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Effect of Fill Time on the Performance of Pilot-scale ASBR and AnSBBR Applied to Sanitary Wastewater Treatment

Luciano Farias de Novaes · Lucas Oliveira Borges · José Alberto Domingues Rodrigues · Suzana Maria Ratusznei · Marcelo Zaiat · Eugenio Foresti

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Abstract Many lab-scale studies have been carried out regarding the effect of feed strategy on the performance of anaerobic sequencing batch reactors (ASBR); however, more detailed pilot-scale studies should be performed to assess the real applicability of this type of operation. Therefore, the objective of this work was to assess the effect of feed strategy or fill time in a 1-m^3 mechanically stirred pilot-scale sequencing batch reactor, treating 0.65 m^3 sanitary wastewater in 8-h cycles at ambient temperature. Two reactor configurations were used: one containing granular biomass (denominated ASBR) and the other immobilized biomass on polyurethane foam as inert support (denominated anaerobic sequencing batch biofilm reactor (AnSBBR)). The reactors were operated under five distinct feed strategies, namely: typical batch and fed-batch for 25%, 50%, 75%, and 100% of the cycle length. Stirring frequency in the ASBR was 40 rpm with two flat-blade turbine impellers and 80 rpm in the AnSBBR with two helix impellers. The results showed that both the ASBR and AnSBBR when operated under typical batch, fed-batch for 50% and 75% of the cycle length, presented improved organic matter removal efficiencies, without significant differences in performance, thus showing important operational flexibility. In addition, the reactors presented operation stability under all conditions.

Keywords ASBR · AnSBBR · Fill time · Mechanical stirring · Anaerobic reactor · Sanitary wastewater

Nomenclature

BA	Bicarbonate alkalinity, mgCaCO$_3$.L^{-1}
C_S	Organic matter concentration in the reactor measured along profiles, mgCOD.L^{-1}

J. A. D. Rodrigues (✉) · S. M. Ratusznei
Escola de Engenharia Mauá, Instituto Mauá de Tecnologia (EEM/IMT), Praça Mauá 1, CEP 09.580-900, São Caetano do Sul, SP, Brazil
e-mail: rodrigues@maua.br

L. F. de Novaes · L. O. Borges · M. Zaiat · E. Foresti
Departamento de Hidráulica e Saneamento, Escola de Engenharia de São Carlos, Universidade de São Paulo (SHS/EESC/USP), Av. Trabalhador São-Carlense 400, CEP 13.566-590, São Carlos, SP, Brazil

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C_{S0}	Initial organic matter concentration in the reactor measured along profiles, mgCOD.L^{-1}
C_{SF}	Organic matter concentration for filtered samples, mgCOD.L^{-1}
C_{SI}	Organic matter concentration in the feed for unfiltered samples, mgCOD.L^{-1}
C_{SR}	Residual filtered organic matter concentration measured along profiles, mgCOD.L^{-1}
C_{ST}	Organic matter concentration for unfiltered samples, mgCOD.L^{-1}
$C_{X\text{-}TS}$	Concentration of biomass in the reactor in terms of total volatile solids, kgTS.m^{-3} (ASBR) or kgTS.kg-support^{-1} (AnSBBR)
$C_{X\text{-}TVS}$	Concentration of biomass in the reactor in terms of total volatile solids, kgTVS.m^{-3} (ASBR) or kgTVS.kg-support^{-1} (AnSBBR)
k_1	First order apparent kinetic constant, h^{-1}
N	Agitator speed, rpm
P_W	Power of 3-hp reduction motor (P_W) with capacity of 250 rpm, vertical shaft and impellers to promote mixing, and a frequency inverter to enable control of the required rotations
Q_{feed}	Feed flow rate, L.h^{-1}
t	Cycle time, min or h
T	Temperature of the liquid medium inside the reactors, °C
$t_{biomass}$	Time for the wastewater to reach the biomass contained in a stainless steel basket distanced 15 cm from the AnSBBR bottom, min or h
t_C	Total cycle time, min or h
t_F	Fill time, min or h
$t_{impeller}$	Time for the wastewater to reach the impeller distanced 33 cm from the AnSBBR bottom, min or h
TS	Total solids, mg.L^{-1}
TSS	Total suspended solids, mg.L^{-1}
TVA	Total volatile acids, mgHAc.L^{-1}
TVS	Total volatile solids, mg.L^{-1}
V	Volume of wastewater in the reactor, L
VSS	Volatile suspended solids, mg.L^{-1}
ε_{SF}	Organic matter removal efficiency for filtered samples, %
ε_{ST}	Organic matter removal efficiency for unfiltered samples, %

Introduction

The main feature in an anaerobic sequencing batch reactor (ASBR) is to charge it with wastewater at the start and discharge it at the end of the treatment, repeating this operation at each new batch. However, by varying the fill time, the system can be operated in a typical batch mode when fill time is very short in relation to total cycle length or in fed-batch mode when the feed stage is significant in relation to total cycle length. The need to increase fill time usually arises from a reduced availability of wastewater. This reduced availability results in lower substrate concentrations in the reactor over the course of the entire cycle, leading to lower average reaction rate compared to that obtained in a typical batch mode and may reduce overall process efficiency. Employing longer fill times results in lower volatile acids concentrations, conferring increased system stability and flexibility [1].

