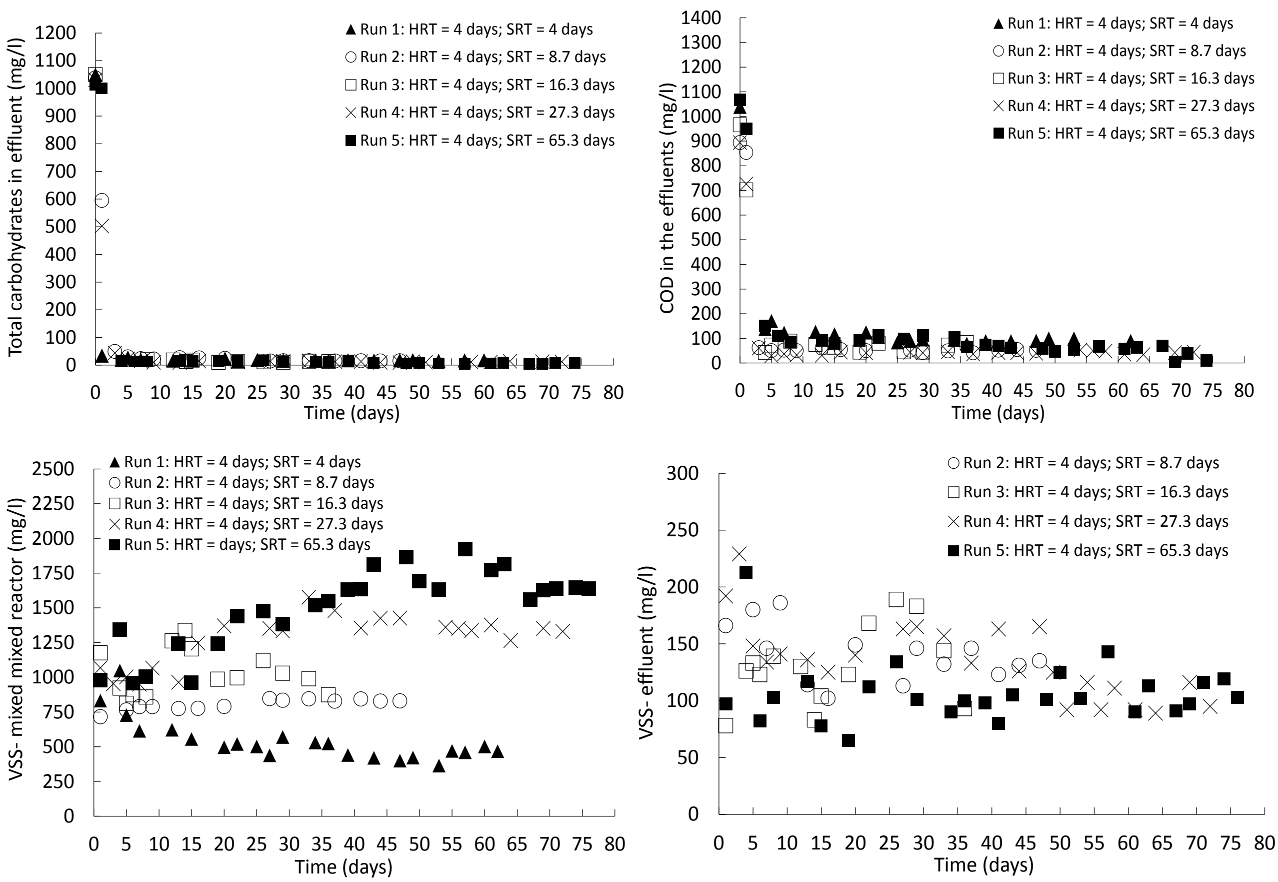

Figure 1. First set of runs (1 – 5): profiles of COD, total carbohydrates, and biomass concentration in the well-mixed reactor and in the effluent from start-up to steady state. OLR = 0.27 g COD/l/day.

Figure 2 reports the performance of the reactors for the second set of runs (6 – 9) carried out at HRT of 1 and 0.5 days and corresponding OLR of 1.07 and 2.14 g COD/l/day respectively. In this experiments, more sludge was withdrawn to decrease the SRT as a result of the decrease in HRT. The first two runs in this set (run 6 and 7) showed a drop in both COD and total carbohydrates for the first few days before the process began to fail due to biomass wash-out as shown in the VSS of well-mixed reactor plot. The concentrations of glucose in the effluent began to increase and at steady state the process was only able to achieve 11 % and 25 % glucose removal in terms of COD and 5 and 20 % glucose removal in terms of total carbohydrates for runs 6 and 7 respectively. This indicates that SRT of 1.7 days as in run 7 is not long enough to ensure complete degradation of glucose at this set of conditions. This trend of deterioration of effluent quality observed at shorter SRT is in agreement with the theory of activated sludge systems and has been reported in many literatures (Dionisi et al., 2008; Grady et al., 2011; Zhu et al., 2013).

