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Maximisation of the organic load rate and minimisation of oxygen consumption in aerobic biological wastewater treatment processes by manipulation of the hydraulic and solids residence time

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Abstract

A systematic experimental study of the effect of hydraulic residence time (HRT) and solids residence time (SRT) on conventional suspended-growth biological wastewater treatment processes was carried out. The aim of this study was to identify the conditions that minimise the reactor volume, i.e. maximise the organic load rate (OLR), and minimise the oxygen consumption. Lab-scale sequencing batch reactors (SBRs) were operated with glucose or ethanol as only carbon sources, with HRT in the range 0.25-4 day and SRT in the range 1-71 day. The highest OLR values which gave satisfactory performance were 4.28 and 4.14 gCOD/l.day for glucose and ethanol, respectively, which are among the highest reported for conventional aerobic suspended-growth processes. The highest OLR values were obtained with HRT=0.25 day, SRT=3.1 day for glucose and HRT=0.5 day, SRT=4.9 day for ethanol. The minimum oxygen consumption was 0.36 and 0.69 kg O_2/kg COD removed for glucose and ethanol, respectively. In disagreement with conventional theories, it was found that biomass production also depended on the OLR as well as on the SRT, higher OLRs giving lower biomass production for the same SRT. From the kinetic analysis of the experimental data, this behaviour, which has important consequences for the design of biological wastewater treatment processes, was explained with a higher rate of endogenous metabolism at higher OLRs.

Keywords: Aerobic wastewater treatment; hydraulic residence time (HRT); organic

load rate (OLR); solids residence time (SRT); oxygen consumption.

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1. Introduction

The aim of aerobic biological wastewater treatment processes is to treat the influent wastewater with the highest possible reduction of the COD and BOD, with the minimum possible size of the reaction tank and the minimum possible oxygen consumption. A high COD reduction is required to maintain the high environmental quality of the receiving water body, a small volume of the reaction tank decreases the capital costs and the land usage by the plant, low oxygen consumption minimises the energy costs and the environmental footprint of the plant. In addition, the production of waste sludge needs also to be taken into account in the design of biological treatment processes. Usually, waste sludge is considered a liability which needs to be minimised, but the increasing use of anaerobic digestion to convert sludge into methane is showing that waste sludge can rather be seen as a resource (McCarty et al., 2011).

As far as the reactor volume is concerned, for a given flow rate and composition of the influent wastewater, smaller reactor volumes correspond to lower values of the hydraulic residence time (HRT) and, correspondingly, to higher values of the volumetric organic load rate (OLR). In conventional suspended-growth activated sludge processes, the OLR is typically in the range 0.5-1.5 kg COD/m^3.day (WEF, 2012). Various technologies have been investigated to increase the OLR and therefore decrease the reactor volume, e.g. air-bubble or jet-loop bioreactors, membrane bioreactors or granular sludge. For example, Petruccioli et al. (2000) reported the treatment of winery wastewaters in an air-bubble column bioreactor at organic loads up to 8.8 g COD/l.day, and Bloor et al. (1995) reported treatment of a brewery wastewater in a jet loop reactor at organic loads up to 50 g COD/l.day. Holler and

Trosch (2001) reported successful operation of membrane bioreactors with OLRs of up to 13 g COD/l.day. Liu and Tay (2015) operated aerobic granular reactors with a long-term stable performance at the OLR of 6 g COD/l.day. Although these technologies have been proven successful and are used at full scale, they also have disadvantages and are not always applicable, e.g. membrane bioreactors are subject to fouling and are often expensive and the mechanism of aerobic granulation is not yet completely understood. Other technologies require special reactor types and aerators configurations which are not of general applicability in activated sludge processes.

The maximum OLR that can possibly be achieved in conventional suspended-growth biological processes is limited by the maximum biomass concentration that can be maintained in the biological reactor, which is in turn limited by the negative effect of high biomass concentrations on the aeration efficiency and on the settling rate. However, the biomass concentration also depends on the solids residence time (SRT) and it is therefore conceivable that SRT and HRT might be optimised together to maximise the OLR while still maintaining a biomass concentration that is not too high. In this optimisation, it has to be taken into account that the SRT determines the effluent substrate concentration, the oxygen consumption and the biomass production in the plant (Grady et al., 2011; Dionisi, 2017). In summary, the design parameters HRT and SRT need to be chosen to satisfy the objectives of the highest possible effluent quality, lowest reactor volume and lowest oxygen consumption.

Typically conventional suspended-growth activated sludge processes for carbon removal are operated with values of the SRT in the range 3-15 days (Grady et al., 2011; WEF, 2012). However, recent studies (Jimenez et al., 2015) on the high-rate activated sludge process (HRAS) have shown that efficient COD removal can be obtained even at

SRT lower than 2 days. A study by Ge et al. (2013) has shown, with a slaughterhouse wastewater, that activated sludge processes can be successful even with low SRT values (2-3 days). In that study, operation at low SRT allowed the use of a short HRT and therefore a high organic load rate of up to 5.8 g COD/l.day. These findings were later confirmed in another study from the same group (Ge et al., 2017) using wastewater effluent from a sewer biofilm reactor. The Authors also observed a high anaerobic degradability of the produced sludge and a positive effect of lower SRT in the aerobic process on the anaerobic digestion of the sludge, an effect which was also observed by Gossett et al. (1982) and Bolzonella et al. (2005).

Although several studies have been reported on the effect of HRT and SRT in activated sludge processes, usually these parameters have not been optimised simultaneously for the maximisation of the OLR and the minimisation of the oxygen consumption. Furthermore, there is very little reported information on how the OLR affects the kinetic parameters of activated sludge models, in particular the parameters that mostly affect oxygen consumption and biomass production, i.e. the growth yield and the specific rate of endogenous metabolism. A recent study by Liu and Wang (2015) investigated and modelled the effect of dissolved oxygen and SRT on sludge production, finding that low oxygen concentrations reduce the degradation of cell debris and therefore increase the sludge production. An experimental optimisation of the HRT and SRT for municipal wastewater was carried out by Jimenez et al. (2015), who identified SRT>1.5 days and HRT > 30 min as the optimum conditions for the HRAS process, however they did not attempt to give a quantitative interpretation of their data using kinetic modelling (e.g. determining the growth yield and the rate of endogenous metabolism). The effect of HRT and SRT on activated sludge process performance was investigated by Barr et al. (1996) using a wastewater from Kraft mills. However, in this study the OLR was not optimised and was in all cases below 1.5 kgBOD/m^3.day. Surprisingly, the authors observed that BOD removal was more affected by the HRT than by the SRT. The effect of the SRT on phenol and o-cresol removal was investigated by Nakhla et al. (1994), however this study was carried out at constant HRT and OLR and the process was therefore not optimised. Both studies by Barr et al. (1996) and Nakhla et al. (1994) were carried out with potentially inhibiting wastewaters, which makes it more difficult to interpret their results in terms of optimisation of the operating parameters. As far as nitrogen removal is concerned, the effect of SRT on ammonia removal and nitrate and nitrite production was investigated and modelled in a recent study (Liu and Wang, 2014).

The aim of this study is to carry out a systematic experimental analysis of the optimisation of aerobic biological wastewater treatment processes. In particular, the aim is to identify the conditions that minimise the reactor volume and the oxygen consumption and maximise the biomass production while maintaining a satisfactory performance in terms of COD removal and biomass settling. Also, this study is aimed at determining the effect of the OLR on the biomass growth yield and on the specific rate of endogenous metabolism, which are the most important parameters in the calculation of oxygen consumption and biomass production in biological processes. In this study, we will assume that biomass production is a benefit for the process because of its potential for energy generation using anaerobic digestion. This optimisation study was carried out by running aerobic reactors at different values of HRT and SRT. The study was carried out with two synthetic wastewaters, using glucose and ethanol as only carbon sources.

2. Background theory

In this section we summarise the fundamental theory of activated sludge processes which is behind and has guided our experimental study. The theory in this section is adapted from our recent work (Dionisi, 2017).