Fill time is therefore an operational parameter related to the substrate/microorganism ratio as well as a design parameter, as it defines the number of reactors to be used in the operation. The effect of feed strategy from the relation between fill time (t_F) and cycle time

(t_C) on reactor performance is therefore of great interest. The feed strategy in sequencing batch reactors was investigated by Shizas and Bagley [2] who assessed the effect of t_F/t_C ratio on the performance of five lab-scale reactors applied to the treatment of synthetic wastewater. They verified the following: for a constant cycle length, the increase in t_F/t_C ratio resulted in increased filtered organic matter removal; for constant t_F/t_C ratio, the increase in cycle length resulted in increase in filtered organic matter removal efficiency; and reactor performance was more affected by cycle length than by the t_F/t_C ratio.

In another investigation related to the effect of feed strategy on the performance of an ASBR, Ratusznei et al. [3] assessed a 2.5-L reactor containing immobilized biomass on polyurethane foam in the treatment of synthetic wastewater (500 mg.COD.L^{-1}), with cycle length of 180 min under the following conditions: batch with 3-min fill time and fed-batch followed by batch with fill time of 30, 60, and 180 min. The authors noticed that under fed-batch conditions system efficiency dropped, especially for longer fill times; this decrease was caused by the exposure to air of the biomass without liquid during the fill period. Regarding the same topic, Borges et al. [4] assessed the effect of the fill stage on the behavior of a fed-batch operated mechanically stirred anaerobic sequencing reactor (6.3 L) containing immobilized biomass on polyurethane foam, treating synthetic wastewater (500 mg COD L^{-1}) with 8-h cycle length (t_C). Of the total volume of wastewater fed per cycle, 60% was fed at the beginning of each cycle, sufficient to completely cover the bed, and the remaining volume was added at different fill times (t_F). The authors concluded the following: at $t_F/t_C \leq 0.5$, the system attained organic matter removal efficiency exceeding 75% and 70% for filtered and unfiltered samples, respectively; and at $t_F/t_C > 0.5$, efficiency dropped despite system stability.

Within this context, several studies have been carried out regarding the effect of feed strategy on the performance of lab-scale ASBRs [2, 5–13]; however, more in-depth pilot-scale studies are required to assess the real applicability of this type of operation in the treatment of wastewater.

Therefore, in the present work, an assessment was made of the effect of feed strategy or fill time on the performance of a mechanically stirred pilot-scale ASBR treating sanitary wastewater. Two reactor configurations have been assessed: one containing granular biomass (ASBR) and the other immobilized biomass on polyurethane foam (anaerobic sequencing batch biofilm reactor (AnSBBR)), employing different fill times: typical batch, fed-batch (25%, 50%, and 75% of total cycle length) followed by batch (remaining cycle length) and totally fed-batch (100% of cycle length).

Materials and Methods

Experimental Set-up

Two mechanically stirred ASBRs, made of polyethylene, were used in the experiments: (a) a reactor containing granulated biomass (ASBR) and (b) a reactor containing immobilized biomass (AnSBBR). The construction characteristics of the ASBR and AnSBBR are shown in Fig. 1 and Tables 1 and 2.

The support used to immobilize the biomass in the AnSBBR consisted of 5-cm polyurethane foam cubes. This support was confined in a 1.20-m high cylindrical basket, made of stainless steel 304 perforated sheet with 1.5-cm holes, surrounding the impeller shaft. The distance between the shaft and the inner wall of the basket was 3.5 cm. The basket was divided into four 30-cm compartments to avoid compacting of the foam

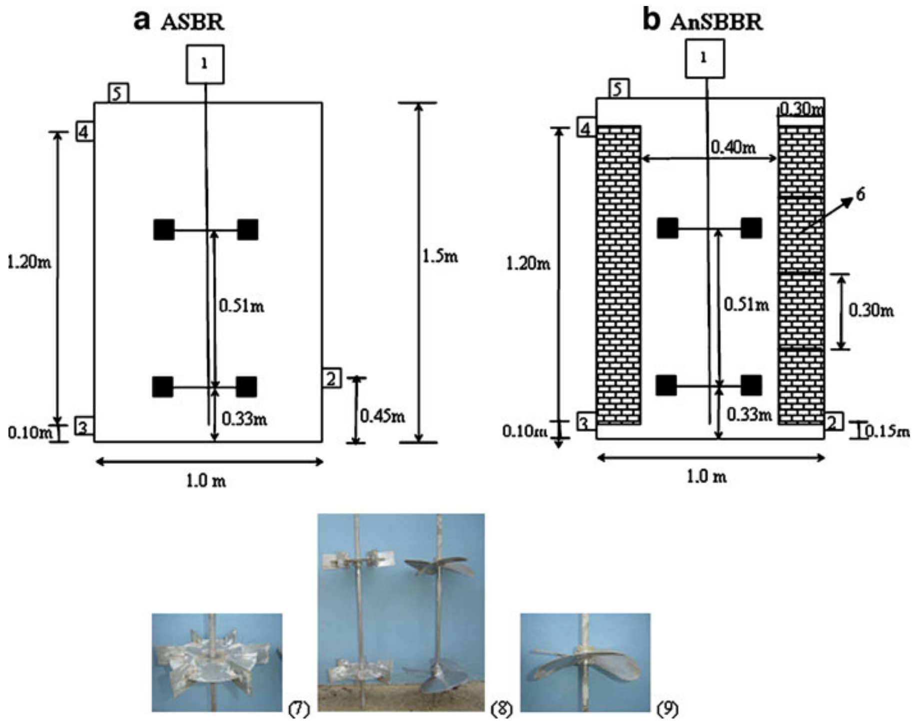

Fig. 1 Configuration of the (**a**) anaerobic sequencing batch reactor (ASBR) and (**b**) anaerobic sequencing batch biofilm reactor (AnSBBR). *1* Mechanical stirring system with adjustable-speed motor and impeller, (*2*) discharge valve, (*3*) feed valve, (*4*) overflow pipe, (*5*) gas outlet, (*6*) basket with immobilized biomass, (*7* and *8*) flat-blade turbine impeller used in ASBR, (*9* and *8*) helix impeller used in AnSBBR