Another important observation from Figure 2 is that although 99 % glucose removal was achieved in run 8 after reaching steady state, the reactor appeared to be failing during the initial stages due to insufficient biomass in the reactor as a result of relatively high biomass losses with the effluent because of poor settling, but then it picked up and stabilised after one solid retention time. This is of course one of the limitations of operating at a high OLR and long SRT where the biomass concentration exceeds certain limits and consequently preventing good settling (Dionisi et al., 2006). As the HRT was decreased to 0.5 days (run 9), it is interesting to observe from Figure 2 that the reactor achieved a stable performance from the start resulting in more than 98 % of glucose removal.

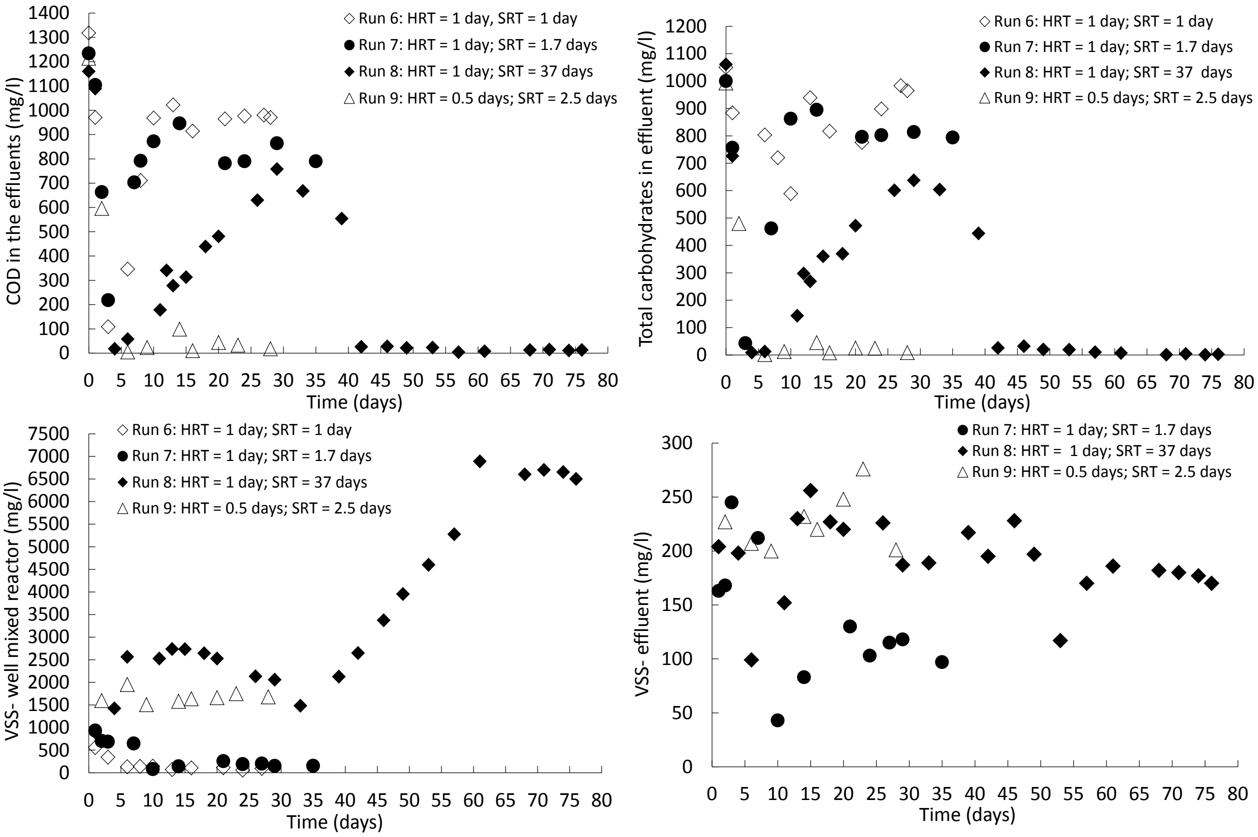

Figure 2. Second set of runs (6– 9): profiles of COD, total carbohydrates, and biomass concentration in the well-mixed reactor and in the effluent from start-up to steady state. OLR = 1.07 g COD/l/day and OLR = 2.14 g COD/l/day.