The equations below refer to a continuous-flow activated sludge process consisting of a perfectly mixed biological reactor followed by a settling tank with biomass recirculation. We assume that the excess sludge is removed from the bottom of the settling tank. We will use the following definitions:

$$HRT = \frac{V}{Q} \qquad (1)$$

$$SRT = \frac{VX}{Q_W X_R + (Q - Q_W) X_{eff}} \qquad (2)$$

$$OLR = \frac{QS_0}{V} \qquad (3)$$

with the following meaning of the symbols: HRT=hydraulic residence time (day); SRT=solids residence time (day); OLR=organic load rate (gCOD/l.day); V = reactor volume (l); Q = influent wastewater flow rate (l/day); S_0 = influent substrate concentration (gCOD/l); X=biomass concentration in the reactor (gVSS/l); X_{eff} = biomass concentration in the supernatant from the settling tank (gVSS/l); X_R = biomass concentration at the bottom of the settling tank and in the recycle stream (gVSS/l); Q_W = sludge waste flow rate (l/day). We will assume that substrate removal and biomass growth are described by Monod kinetics with endogenous metabolism:

$$r_X = \frac{\mu_{max} S}{K_S + S} X; \; r_S = -\frac{\mu_{max} S}{K_S + S} \frac{X}{Y_{X/S}}; \; r_{end} = -bX$$

with the following meaning of the symbols: r_X = biomass growth rate (gVSS/l.day); r_S =

substrate removal rate (gCOD/l.day); r_{end} = rate of endogenous metabolism (gVSS/l.day). μ_{max} (day^{-1}), K_S (gCOD/l) and b (day^{-1}) are kinetic parameters. In this study, a simple model of endogenous metabolism is considered, which assumes that all the biomass that decays is fully oxidised to carbon dioxide and water with no generation of cell debris. More complex models of endogenous metabolism, which include the generation of cell debris or of an endogenous residue, have also been developed (Friedrich and Takacs, 2013; Liu and Wang, 2015; Ramdani et al., 2012).

With these assumptions, the relationship between effluent substrate concentration (S, gCOD/l), SRT and kinetic parameters is:

$$S = \frac{bK_S SRT + K_S}{(\mu_{max} - b)SRT - 1} \qquad (4)$$

Equation (4) shows that, for given kinetic parameters, the effluent substrate concentration depends only on the SRT.

The biomass concentration in the reactor is given by:

$$X = \frac{(S_0 - S)Y_{X/S} SRT}{(1 + b \cdot SRT)HRT} \qquad (5)$$

Equation (5) shows that, for a given influent concentration, the biomass concentration in the reactor depends on the SRT and on the HRT. The biomass concentration increases by increasing the SRT and by decreasing the HRT.

The biomass production and the oxygen consumption per unit of influent flow rate are given by:

$$\frac{P_X}{Q}\left(\frac{kg\,biomass}{day \cdot \frac{m^3}{day}}\right) = \frac{(S_0 - S)Y_{X/S}}{1 + b \cdot SRT} \qquad (6)$$

$$\frac{Q_{O2biomass}}{Q}\left(\frac{kg\,O_2}{day\cdot\frac{m^3}{day}}\right)=\left(S_0-S\right)\left(1-\frac{1.42\cdot Y_{X/S}}{1+b\cdot SRT}\right) \qquad (7)$$

where P_X is the biomass production rate (gVSS/day) and $Q_{O2biomass}$ is the oxygen consumption rate by the biomass (gO_2/day). P_X represents the mass flow rate of biomass leaving the system, which at steady state coincides with the biomass production rate in the system, while $Q_{O2biomass}$ represents the rate at which biomass consumes oxygen in the reactor. Equations (6) and (7) show that, for a given influent composition, the biomass produced and the oxygen consumption per unit volume of treated wastewater depend only on the SRT.

If activated sludge processes are operated in a range of SRT and HRT and data on substrate and biomass concentration in the biological reactor are collected, the parameters $Y_{X/S}$ and b, which determine the production of biomass and the oxygen consumption in the reactor, can be determined by the following linearised equation:

$$\frac{SRT\left(S_0-S\right)}{X\cdot HRT}=\frac{1}{Y_{X/S}}+\frac{b}{Y_{X/S}}SRT \qquad (8)$$

Equation (8) shows that by plotting the variable $\frac{SRT\left(S_0-S\right)}{X\cdot HRT}$ vs the SRT, we should be able to calculate $Y_{X/S}$ and b from the slope and intercept of the regression line.

The design of the secondary settling tank is affected by the settling rate of the sludge, which is inversely proportional to the biomass concentration in the biological reactor, e.g. an exponential decay equation is often used:

$$u_C\left(\frac{m}{h}\right)=\alpha e^{-\beta X} \qquad (9)$$

where u_C is the settling rate, α and β are parameters. Equation (9) shows that the higher the biomass concentration in the reactor, the lower the settling velocity and therefore the larger the area required for the settling tank.

In summary this background theory shows that, for a wastewater of given flow rate and composition and for given kinetic parameters:

- Lower reactor volumes are achieved by decreasing the HRT and, as a consequence, by increasing the OLR;
- Lower reactor volumes give, for a fixed SRT, higher biomass concentrations;
- Higher biomass concentration can have a negative effect on the settling rate and therefore on the design of the secondary settling tank;
- For a fixed HRT, the biomass concentration depends on the SRT, and can be decreased by decreasing the SRT, as long as the SRT is long enough for the desired COD removal;
- Lower SRT gives lower oxygen consumption and higher biomass production.

In conclusion, the analysis of the background theory shows that, in theory, for a given flow rate and composition of the influent wastewater, the appropriate choice of the parameters HRT and SRT can give the optimum combination of high substrate removal, low reactor volume, low biomass concentration, low oxygen consumption and high biomass production.

This paper aims to verify this theory experimentally and to identify the optimum boundary of the parameters HRT and SRT which minimise the reactor volume and oxygen consumption. The study was carried out using synthetic wastewaters made of readily biodegradable substrates. Instead of using a continuous-flow process, our experimental study used sequencing batch reactors (SBRs). In SBRs, reaction and settling are carried out in the same tank and the process is operated as a sequence of phases and cycles, rather than as in continuous flow. However, all the concepts and definitions used in this section apply to SBRs as well, but it has to be considered that SBRs have additional design parameters compared to continuous-flow systems, i.e. the number of cycles and the length of the various phases (Dionisi et al., 2016). In our study the only design parameter, in addition to HRT and SRT, which was changed significantly in one of the runs is the length of the feed and its effect will be discussed in the Results and Discussion section.

3. Methods

3.1 Wastewaters and inoculum

Two wastewaters were used in this study. One wastewater had glucose and one had ethanol as only carbon source. The concentration of glucose and ethanol was 1 g/l. In both cases nutrients were added to the wastewater before feeding to the reactors: NH_4Cl (0.8 g/l), K_2HPO_4 (3.5 g/l), NaH_2PO_4 (2.4 g/l), thiourea (20 mg/l). The inoculum used in this study was a soil from Craibstone farm in Aberdeen (0.1 gVSS/g soil). The soil was homogenised and sieved (150 mm size) and then stored in plastic containers at room temperature before inoculation.

3.2 Reactor set-up

The reactors used were glass containers with a working volume of 1L. VELP SP 311 peristaltic pumps (Italy) were used to fill the reactors during fill phases and empty the reactors during effluent withdrawal phases. A Stuart CD162 magnetic stirrer (UK) and magnetic stirrer bars were used to ensure mixing in the reactor. Oxygen was supplied to the well-mixed reactors via fine bubble air diffusers from an Interpet Airvolution AV Air Pump (UK). Throughout these experiments, the dissolved oxygen concentration levels in the reactors were always kept high (> 2 mg O_2/l) and therefore there was no oxygen limitation. The length of each treatment phase during a cycle was controlled using a programmable 20 – 250 V Energenie Four Socket Power Management System (UK).