particles. The ASBR was equipped with four stainless steel baffle plates (10 cm wide and distance of 90° between one another) to increase turbulence and consequently improve contact between the substrate and microorganisms.

Reactor feeding was accomplished by means of centrifugal pumps. Discharge was accomplished by gravity using a solenoid valve at the lower side of the reactor. A 3-hp

Table 1 Construction details of the anaerobic sequencing batch biofilm reactor and the anaerobic sequencing batch reactor.

Configuration	AnSBBR	ASBR
Total volume (m^3)	1.18	1.18
Work volume (m^3)	1.00	1.00
Sludge volume (m^3)	–	0.35
Inert support+immobilized sludge volume (m^3)	0.35	–
Support material volume (kg; density 23 $kg.m^{-3}$)	0.30	–
Support material mass (kg)	7.0	–
Liquid volume (m^3)	0.65	0.65
Gas volume (m^3)	0.18	0.18
Height (m)	1.50	1.50
Diameter (m)	1.00	1.00

Table 2 Construction parameters of the impellers.

Impeller type	Li/Di	hi/Di	Dr/Di	Hi/Di	Dr/Hi	*n*	Di (cm)
Flat-blade turbine	0.25	0.20	3	1	3	6	33
Helix impeller (pitch = 1)	–	–	3	1	3	3	33

Li blade length, *Di* impeller diameter, *hi* height of impeller blade, *Dr* reactor diameter, *Hi* clearance between impeller and reactor base, *n* number of blades.

reduction motor (P_W) was installed with capacity of 250 rpm, vertical shaft and impellers to promote mixing, and a frequency inverter to enable control of the required rotations. Floating buoys were installed in the reactor to control the liquid level. An automatic timer system was used for switching on and off the following equipment: feeding pumps, solenoid valves (used for discharge), and agitation system (reduction motor unit).

The impellers used in this study were (Fig. 1) (1) six-vertical-flat-blade turbine impeller in the ASBR and (2) three-blade helix impeller in the AnSBBR. Two impellers of the same type were installed in each reactor. All impellers were made of 2-mm thick stainless steel 304 sheet. Construction details of the impellers are shown in Fig. 1 and Table 2; dimensions are based on those used in another work [14].

Inoculum and Biomass Immobilization Procedure

Both reactors (ASBBR and AnSBBR) were inoculated with sludge from an up-flow anaerobic sludge blanket reactor treating wastewater from a poultry slaughterhouse. This inoculum presented total volatile solids (TVS) and total solids (TS) of 51 and 62 g/L, respectively.

The immobilization procedure for the AnSBBR consisted of crushing the sludge in a mixer, completely immersing the foam (inert support) with the obtained suspension, followed by homogenization and 2-h rest [15]. Poorly adhered solids were washed off and the medium drained. The inert support used consisted of 5-cm polyurethane foam cubes with apparent density of 23 $kg.m^{-3}$ and porosity of 95%. One of the main advantages of using polyurethane foam is related to its high porosity, which allows immobilization of a significant amount of biomass that will not become detached during the charge, discharge, and reaction stages in the reactor.

Wastewater

The wastewater used was sanitary wastewater from the Campus of the Universidade de São Paulo in São Carlos (São Paulo, Brazil).

Physical–chemical Analyses

The reactor was monitored by taking influent and effluent samples and measuring organic matter concentration as chemical oxygen demand (COD) for unfiltered (C_{ST}) and filtered samples (C_{SF}), bicarbonate alkalinity (BA), total volatile acids (TVA), TS, TVS, total suspended solids, and volatile suspended solids, as well as pH. These parameters were monitored at least three times a week. The analyses of the parameters were in accordance with *Standard Methods for the Examination of Water and Wastewater* [16].

After attaining operation stability, i.e., as soon as the monitored parameters remained constant in the effluent, samples were taken over the course of the cycle time to obtain profiles of the following variables: organic matter concentration for unfiltered and filtered samples, partial alkalinity, intermediate alkalinity, total alkalinity, BA, TVA, as well as pH and temperature.

At the end of each condition, in the AnSBBR, the amount of biomass adhered to the inert support medium was quantified. To this end, polyurethane foam was collected from the center of the reactor and cut into eight parts; each part was washed with distilled water, and the wash water was collected in porcelain capsules after which it was possible to calculate values of TS and TVS per gram of foam contained in the reactor, obtaining the amount and concentration of biomass in the reactor ($C_{\text{X-TVS}}$ and $C_{\text{X-TVS}}$). The solids adhered to the polyurethane foam were determined by removing the biomass with distilled water from approximately four cubes of the support. The washed foam cubes were then dried at 105 °C for 24 h to determine the dry weight.