As expected, the biomass concentration was somewhat proportional to the OLR when compared with previous runs: OLR of 0.27 g COD/l/day and SRT of 4 days yielded approximately 470 mg biomass/l, while OLR of 2.14 g COD/l/days and SRT of 2.5 days yielded approximately 1680 mg biomass/l. The biomass concentrations in the effluents of this second set of runs were in the range of 110 – 235 mg/l. There wasn’t any effluent withdrawal for run 6 because the HRT was equal to the SRT. About 2 - 14 % of biomass in the reactors was lost in the effluents for run 8 and 9 indicating good settling despite the high biomass concentrations. The average values of the substrate and biomass concentration for all the HRT and SRT are shown in Figure 3. Substrate concentration was expressed in terms of total carbohydrates because it gives a better measurement of glucose removal than COD.

In this study, a successful operation of the SBR was achieved with OLR of 2.14 g COD/l/day and SRT of 2.5 days. Table 3 summarises the results of some literate studies on their successful operation of aerobic activated sludge processes at various values of the OLR and SRT. Although the wastewaters in the cited literature are composed of different substrates from the substrate considered in this study, the OLR achieved in this study (2.14 g COD/l/day) was higher than most of the values achieved in the literature for aerobic operations (normally around 1 – 1.4 g COD/l/day as shown in Table 3). The minimum SRT achieved in this study (2.5 days) was also shorter than most of the values reported in the literature (normally 4 – 20 days as shown in Table 3).

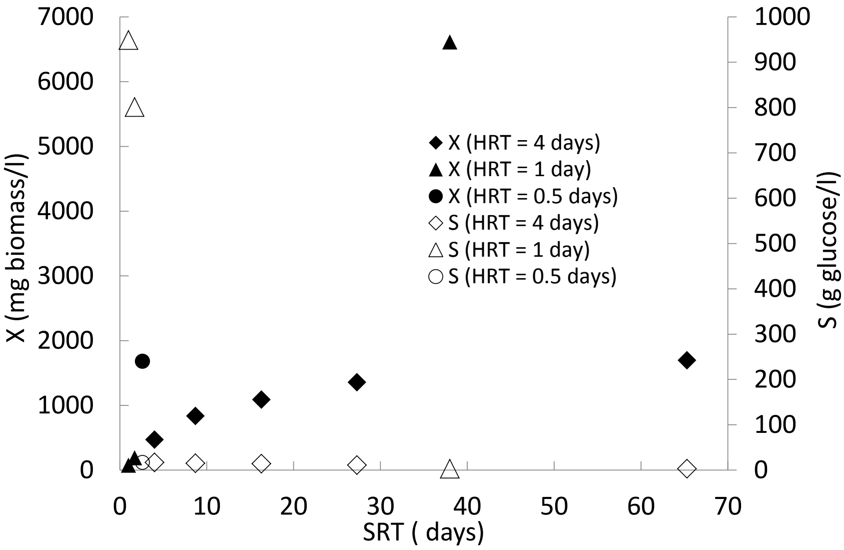

Figure 3. Average steady state values of biomass and substrate concentration as a function of the different SRTs and HRTs. *X* and *S* are the biomass and substrate respectively.

Table 3. Comparison of the results obtained in this study with other studies reported in the literature

Reference	Length of cycle (hour)	SRT (days)	OLR (g COD/l/day)
Beun et al. (2002)	4	4	1.15
Serafirm et al. (2004)	8	10	0.9
Dionisi et al. (2008)	6	4	1
Li et al. (2008)	8	14.5 - 25	1.2
Hajiabadi et al. (2009)	24	5	1.4
Ge et al. (2013)	3	2 – 3.8	1.4 – 2.8
Rodríguez et al. (2013)	8	30	3.24
This study	6	2.5	2.14

From the set of experiments carried out in this study, HRT of 0.5 days and SRT of 2.5 days are the optimum operating parameters for the treatment of glucose wastewater at OLR of 2.14 g COD/l/day and thus the minimum SBR volume corresponds to value of the HRT from this correlation: HRT = V/Q, where V is the reactor volume and Q is the daily flow rate.

As stated in the Introduction, the SRT affects the aeration requirements and sludge production in activated sludge processes. The oxygen consumed and sludge produced at various SRTs in the SBR runs can be approximated using conventional activated sludge correlations below: (Dionisi, in press)

$$Biomass\ produced\ \left(\frac{\frac{g\ biomass}{day}}{\frac{l\ feed}{day}}\right) = X \cdot \frac{HRT}{SRT} \qquad (2)$$

$$Oxygen\ consumed\ \left(\frac{\frac{g\ O_2}{day}}{\frac{l\ feed}{day}}\right) = (S_0 - S) - X \cdot \frac{HRT}{SRT} \cdot 1.42 \qquad (3)$$