3.3 Experimental design and SBR operation

A total of twenty SBR runs were carried out, eleven with glucose and nine with ethanol, with different values of HRT, SRT and OLR. The summary of the operating parameters of the various runs in reported in Tables 1 and 2 (where VER=volumetric exchange ratio=volume of feed per cycle/reactor volume). The runs were carried out at room temperature, the temperature in the reactors was measured and was in all cases in the range 20-22 ^{O}C. In all the runs except 1G, 6G, 1E, 5E, the Effluent Withdrawal phase followed the Settle phase and was used to remove the clarified effluent supernatant. In runs 1G, 6G, 1E and 5E the SRT and the HRT coincided, therefore the volume of sludge removed needed to coincide with the volume fed every cycle. Therefore, in these runs the Effluent Withdrawal phase was set immediately before the Settle phase and removed the completely mixed sludge, with no removal of the clarified effluent.

The fill and react phase were aerated. The main design parameters were the HRT and SRT. The HRT was controlled by changing the overall daily flow-rate into the reactors. Changes in the HRT resulted in changes to the VER, because $VER = \frac{1}{No\ cycles \cdot HRT}$, where *No cycles* is the number of cycles per day. *No cycles* was set to 4 for all the runs except runs 10G and 11G, where it was set to 6 in order to keep the VER below its maximum value of 100%. Therefore, the length of the cycle was 360 mins for all the runs except runs 10G and 11G, where it was 240 mins. The SRT in each run was controlled by changing the sludge withdrawal rate (Q_W) and by measuring the solid losses with the effluent. In all runs except 1G, 6G, 1E, 5E the sludge withdrawal was done manually once per day from the mixed reactor at the end of the reaction phase. In runs 1G, 6G, 1E, 5E (SRT=HRT) the sludge withdrawal was done using the Effluent Withdrawal pump, as described above. The average SRT was calculated at the end of each run from the steady-state concentrations of solids in the well-mixed reactor and in the effluent according to equation (2), with X_R=X. The length of the Fill and Effluent Withdrawal phases was set to be as short as possible and was limited by the maximum flow rates of the available pumps. In some runs, the length of these phases was longer than in other runs due to the availability of pumps with lower maximum flow rate.

Table 1. Operating parameters for the SBRs treating the glucose wastewater.

Run	HRT (day)	VER (%)	OLR (g COD/l.day)	Q_W (ml/day)	Aver. SRT (day)	Length of the Phases in each cycle (min)			
						Fill	*React*	*Settle*	*Effluent Withdr.*
1G	4	6.25	0.27	250	4	2	298	58	2
2G	4	6.25	0.27	90	8.7	2	298	58	2
3G	4	6.25	0.27	35	16.3	2	298	58	2
4G	4	6.25	0.27	18	27.3	2	298	58	2
5G	4	6.25	0.27	0	65.3	2	298	58	2
6G	1	25	1.07	1000	1	5	295	55	5
7G	1	25	1.07	350	1.7	5	295	55	5
8G	1	25	1.07	0	37	5	295	55	5
9G	0.5	50	2.14	100	2.6	10	285	55	10
10G	0.25	66.7	4.28	70	3.1	10	180	40	10
11G	0.25	66.7	4.28	0	2.9	10	180	40	10

Table 2. Operating parameters for the SBRs treating the ethanol wastewater.

Run	HRT (day)	VER (%)	OLR (gCOD/l.day)	Q_W (ml/day)	Aver. SRT (day)	Length of the Phases in each cycle (min)			
						Fill	*React*	*Settle*	*Effluent Withdr.*
1E	4	6.25	0.52	250	4	9	291	51	9
2E	4	6.25	0.52	90	8.2	2	298	58	2
3E	4	6.25	0.52	18	20.9	2	298	58	2
4E	4	6.25	0.52	0	70.8	2	298	58	2
5E	1	25	2.07	1000	1	5	295	55	5
6E	1	25	2.07	360	1.7	5	295	55	5
7E	1	25	2.07	0	5.1	35	265	25	35
8E	1	25	2.07	0	9.4	5	295	55	5
9E	0.5	50	4.14	60	4.9	10	315	25	10

At the start-up, 5 g of the well-sieved soil was mixed with 1 L of wastewater feed. The cycle was initiated with the settle phase, followed by effluent withdrawal. Then the first feed was introduced and reactor operation continued according to the programmed cycle pattern. The length of each run was at least 2 times the average SRT for the run, with a minimum of 25 days, and, in any cases, each run was operated until the substrate and biomass concentration and the SRT had reached steady state. At the end of each run, the reactor was cleaned and a new run was started with a fresh inoculum. Sampling was done three times per week. Biomass concentration and substrate concentration in the effluent were measured by sampling the reactors at the end of the reaction phase, while biomass concentration in the effluent was measured by sampling the collected effluents from the reactors.

3.4 Analytical methods

Biomass concentration was measured as volatile suspended solids (VSS) in accordance with Standard Methods (APHA, 1998), using a Whatman 1822 – 047 Grade GF/C glass fibre filter paper of 1.2 µm pore size. Ethanol concentration using gas chromatography (GC) using a Thermo Scientific Trace 1300 GC coupled to a Flame Ionisation Detector (FID). The GC column used was a TraceGold TG-WaxMS B GC column (30 m length). Glucose concentration was measured using the anthrone method. Prior to the glucose and ethanol analyses, samples were filtered through a Millet syringe filter of 0.45 µm pore size. Soluble COD in the effluent was also measured, after filtration, using COD cell test kits (Merck).

3.5 Data analysis

The biomass produced per unit volume of influent wastewater was calculated in each run from the steady-state values of the biomass concentration (X), HRT and SRT according to equation (10):

$$\text{Biomass produced}\left(\frac{\text{g biomass}}{\text{l influent wastewater}}\right)=\frac{\text{HRT}\cdot\text{X}}{\text{SRT}} \quad (10)$$

The oxygen consumption by the microorganisms was calculated in each run using the experimental data on biomass produced, influent (S_0) and effluent (S) COD concentrations and using the COD balance, according to equation (11):

$$\text{Oxygen consumed}\left(\frac{\text{g oxygen}}{\text{l influent wastewater}}\right)=\left(\text{S}_0-\text{S}\right)-\frac{\text{HRT}\cdot\text{X}}{\text{SRT}}1.42 \qquad (11)$$

where the factor 1.42 is the COD conversion factor for biomass, assuming its empirical formula is $C_5H_7O_2N$.

The fraction of the removed COD which was converted to biomass was calculated according to equation (12):

$$\text{Fraction of removed COD converted to biomass}=\frac{1.42\cdot\text{HRT}\cdot\text{X}}{\text{SRT}\cdot\left(\text{S}_0-\text{S}\right)} \quad (12)$$

The fraction of the removed COD which was oxidised was calculated from the COD balance as:

$$\begin{aligned}&\text{Fraction of removed COD which was oxidised}=\\&=1-\text{Fraction of removed COD converted to biomass}\end{aligned} \quad (13)$$

The kinetic parameters $Y_{X/S}$ and b were calculated by linearising the experimental data according to equation (8) in Section 2.

4. Results and Discussion

4.1. Minimum SRT for substrate removal

Since the SRT is the only (for continuous-flow systems) or the main (for SBR systems) parameter that determines the effluent substrate concentration, the first step was to determine how the glucose and ethanol removal were affected by the SRT (Figure 1). For both substrates the removal was virtually complete at high SRT and incomplete or very low at low SRT. The minimum SRT for high removal efficiency (assumed to be >90%) was in the range 2.5-3.0 days for glucose and 1.7 days for ethanol. For glucose it can be observed that the removal was complete in Run 9G, operated at an SRT of 2.6 days, while it was incomplete in run 11G, which had an average SRT of 2.9 days. These two values of the SRT are very similar and indicate that the performance of the process can be quite unstable if the SRT is close to its lowest limit for complete substrate removal. For ethanol, substrate removal was incomplete in run 7E, where the SRT was higher than in runs where complete or almost complete removal was observed (Runs 9E, 4E, 6E). The likely explanation for this behaviour is that in Run 7E the feed length was the longest among all the investigated runs. Long feed means lower average substrate concentration during the cycle and therefore lower average substrate removal rate, for the same value of the SRT (Dionisi et al., 2016).