The granulated biomass present in the ASBR was quantified in terms of TS and TVS collecting a sample of 100 mL mixed liquor when the agitation was turned on to obtain a representative quantification, obtaining the amount and concentration of biomass in the reactor ($C_{\text{X-TVS}}$ and $C_{\text{X-TVS}}$).

Both procedures were performed according to *Standard Methods for the Examination of Water and Wastewater* [16].

Reactor Operation

The reactors were operated at ambient temperature in 8-h cycles, i.e., three cycles a day. At the beginning of the cycle, the reactors were fed with 0.65 m^3 sanitary wastewater each, within approximately 30 min. Feed time and feed flow rate were equal for both reactors and therefore presented the same influent. Next, agitation was started at a fixed rate (40 rpm in the ASBR and 80 rpm in the AnSBBR). Discharge was also carried out in approximately 30 min, after which a new cycle started.

Agitation and impeller types were determined in a previous work [17], in which it was concluded that the condition presenting the best performance for the ASBR was utilization of two flat-blade turbine impellers and agitation rate of 40 rpm and for the AnSBBR, the condition presenting the best performance was utilization of two helix impellers and agitation rate of 80 rpm.

Duration of the react step was different for the two configurations. In the ASBR, react was 6 h, followed by 1 h settling during which agitation was interrupted (0.5 h for feed, 0.5 h for withdrawal, 1 h for sedimentation, and 6 h for react step). It should be mentioned that the 1-m^3 volume in the ASBR consisted of 0.35 m^3 mixed liquor which remained in the reactor after settling and 0.65 m^3 fed/discharged (i.e., treated) wastewater per operational cycle. In the AnSBBR, the react step lasted 7 h since there was no need for settling (0.5 h for feed step, 0.5 h for withdrawal, and 7 h for the react step). The volume in the AnSBBR of 1 m^3 consisted of 0.35 m^3 polyurethane foam and adhered biomass, which remained in the reactor, and 0.65 m^3 fed/discharged (i.e., treated) wastewater per operational cycle.

It should be mentioned that the 1-h settling period used in the ASBR had been previously defined in a settling experiment in an acrylic vessel (square section of 25 cm). In this experiment, the behavior of a mixture of influent wastewater and sludge was visually accompanied. A period of 1 h showed to be ideal for the settling of 45 cm solids, corresponding to the height of the solids discharged from the reactor. At longer times, the biomass tended to float, and part of it remained in the supernatant of the reactor.

Reactor Operation-Fed-Batch

At this stage, the reactors were operated analogously to a typical batch system regarding settling (ASBR), agitation, and discharge (ASBR and AnSBBR); however, feed strategy was modified, and consequently, the react step. Total cycle length was 8 h.

In this way, four feed strategies were assessed, i.e., the reactor was operated employing different fill times (t_F): (1) feeding during 25% of the cycle, i.e., fed-batch during 25% of total cycle length and batch during the remaining cycle length; (2) feeding during 50% of the cycle, i.e., half of the total cycle length in fed-batch and the other half in batch; (3) feeding during 75% of the cycle; and (4) feeding during 100% of the cycle, i.e., typical fed-batch.

The fill of the ASBR and AnSBBR were different for a same feed strategy condition, because fill time was calculated from a relation with the reaction stage, i.e., the difference between total cycle length and settling time (in the case of ASBR only) and discharge time (ASBR and AnSBBR). So, since the ASBR required 1 h settling and since fill time (t_F) is a percentage of the possible feeding time, distinct values of fill time have been obtained for the two configurations (ASBR and AnSBBR). Table 3 contains the fill time (t_F) for the ASBR and AnSBBR for the four assessed feed strategies.

Since the biomass in the reactor AnSBBR was contained in a stainless steel basket 15 cm from the reactor bottom, at a certain fill time, denominated $t_{biomass}$, the water level did not reach the biomass, and at a much longer time, the impeller, denominated $t_{impeller}$, as the distance between impeller and reactor bottom was 33 cm. Since feed flow rate for the four feed strategies were different, $t_{biomass}$ and $t_{impeller}$ were assessed for each condition. Table 3 contains feed flow rate (Q_{feed}), total fill time (t_F), time for the water level to reach the biomass ($t_{biomass}$), and time for the water level to reach the impeller ($_{impeller}$) in the AnSBBR for the four assessed feed strategies.

Composite influent samples were obtained during fed-batch, i.e., for each feed strategy, four points were monitored as follows: at time zero (0), at time corresponding to 30%, 60%, and 90% of total fill time. For instance, for the condition: fed-batch during 25% of the cycle in the ASBR reactor, where total fill time was 98 min, influent samples were monitored at the following times: 0, 29.4, 58.8, and 88.2 min.

Table 3 Feed flow rate (Q_{feed}), fill time (t_F), time for the feed to reach the biomass in the anaerobic sequencing batch biofilm reactor (AnSBBR; $t_{biomass}$), and time for the feed to reach the impeller ($t_{impeller}$) in the AnSBBR.

Reactor		Fed-batch during			
		25%	50%	75%	100%
ASBR	Q_{feed} (L.min^{-1})	6.63	3.33	2.22	1.67
	t_F (min)	98.0	195.0	293.0	390.0
	$t_{biomass}$ (min)	–	–	–	–
	$t_{impeller}$ (min)	–	–	–	–
AnSBBR	Q_{feed} (L.min^{-1})	5.78	2.89	1.93	1.44
	t_F (min)	112.5	225.0	337.5	450.0
	$t_{biomass}$ (min)	20.4	40.0	60.0	82.0
	$t_{impeller}$ (min)	33.0	66.0	100.0	134.0

Kinetic Study

For each operational condition, a first order kinetic model was fitted to the experimental data of the filtered organic matter concentration profiles. The residual filtered organic matter concentration (C_{SR}) was also taken into account, i.e., organic matter concentration in the reactor at which reactor rate is zero.