Where S_0 and S are the COD in the feed and in the reactor effluent respectively, and 1.42 is the

COD conversion of biomass. Figure 4 shows the values of the oxygen consumed and sludge produced as a function of the SRT. Run 6 and 7 were excluded from the plot because the process failed. From the plot, as expected, oxygen consumption increased with SRT due to endogenous metabolism while the sludge produced decreased inversely with the SRT due to withdrawing more sludge at shorter SRT. The highest oxygen consumed was 950 mg O_2/day and the lowest sludge produced was 104 mg biomass/day for every litre per day of the wastewater feed was for the SBR run with SRT = 65.3 days (run 8). The oxygen consumed and sludge produced at the highest OLR (2.14 g COD/l/day) and shortest SRT were 624 mg O_2/day and 323 mg biomass/day for every litre per day of wastewater feed.

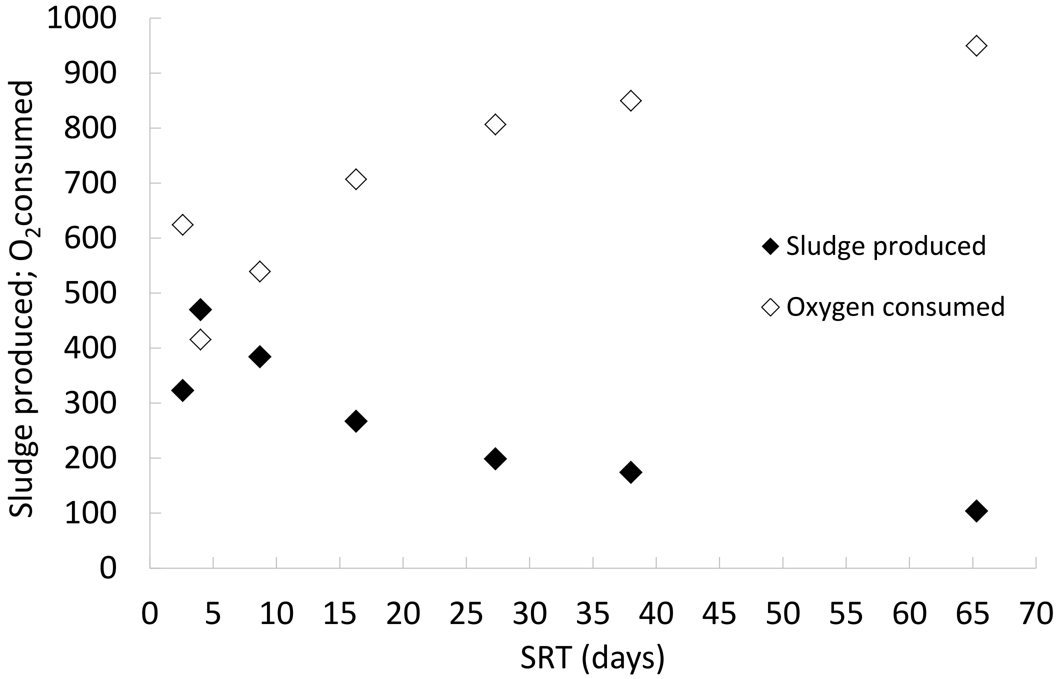

Figure 4. Calculated values of the oxygen consumed and sludge produced as a function of the SRT.

If the process were to be operated at OLR of 2.14 g COD/l/day and at a SRT longer than the optimum, the biomass concentration (X) will increase with the SRT, consequently increasing the oxygen consumption and reducing the biomass production. This operation in reality will be costlier than at the optimum because more energy is needed for the aeration and less energy will be recovered from the sludge if it undergoes treatment in an AD.

CONCLUSION

Synthetic wastewater composed of glucose was treated in aerobic sequencing batch reactors under nine different SRTs (1, 1.7, 2.5, 4, 8.7, 16.3, 27.3, 37 and 65.3 days). The SRTs in each run was controlled by the sludge withdrawal rate. The reactor was inoculated with soil and the reactor performance was monitored in terms of effluent and sludge quality. The reactors were subjected to different OLRs in the range of 0.27 – 2.14 g COD/l/day at different values of the SRT. The process achieved a successful operation in terms of glucose removal (> 98%) with an OLR of 2.14 g COD/l/day at 2.5 days SRT, which is higher than most of the reported values in the literature for activated sludge. The process however failed at lower SRTs, achieving only 5 and 20 % glucose removal for 1 and 1.7 days SRT respectively. The study showed that the reactor volume and oxygen consumption could be minimised by operating the process at the optimum HRT and SRT. The results showed the possibility of achieving a successful process operation upon increasing the OLR (HRT < 0.5 days) if the SRT is maintained at its optimum.

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