The determination of the minimum SRT that is required for substrate removal is important because, as discussed in Section 2, the conditions of minimum reactor volume and minimum oxygen consumption are expected to be found at the lowest SRT. Considering literature studies where aerobic wastewater treatment was operated at low SRT, the minimum SRT which was successfully applied for the removal of organic carbon was 0.6 day (Bloor et al., 1995). That study was carried out on brewery wastewater at an unspecified temperature and achieved the highest reported OLR for aerobic processes, 52 kg COD/m^3.day, due to the very low SRT and the use of the jet loop reactor. Jimenez et al. (2015) obtained a COD removal of approximately 80% with SRT of 2 days. Ge et al. (2013, 2017) successfully operated aerobic treatment at SRT values in the range 1.5-3 day at 20-22 ^{O}C. For a synthetic glucose-based wastewater at thermophilic (58 ^{O}C) temperatures, the efficiency of COD removal was found to decrease for SRT lower than 2-3 days (Surucu et al., 1976), in agreement with the present study. In summary, while there is little literature study for the minimum SRT for ethanol as only carbon source, overall our data on the effect of SRT on process performance are in agreement with other literature studies and confirm the possibility of achieving high efficiencies of COD removal even at low values of the SRT. Since the minimum SRT has implications for the minimum HRT and maximum OLR and for the minimum oxygen consumption, further study will need to be dedicated to determine the minimum SRT for more complex wastewaters, which include slowly biodegradable substrates, and for nitrification/denitrification processes, when nitrogen removal is required.

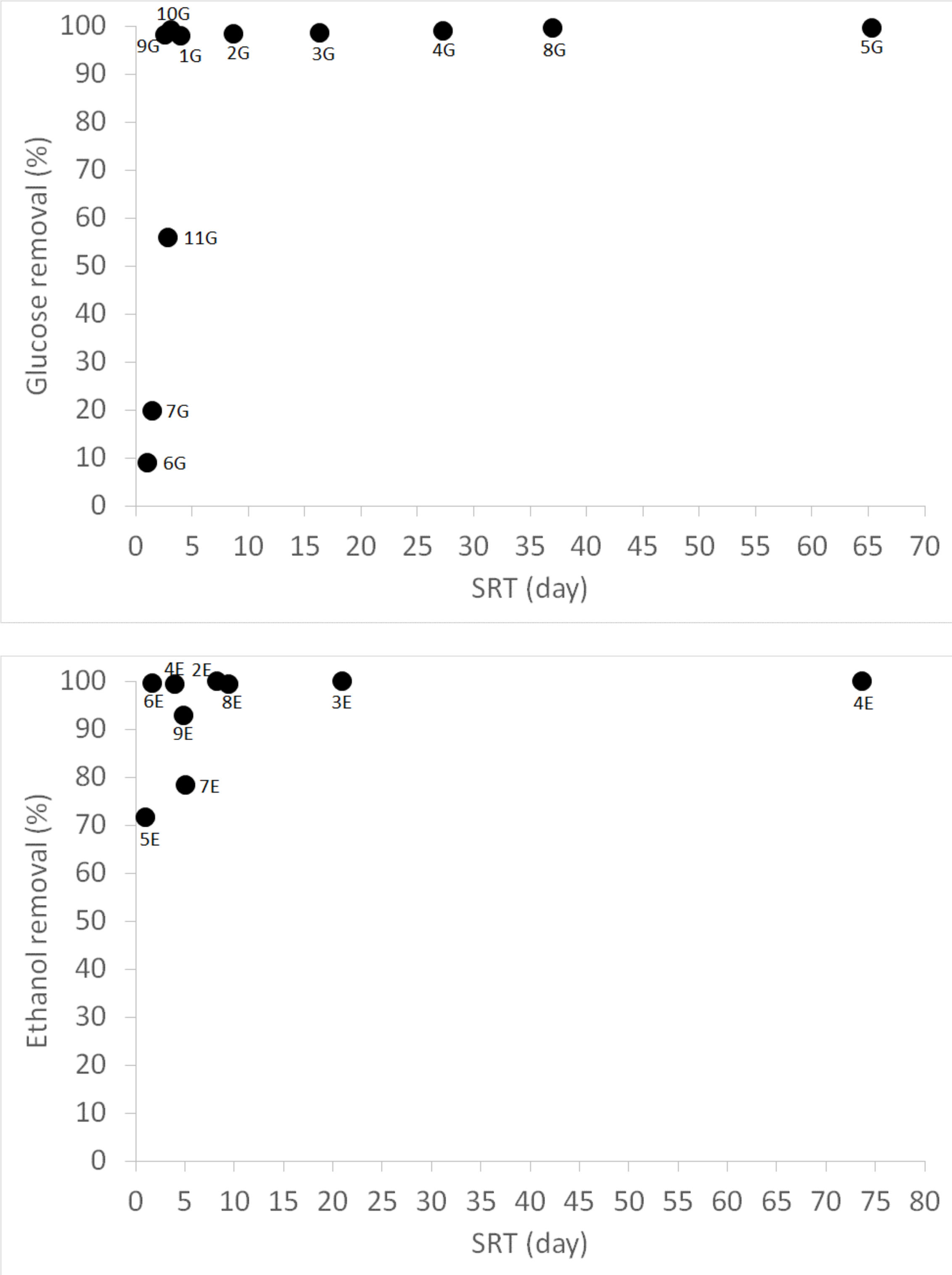


Figure 1. Effect of the SRT on the glucose (top) and ethanol (bottom) removal.

4.2. Maximisation of the OLR

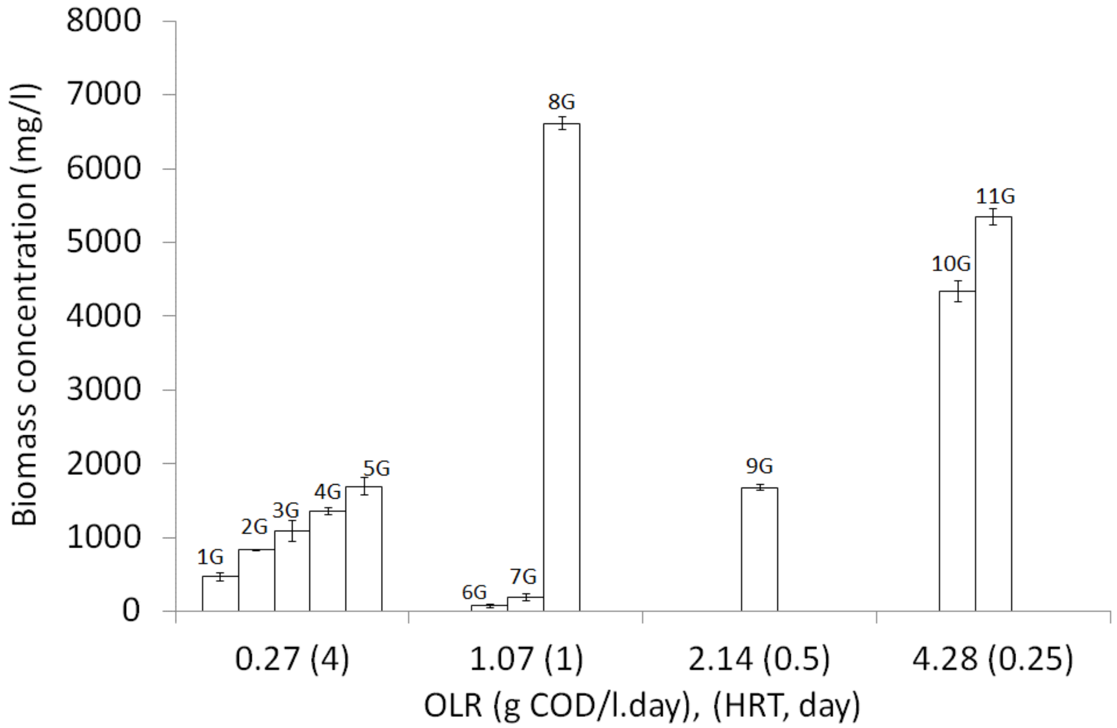
Figure 2 shows the effect of the HRT (or of the OLR, which is inversely proportional to the HRT) on the biomass concentration in the reactor. For a fixed HRT (or OLR), the biomass concentration is a function of the SRT, as expected, as shown, in the runs at 0.27 g COD/l.day for glucose and at 0.52 g COD/l.day for ethanol. As the OLR is increased (i.e. the HRT is decreased), the biomass concentration was kept within acceptable levels by decreasing the SRT. For example, in the glucose reactors the biomass concentration was very high, 6.9 g VSS/l, in Run 8G (OLR equal to 1.07 g COD/l.day and SRT 37 days) and the OLR could not have been increased further at the same SRT, otherwise the biomass concentration would have been too high and the settling rate would have been compromised. Therefore the runs at higher OLR (Runs 9G, 10G, 11G at OLR of 2.14 and 4.28 g COD/l.day) were carried out at lower SRT, in the range 2.6-3.1 days. This allowed obtaining lower biomass concentrations at high OLR than at low OLR, confirming what was expected according to the background theory in Section 2. The same effect was observed for ethanol. For example, thanks to their lower SRT, Runs 8E and 9E had lower biomass concentration in the reactor than Run 4E, in spite of their higher OLR.