The model of a typical batch process is given by Eq. 1, where C_S is the filtered organic matter concentration in the reactor, C_{S0} is the filtered organic matter concentration in the reactor at the beginning of the cycle, k_1 is the apparent first order kinetic constant, t is the time over the course of the cycle, and C_{SR} is the residual filtered organic matter concentration. This model (Eq. 1) was obtained from the mass balance of a batch reactor, i.e., when fill and discharge times can be neglected. Parameters were obtained by fitting a non-linear algebraic equation using the Levenberg–Marquardt method through Microcal Origin 6.1® software [18].

$$C_S = C_{SR} + (C_{S0} - C_{SR}).\exp(-k_1 \cdot t) \tag{1}$$

For the fed-batch conditions, the mass balance is different from that used for a typical batch, because the fill time cannot be neglected when compared to total cycle length. Variation in reactor volume with fill time should also be considered. So, from the mass balance for the system operated in fed-batch mode, the model presented in Eqs. 2 and 3 was obtained, where Q_{feed} is feed flow rate, C_{SI} is organic matter concentration in the feed, and the remaining variables are the same as those of a typical batch. The parameters were obtained by fitting an ordinary non-linear differential equation using fourth order Runge–Kutta method and constant step for integrating and by the Marquardt method to determine the parameters in numeric routines implemented in Excel® [18, 19].

$$\frac{dC_S}{dt} = \frac{Q}{V} \cdot (C_{SiI} - C_S) - k_1 \cdot (C_S - C_{SR}) \tag{2}$$

$$\frac{dV}{dt} = Q \tag{3}$$

Results and Discussion

AnSBBR

Table 4 contains average values of the monitored variables during AnSBBR operation at the five feed strategies. These average values correspond to the assays performed over the course of 21 days for each operational condition. It can be seen that for all operation conditions, effluent pH did not vary significantly and remained within the optimum stability range for methane formation. It can also be seen that on average, BA was produced and volatile acids concentration decreased in relation to the influent, evidencing system stability for all assessed operation conditions. The organic matter concentration in the influent presented considerable standard deviation. In addition, solids concentration in the influent was high and presented also high standard deviation, evidencing unsatisfactory performance of the system in solids removal.

Table 4 Mean values (nine samples for each condition) of the monitored variables during operation of the anaerobic sequencing batch biofilm reactor and anaerobic sequencing batch reactor.