The operation at high OLR can only be considered successful if the high OLR does not impact negatively on the settleability of the sludge, which in this study was measured by the biomass concentration in the effluent collected after the settling phase (Figure 3). In Figure 3, runs 1G, 6G, 1E, 5E are not reported because in those runs the SRT was set equal to the HRT and the effluent was collected from the completely mixed reactor, with no effluent collection after the settling phase. For the glucose runs, the biomass in the effluent was in the range 100-250 mg VSS/l for all the runs except Run

11G. The high solid losses in the effluent in Run 11G can be explained considering that in this run a high OLR was applied and no sludge withdrawal. In the absence or with low solid losses in the effluent, this would have caused a very high biomass concentration in the reactor with consequent very low settling velocity. Therefore, the high solid losses in the effluent were the reaction of the system to the high OLR with no sludge withdrawal and indicated that the process cannot be operated at high OLR without control of the SRT. In summary, as far as the maximisation of the OLR is concerned, the most successful run for the glucose reactor was Run 10G, where the high OLR of 4.28 g COD/l.day was maintained with complete substrate removal and with solid losses in the effluent which were similar to the other runs. For the ethanol runs, the solid losses in the effluent were always in the range 150-300 mg/l, indicating that the highest OLR could be maintained without a negative impact on this variable. Interestingly, the highest solid losses with the effluent were observed for Run 7E, where the feed length was the longest, therefore indicating that the long feed length has a negative effect on the settling properties. Indeed runs 6E, 7E, 8E were operated at the same OLR and HRT but the length of the Fill phase was considerably longer in run 7E (35 mins vs 5 mins in runs 6E and 8E). In SBRs, the shorter the feed length, the higher the substrate gradients in the system, and high substrate gradients are known to favour the development of well settling sludge (Dionisi et al., 2006a; Martin et al., 2003). For the ethanol runs it can be concluded that the run that gave the highest OLR with an acceptable performance was Run 9E, with a OLR of 4.14 g COD/l.day, over 90% substrate removal and acceptable solid losses in the effluent.

The maximum values of the OLR determined in this study, 4.28 and 4.14 g COD/l.day, are among the highest reported for aerobic suspended-growth conventional activated sludge processes (Table 3). In Table 3 we have not considered non-conventional processes, e.g. the air bubble or the jet loop reactor discussed in the Introduction, membrane reactors or granular sludge. However, it is important to observe that the high OLRs obtained in this study are in the range of values reported for membrane or granular reactors, e.g. Trussel et al. (2006) reported operation of membrane bioreactors in the OLR range 2.2-8.2 g COD/l.day, which are among the highest reported for MBRs, and Liu et al. (2005) operated granular-sludge reactors with OLRs of up to 4.0 g COD/l.day, even though granulation allowed the achievement of OLR as high as 15 g COD/l.day (Moy et al., 2002).

In summary, our experimental study has showed that the simultaneous optimisation of the HRT and SRT allows the operation of conventional suspended-growth processes at very high OLR, with consequent minimisation of the reactor volume and plant footprint.



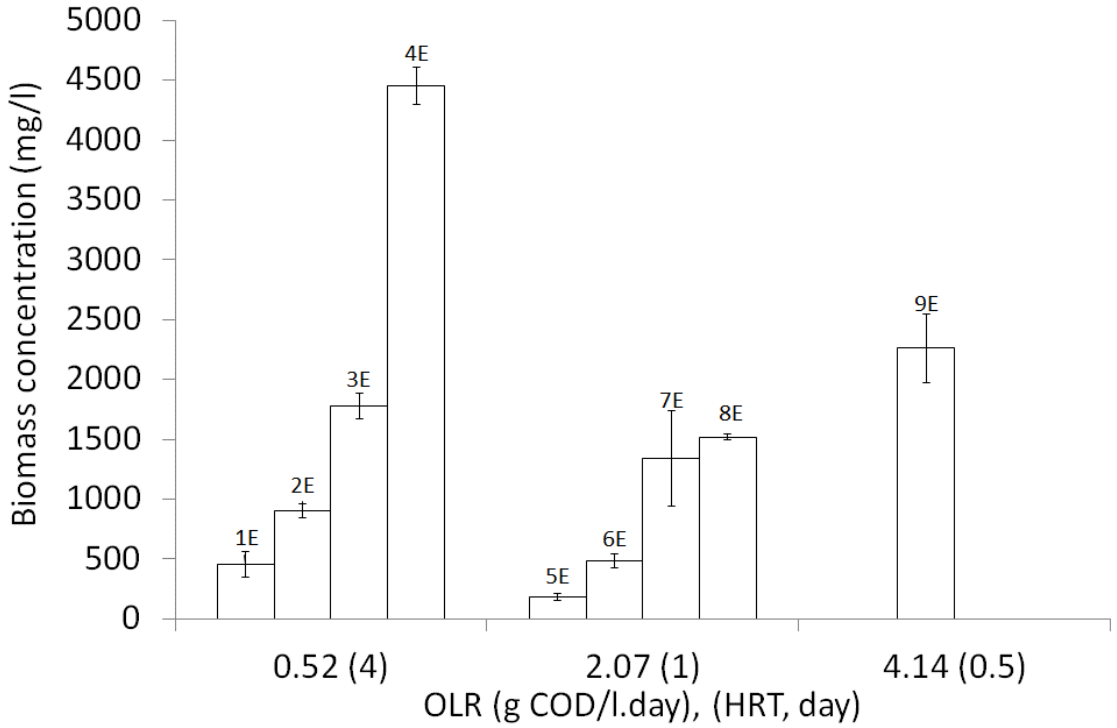
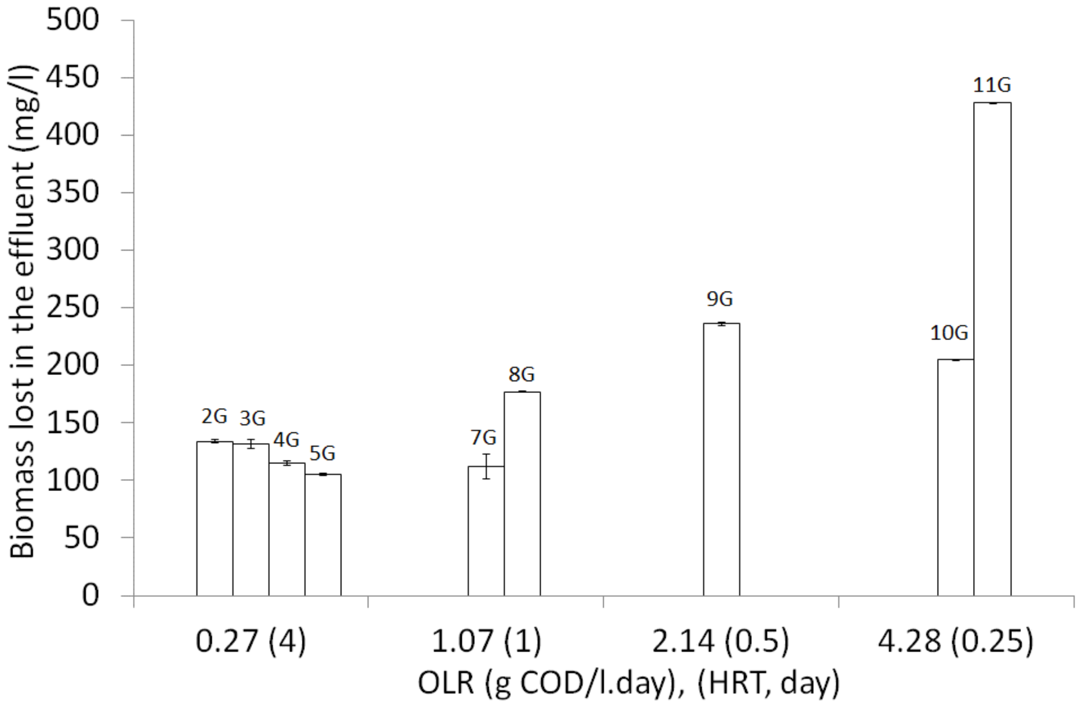