Parameter	Typical batch		Fed-batch 25% of the cycle		Fed-batch 50% of the cycle		Fed-batch 75% of the cycle		Typical fed-batch	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
AnSBBR										
pH	7.16 ± 0.08	6.88 ± 0.05	7.41 ± 0.09	7.03 ± 0.09	7.20 ± 0.17	6.94 ± 0.08	6.91 ± 0.14	6.89 ± 0.07	6.70 ± 0.20	6.64 ± 0.15
T (°C)	24.3 ± 1.1	23.4 ± 1.9	23.2 ± 1.4	21.2 ± 1.3	26.3 ± 1.60	24.4 ± 1.06	28.5 ± 2.7	27.2 ± 2.4	27.2 ± 1.0	25.6 ± 1.0
C_{ST} (mgCOD L^{-1})	703 ± 97	207 ± 13	609 ± 153	239 ± 104	775 ± 16	244 ± 34	650 ± 53	194 ± 43	518 ± 91	237 ± 33
ε_{ST} (%)	–	70.2 ± 3.3	–	61.6 ± 4.7	–	67.5 ± 4.2	–	69.9 ± 4.3	–	53.6 ± 3.9
C_{SF} (mgCOD L^{-1})	322 ± 23	156 ± 22	274 ± 103	153 ± 87	336 ± 80	145 ± 22	294 ± 19	115 ± 33	238 ± 42	147 ± 33
ε_{SF} (%)	–	77.6 ± 3.5	–	75.8 2 ± 4.3	–	80.2 ± 3.8	–	82.2 ± 4.1	–	71.5 ± 3.7
BA (mgCaCO$_3$L^{-1})	95.3 ± 9.0	163.4 ± 10.1	158.0 ± 8.2	193.0 ± 20.0	157.1 ± 11.6	201.2 ± 10.8	142.5 ± 13.2	202.0 ± 23.9	136.9 ± 19.0	179.1 ± 11.1
TVA (mgHAc L^{-1})	64.5 ± 5.1	33.9 ± 7.7	40.6 ± 8.5	30.1 ± 17.0	56.1 ± 11.7	36.1 ± 11.9	53.8 ± 4.3	32.3 ± 5.0	44.5 ± 10.7	31.3 ± 7.9
TS (mg L^{-1})	808 ± 54	495 ± 56	634 ± 251	436 ± 253	902 ± 236	681 ± 25	739 ± 109	479 ± 118	59 ± 125	395 ± 142
TSS (mg L^{-1})	203 ± 31	132 ± 21	332 ± 233	228 ± 174	372 ± 98	301 ± 75	262 ± 381	201 ± 167	190 ± 98	155 ± 104
VSS (mg L^{-1})	158 ± 29	105 ± 21	273 ± 171	95 ± 144	298 ± 77	227 ± 56	226 ± 318	159 ± 261	107 ± 65	84 ± 51
ASBR										
pH	7.16 ± 0.06	6.77 ± 0.15	7.41 ± 0.09	6.98 ± 0.07	7.20 ± 0.17	6.92 ± 0.26	6.91 ± 0.14	6.73 ± 0.08	6.70 ± 0.20	6.46 ± 0.15
T (°C)	25.9 ± 1.5	22.9 ± 0.9	23.2 ± 1.4	20.9 ± 1.8	26.3 ± 1.6	24.7 ± 1.1	28.5 ± 2.7	27.1 ± 2.3	27.2 ± 1.0	25.7 ± 1.0
C_{ST} (mgCOD L^{-1})	730 ± 138	221 ± 45	609 ± 153	268 ± 77	775 ± 16	221 ± 22	650 ± 53	191 ± 31	518 ± 92	250 ± 29
ε_{ST} (%)	–	69.0 ± 8.3	–	56.8 ± 4.7	–	70.3 ± 3.9	–	70.3 ± 4.8	–	50.9 ± 5.3
C_{SF} (mgCOD L^{-1})	380 ± 126	143 ± 27	274 ± 103	147 ± 66	336 ± 80	113 ± 29	294 ± 19	93 ± 14	238 ± 43	147 ± 22
ε_{SF} (%)	–	80.1 ± 3.9	–	76.3 ± 4.1	–	84.4 ± 3.3	–	85.4 ± 4.1	–	71.4 ± 5.1
BA (mgCaCO$_3$L^{-1})	103.1 ± 11.0	127.8 ± 16.9	158.1 ± 8.2	183.5 ± 28.4	157.3 ± 12.0	199.2 ± 20.2	142.8 ± 13.1	206.5 ± 10.2	136.8 ± 19.0	179.1 ± 12.1
TVA (mgHAc L^{-1})	62.4 ± 7.0	58.7 ± 13.6	41.3 ± 8.1	34.2 ± 10.0	56.6 ± 12.4	34.4 ± 14.0	54.9 ± 4.4	28.0 ± 10.1	45.2 ± 10.1	39.3 ± 12.2
TS (mg L^{-1})	852 ± 166	596 ± 100	634 ± 251	501 ± 217	902 ± 236	643 ± 192	739 ± 109	531 ± 212	591 ± 125	448 ± 123
TSS (mg L^{-1})	253 ± 109	128 ± 55	332 ± 233	18 ± 192	372 ± 98	211 ± 58	262 ± 381	185 ± 95	190 ± 98	137 ± 101
VSS (mg L^{-1})	208 ± 96	104 ± 48	273 ± 171	150 ± 153	298 ± 77	159 ± 47	226 ± 318	133 ± 87	107 ± 65	81 ± 55

Analysis of the data of the four fed-batch feed strategies shows that when the AnSBBR is operated in typical fed-batch mode, organic matter removal efficiencies are much lower compared to the other feed strategies. When operated in fed-batch mode during 75% of the cycle organic matter, removal efficiencies were higher in relation to the other conditions; however, no pronounced differences were observed between fed-batch during 50% and 75% of the cycle, evidencing system flexibility as to feed strategy which is an advantage in cases where generation of wastewater is not continuous. Comparing typical batch and fed-batch during 50% and 75% of the cycle, the system show similar behavior regarding filtered organic matter removal with a slightly better performance of the fed-batch feed strategy during 75% of the cycle.

It should be mentioned that in the typical fed-batch, the influent organic matter concentration regarding unfiltered samples was lower than that of the other assessed conditions; as described in the methodology used to measure the influent organic matter, composite sampling was performed during the fill time, and it was verified that at the longer feed period, the influent organic load decreases considerably due to oscillations in the physical–chemical characteristic of the sanitary wastewater over the course of a day.

These results obtained with the AnSBBR showed that a higher t_F/t_C ratio, i.e., longer feed time maintains removal efficiency in terms of dissolved organic matter and improves removal efficiency in terms of particulate organic matter. The reason for this behavior may be attributed to the longer time available for hydrolysis/dissolution of the particulate matter as a result of gradual feeding of the reactor. However, this behavior reaches a limit at $t_F/t_C = 0.75$ likely due to lack of substrate.

It should be mentioned that in this work, no extracellular polymers were formed when fill time was increased (increase in t_F/t_C), in contrast to the work of Ratusznei et al. [3] who treated synthetic wastewater in an AnSBBR and observed formation of extracellular polymers when fill time was increased, impairing reactor mixing. The synthetic wastewater used in their work was based on carbohydrates (sucrose, starch, and cellulose), protein (meat extract), lipids (soy bean oil) at a total concentration of 500 mgCOD/L, and sodium bicarbonate (200 mg/L). Formation of extracellular polymers was minimized when the biomass was not exposed to air according to results obtained by Borges et al. [4]. Since in the assays with sanitary wastewater no extracellular polymers were formed even at longer fill times, it is believed that the composition of the synthetic wastewater likely stimulated in some way formation of these polymers. Moreover, in the larger pilot-scale reactors, the higher amount of moisture retained in the foam (inert support) in some way "protected" the biomass from exposure to air.