Figure 2. Biomass concentration at the end of the reaction phase for the glucose (up) and ethanol (bottom) reactors.



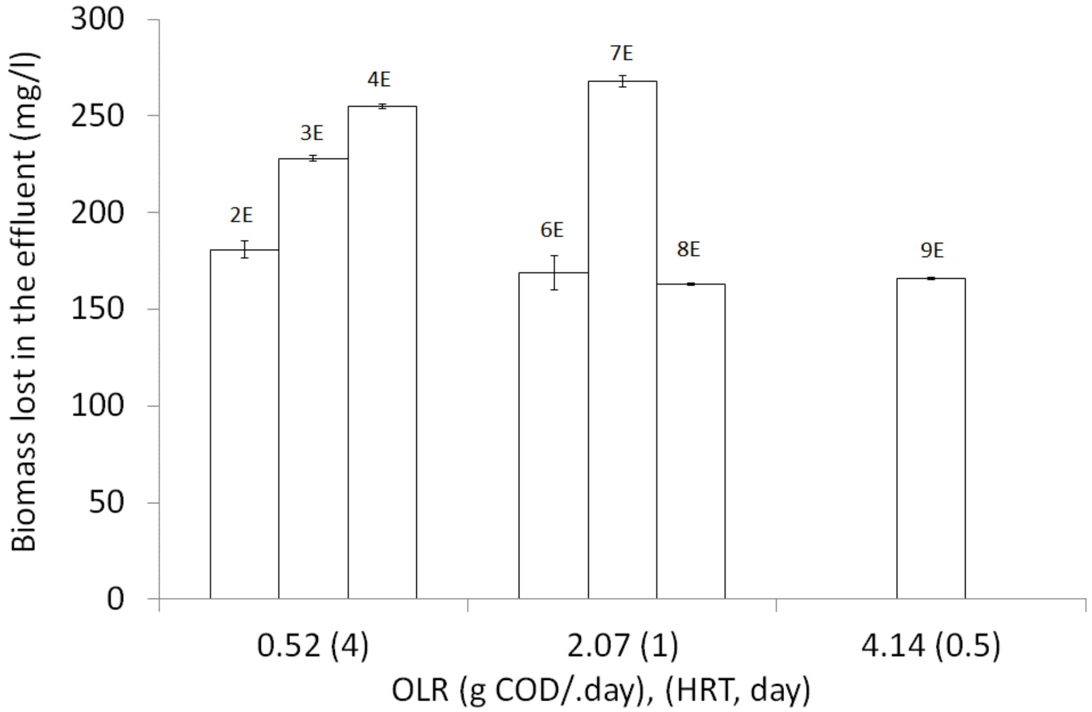


Figure 3. Biomass concentration in the effluent for the glucose (up) and ethanol (bottom) reactors.

Table 3. Aerobic studies carried out at high OLR with conventional suspended-growth activated sludge processes.

Reference	Wastewater	HRT (day)	SRT (day)	OLR (g COD/l.day)
Kanimozhi et al. (2014)	Anaerobically digested distillery	1.0	N.R.	3.6
Ge et al. (2013)	Slaughterhouse	0.5	2	5.8
Rodríguez et al. (2013)	Animal food factory	0.75	30	4.55
Yoong et al. (2000)	Phenol	0.42	4	3.12
This study (glucose)	Glucose	0.25	3.1	4.28
This study (ethanol)	Ethanol	0.5	4.9	4.14

4.3. Minimisation of oxygen consumption

In addition to the OLR, the optimum design of biological processes requires the minimisation of the oxygen consumption and the maximisation of the produced biomass, assuming that the produced biomass is used in anaerobic digesters for energy generation. Figure 4 shows the oxygen consumption and the produced biomass for the glucose and ethanol reactors. It is expected that the biomass produced and oxygen consumed (per unit volume of influent wastewater) only depend on the SRT (equations (6) and (7) in Section 2). However, both the glucose and ethanol runs indicate that, in disagreement with the theory, the OLR also affects the biomass and oxygen production. Indeed, for the glucose reactor Runs 1G-5G and 8G give the expected trend, while Runs 10G and 9G give lower biomass produced and higher oxygen consumption than the other runs, in spite of their lower SRT. Similarly for ethanol, Runs 1E-4E gave the expected trend, while Runs 6E, 9E and 8E gave lower biomass production (and hence higher oxygen consumption) in spite of having similar SRT as the other Runs. In general the results obtained with the two substrates indicate that at higher OLR the biomass production decreases for the same SRT, and this causes, from the COD balance, an increase in oxygen consumption. More insight into biomass production and oxygen consumption is shown in Figure 5, which shows the fraction of the removed COD which is converted into biomass or oxygen in the various runs. The trend is the same as reported in Figure 4, however Figure 5 highlights an important difference between glucose and ethanol. For glucose, the minimum value of the fraction of oxidised COD is 36% (Run 1G), while for ethanol it is 69% (Run 1E) and in general the fraction of oxidised COD, i.e. the oxygen consumption by the microorganisms, is significantly larger for glucose than for ethanol. In general, the results of this study indicate that, at least for the wastewaters considered here, the operating parameters that give the maximum organic load are not the same that give the minimum oxygen consumption. If minimising oxygen consumption is the priority, the operating conditions of Runs 1G and 1E, low OLR and low SRT, are to be preferred while if the minimisation of reactor volume is the priority, the conditions of Runs 10G and 9E, high OLR and low SRT, have to be chosen.

The obtained data were analysed to calculate the kinetic parameters $Y_{X/S}$ and b (Figure 6). For the glucose runs, Runs 1G-5G and 8G were considered, while Runs 9G and 10G were excluded, because of their deviation from the theory. For the ethanol runs, two plots were generated, one for the runs at lower OLR and one for the runs at higher OLR. For glucose, the obtained values of the parameters were $Y_{X/S}$ = 0.60 g biomass/g COD and b = 0.08 day^{-1}. For the ethanol runs we obtained, at higher OLR, $Y_{X/S}$ = 0.18 g biomass/g COD, b = 0.13 day^{-1}, and, at low OLR, $Y_{X/S}$ = 0.23 g biomass/g COD and b = 0.01 day^{-1}.