Within this context, it should be mentioned that Ratusznei et al. [3] verified that composition and concentration used in the synthetic influent indicated that reduction in efficiency occurred due to probable exposure to air and formation of extracellular polymers, especially at longer fill times (t_F/t_C) and not due to the possibility of toxic effects, according to results obtained by Borges et al. [4]. Results of profiles run during the operation cycle of organic matter, BA and TVA confirmed non-occurrence of toxic effects.

Concentrations of TS and TVS in the polyurethane foam inside the AnSBBR, listed in Table 5, did not present significant differences with changing conditions, indicating reactor stability and efficiency of the inert support in maintaining the biomass adhered to its surface during the assays with mechanical stirring and different fill times, confirming in pilot-scale the results obtained in lab-scale [9, 10, 13, 15, 19].

Time profiles of filtered organic matter concentration in the AnSBBR operated at the four fed-batch strategies show that at fed-batch during 25% of the cycle, after 2-min react, the unfiltered organic matter concentration equaled 700 mg L^{-1}, value close to that of the

Table 5 Total solids (TS) and total volatile solids (TVS) in the polyurethane foam of the anaerobic sequencing batch biofilm reactor.

Operational conditions	$C_{X\text{-}TS}$ (kgTS kg-support^{-1})	$C_{X\text{-}TVS}$ (kgTVS kg-support^{-1})	$C_{X\text{-}TS}$[a] (kgTS m^{-3})	$C_{X\text{-}TVS}$[a] (kgTVS m^{-3})
Typical batch	0.602	0.448	4.21	3.14
Fed-batch 25% of the cycle	0.629	0.426	4.40	2.98
Fed-batch 50% of the cycle	0.651	0.481	4.56	3.68
Fed-batch 75% of the cycle	0.617	0.415	4.32	2.91
Typical fed-batch	0.640	0.425	4.48	2.98

[a] Concentration values in the AnSBBR calculated considering liquid volume of 1.0 m^3 and 7.0 kg-support.

influent (721 mg L^{-1}) at time zero, because as mentioned previously, the volume of wastewater after the 2-min feeding did not yet reach the support medium due to the 15-cm clearance between the reactor bottom and the basket containing the support medium with biomass. Hence, the sample collected 2 min after feeding will be similar to the influent sample. As described earlier (Table 3), at fed-batch during 25% of the cycle, the water level takes 20 min to reach the support medium and 33 min to reach the impeller. Thus, the substrate consumption reaction occurred around 20 to 30 min when the wastewater came in contact with the microorganisms.

Similar behavior was seen for fed-batch during 50%, 75%, and 100% of the cycle; at fed-batch during 50% of the cycle, substrate consumption reactions started approximately 40 min after feeding. Prior to this period, the changes in concentration are justified by the variation in influent organic matter concentration. At fed-batch during 75% of the cycle, substrate consumption reactions started approximately 100 min after feeding. At typical fed-batch, substrate consumption reactions started approximately 2 h after feeding. This characteristic should be considered in full-scale reactors where this problem may be avoided by maintaining a residual liquid volume in the reactor to promote contact of the influent wastewater with the biomass and with the impeller from the start of the cycle.

Table 6 contains the kinetic parameters fitted by the first order kinetic model with residual substrate concentration to the monitored time profiles in the AnSBBR. It can be seen that at typical batch and fed-batch during 50% and 75% of the cycle, the system presents similar k_1 values, showing operational flexibility of the system, i.e., assimilation of the substrate took place at approximately the same specific rate regardless of fill time. This behavior can be explained by two opposite biochemical processes, i.e., with increase in fill time, less soluble substrate became available and hydrolysis/dissolution of particulate substrate increased (as previously mentioned). There was thus an equilibrium resulting in

Table 6 Kinetic parameters fitted by the first order model of the anaerobic sequencing batch biofilm reactor.

Operational conditions	k_1 (h^{-1})	C_{SR} (mgCOD L^{-1})	r^2
Typical batch	1.05	257	0.968
Fed-batch during 25% of the cycle	0.394	226	0.991
Fed-batch during 50% of the cycle	0.954	304	0.983
Fed-batch during 75% of the cycle	0.867	139	0.995
Typical fed-batch	2.40	217	0.993

Average amount of biomass in the AnSBBR=3.1 kgTVS (0.439 kgTVS/kg-support×7.0 kg-support).

the observed behavior. It can also be seen that under all conditions, the model displayed a good fit ($r^2 > 0.90$). However, as mentioned, the kinetic parameter of the typical fed-batch can not be considered in this comparison with the other conditions, because the values of the time profile obtained at this condition were approximately constant, i.e., the organic matter concentration in the reactor did not change during the cycle since feeding took place over the course of the entire react period, which jeopardizes the kinetic fit by the numerical routine used. It should be pointed out that in the kinetic fit to the time profile data, the initial time zero was considered the time at which substrate consumption started, i.e., the instant at which the water level reached the biomass.

ASBR

Table 4 contains the average values of the monitored variables during ASBR operation at the five feed strategies. These values correspond to the assays carried out during 21 days for each assessed operational condition. The ASBR when operated under typical batch and fed-batch during 50% and 75% of the cycle tended to achieve higher organic matter removal efficiencies in relation to the other conditions, showing system flexibility as to feed strategy, favoring applications where wastewater is not generated continuously. BA in the effluent was also seen to be superior to that in the influent, and TVA in the influent always tended to be superior to that in the effluent in all assessed conditions; and in addition, effluent pH did not vary significantly, remaining within the optimum range for methane formation. These facts show that the system presented operational stability in all the submitted situations.