The lowest oxygen consumption found in this study, 0.36 kg O_2/kg COD removed, is among the lowest reported in the literature for aerobic processes. Surucu et al. (1976)

reported an oxygen consumption of approximately 0.65 kg O_2/kg COD removed at a SRT of 2 day. Ge et al. (2013, 2017) obtained an oxygen consumption of 0.15-0.3 kg O_2/kg removed COD at SRT values of 2-3 day and Jimenez et al. (2015) reported oxygen consumptions in the range 0.2-0.5 kg O2/kg COD in the SRT rage 0.1-2 days. When studies are carried out at larger SRT, much larger oxygen consumptions are observed, e.g. Ouyang and Junxin (2009) observed over 0.70 kg O_2 consumed/kg COD for SRT of 10 day.

The decrease in observed yield which we observed at higher OLR has important consequences for the design of biological wastewater treatment processes. From the point of view of maximising the OLR, it can be considered an advantage, because it means that the biomass concentration does not increase linearly as the OLR is increased, for a fixed SRT. This means, in turn, that higher OLR values are possible than what is possible to estimate based on the biomass concentrations obtained at low OLR values. However, from the point of view of the simultaneous minimisation of reactor volume and oxygen consumption, the decrease in observed yield as the OLR increases is a disadvantage. Indeed, our study shows that the runs with the highest OLR and lowest SRT are not the ones which give the lowest oxygen consumption. This is not in agreement with the theory reported in Section 2, however, a decrease in observed yield at higher OLR has already been reported by Dionisi et al. (2006b). Our kinetic analysis for the ethanol runs shows that the reason for the lower biomass production and higher oxygen consumption observed at high OLR is mainly the fact that at high OLR the microbial kinetics is described by a larger value of the endogenous metabolism coefficient *b*. Indeed, for ethanol the parameter b was 0.13 day^{-1} at higher OLR and 0.01 day^{-1} at lower OLR, while the parameter $Y_{X/S}$ was only slightly different (0.18 vs

0.23 g biomass/ g COD) at higher and lower OLR. It remains to be investigated whether this effect of the OLR on the rate of endogenous metabolism is specific for the wastewaters considered here or is more general. If it is general, then conventional models for biological wastewater treatment processes will need to be modified, e.g. by using different values of the endogenous metabolism parameter at different values of the OLR. The kinetic analysis also shows that the reason for the higher biomass production and lower oxygen consumption for glucose than for ethanol is in the higher growth yield ($Y_{X/S}$=0.60 g biomass/g COD for glucose, $Y_{X/S}$=0.18-0.23 g biomass/g COD for ethanol).

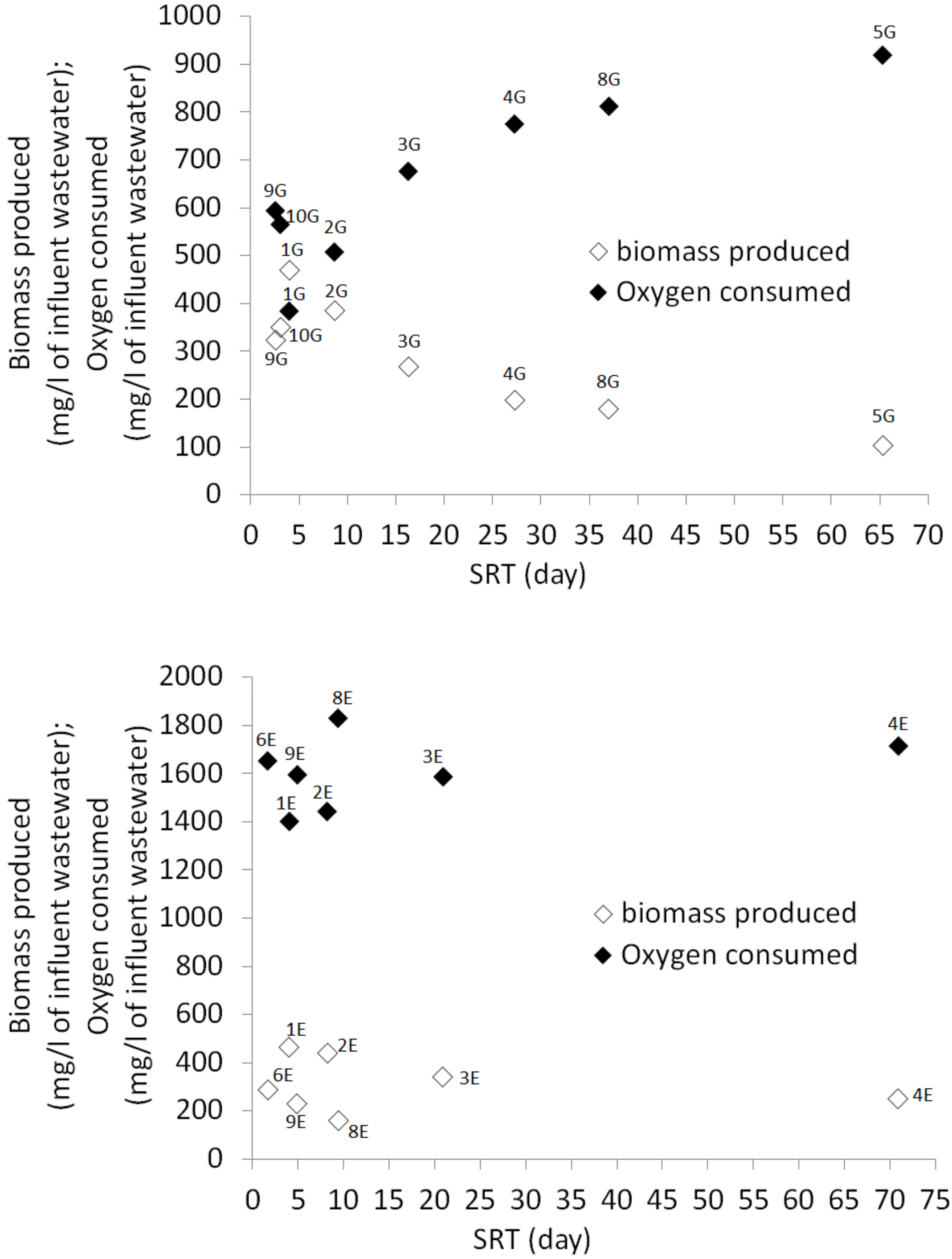


Figure 4. Biomass produced and oxygen consumed for the glucose (top) and ethanol runs (bottom).

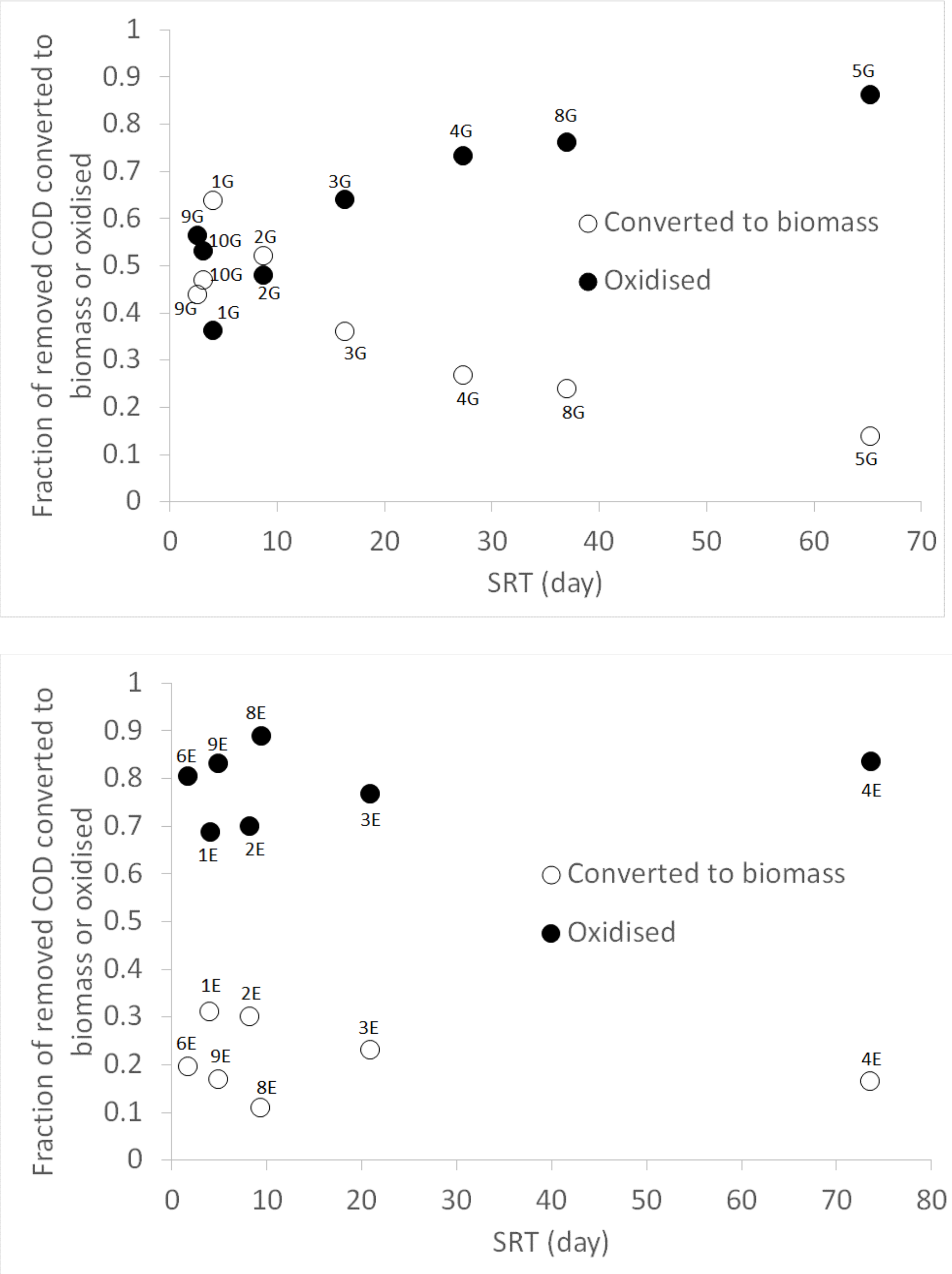


Figure 5. Distribution of the removed COD between oxidised and converted to biomass for the glucose (top) and ethanol (bottom) runs.

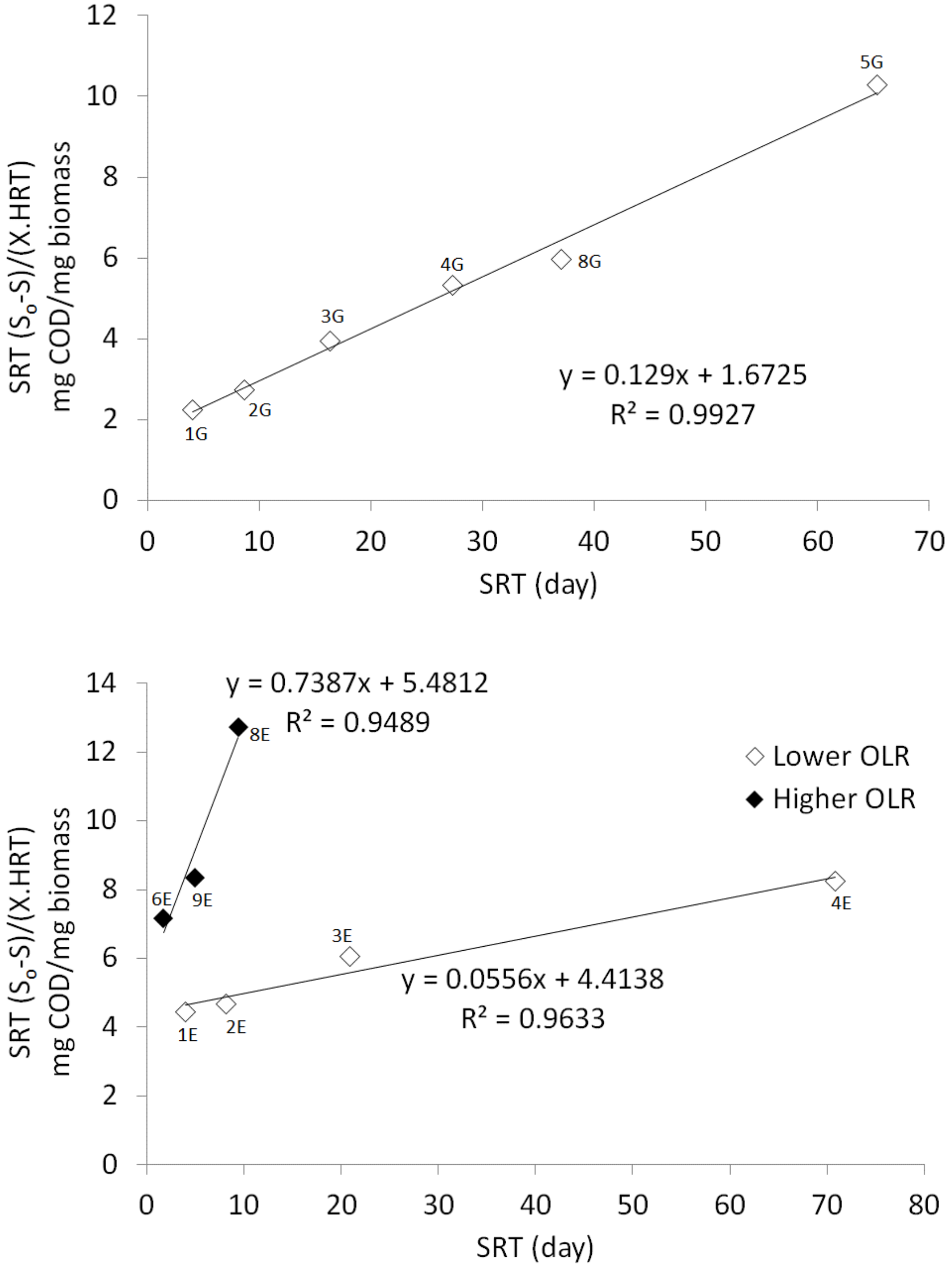


Figure 6. Linearisation of the experimental data for the calculation of the kinetic parameters $Y_{X/S}$ and *b.* Glucose (top) and ethanol (bottom) runs.

4. Conclusion

This study has shown that it is possible to operate conventional suspended-growth aerobic processes at high OLR, up to 4.28 g COD/l.day, by simultaneous optimisation of the HRT and SRT. The operating conditions which gave the highest OLR, and therefore the minimum reactor volume, were HRT=0.25 day and SRT=3.1 day for the glucose wastewater and HRT=0.5 day and SRT=4.9 day for the ethanol wastewater.

The values of the HRT and SRT that gave the minimum oxygen consumption were not the same that gave the highest OLR. The minimum oxygen consumption was obtained at HRT=SRT=4 day for both glucose and ethanol. The oxygen consumption per unit of COD removed was higher for ethanol than for glucose. The minimum oxygen consumption was 0.36 and 0.69 kg O_2/kg COD removed for glucose and ethanol respectively.

In disagreement with the conventional theory, biomass production and oxygen consumption per unit of removed substrate were observed to depend on the OLR as well as on the SRT. Biomass production decreased and oxygen consumption increased at higher OLR. This behaviour has important consequences for the design of biological wastewater treatment processes and will need to be investigated further with wastewaters of different composition.

Overall this study has shown the importance of optimising the SRT and HRT to achieve the optimum performance of the process. Further study is needed for wastewaters of different and more complex composition and for nitrification/denitrification processes for nitrogen removal.

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