Table 7 lists the concentrations of TS and TVS in the sludge mass of the ASBR and allows verifying that the solids concentration in the sludge mass did not present significant differences with changing conditions. It can thus be seen that the pilot-scale system managed to retain the biomass during operation with mechanical stirring and different fill times, confirming results obtained in lab-scale [8, 14].

The results obtained in this work corroborate the results of other projects developed to investigate the effect of feed strategy in ASBR and AnSBBR reactors applied to the treatment of different effluents [4, 8, 9, 11, 13, 15, 19] that the t_F/t_C ratio presents similar behavior, i.e., up to 0.5 efficiency improves and above 0.75 efficiency drops. These results were obtained at different cycle lengths, biomass concentration, organic loading rates, and influent concentration levels.

Table 7 Total solids (TS) and total volatile solids (TVS) in the sludge mass of the anaerobic sequencing batch reactor.

Operational conditions	$C_{X\text{-}TS}$[a] (kgTS m^{-3})	$C_{X\text{-}TVS}$[a] (kgTVS m^{-3})	$C_{X\text{-}TS}$[b] (kgTS m^{-3})	$C_{X\text{-}TVS}$[b] (kgTVS m^{-3})
Typical batch	12.6	9.80	4.41	3.43
Fed-batch 25% of the cycle	11.7	10.4	4.10	3.64
Fed-batch 50% of the cycle	12.1	10.7	4.24	3.75
Fed-batch 75% of the cycle	11.3	10.5	3.96	3.68
Typical fed-batch	11.6	10.9	4.06	3.82

[a] Concentration values in the ASBR calculated considering liquid volume of 0.35 m^3.

[b] Concentration values in the ASBR calculated considering liquid volume of 1.0 m^3.

Time profiles of filtered organic matter concentration in the ASBR operated under the four fed-batch feed strategies showed that for the fed-batch during 25% of the cycle, after 2-min react, the unfiltered organic matter concentration equaled 416 mg L^{-1}, whereas influent concentrations was 721 mg L^{-1}, which shows the effect of initial dilution of organic matter due to the liquid accumulated at the granulated sludge. It can also be seen that the organic matter increased up to 30 min of the cycle, because during this period, the system was being fed with an influent containing an organic matter concentration and the degradation rate of organic matter by the microorganisms is proportionally lower than the feed rate of substrate. Thus, there is a point at which the degradation rate of organic matter by the microorganisms is higher than the feed rate of organic matter by the incoming influent, leading to a decrease in concentration. For the fed-batch during 25% of the cycle, this point was situated between 30 and 60 min of react.

When the system was operated under fed-batch during 50% of the cycle, similar behavior was observed; the organic matter concentration increased up to 60 min of the cycle, after which, the degradation rate of organic matter by the microorganisms was higher than the feed rate of organic matter by the incoming influent, resulting in a decrease in concentration in the system. When the system operated under fed-batch during 75% of the cycle, differently from the conditions fed-batch during 25% and 50% of the cycle, no increase in organic matter concentration was observed at the beginning of the profile. This can be justified by the lower feed flow rate at fed-batch during 75% of the cycle compared to 25% and 50% and, consequently, the feed rate of organic matter by the incoming influent is proportionally lower than the degradation rate of organic matter by the microorganisms. Similar behavior was observed under the typical fed-batch condition.

Table 8 contains the kinetic parameters fitted to the first order kinetic model with residual substrate concentration to the time profiles monitored in the ASBR. It can be seen that the typical batch and fed-batch during 75% of the cycle presented similar k_1 values, evidencing operational flexibility of the system. It can also be seen that under all conditions, the model displayed a good fit ($r^2 > 0.90$). However, as mentioned for the other reactor, the kinetic parameter of the typical fed-batch should not be considered in this comparison with the other conditions, because the values of the time profile obtained at this condition were approximately constant as a result of the gradual feeding of influent during this fill time, which jeopardized the numerical fit. It should be mentioned that the kinetic parameters of the ASBR reactor were superior to those of the AnSBBR, despite the amount of TVS present in the sludge (which is a measurement proportional to biomass) being very similar. Such behavior may be justified by the fact that in the ASBR, the biomass remains in contact with the wastewater during the whole cycle, as it is not immobilized on a support as in the AnSBBR.

Table 8 Kinetic parameters fitted by a first order model of the anaerobic sequencing batch reactor.

Operational conditions	k_1 (h^{-1})	C_{SR} (mgCOD.L^{-1})	r^2
Typical batch	1.09	317	0.921
Fed-batch 25% of the cycle	1.00	322	0.904
Fed-batch 50% of the cycle	1.97	240	0.938
Fed-batch 75% of the cycle	1.04	184	0.969
Typical fed-batch	3.30	272	0.942

Average amount of biomass in the ASBR=3.6 kgTVS (10.5 kgTVS/m^3 ×0.35 m^3).

Conclusions

The ASBR and AnSBBR when operated under typical batch mode and fed-batch mode during 50% and 75% of the cycle presented the best removal efficiencies of organic matter. The organic matter removal decreased when the reactors were operated fed-batch wise during 25% of the cycle. The worst performance regarding organic matter removal occurred when the reactor operated under typical fed-batch mode, showing that there is a limit between substrate consumption by the microorganisms and substrate supply by reactor feed. Operating stability was achieved under all operational conditions, and no significant difference was observed in performance of the ASBR and AnSBBR when operated under typical batch mode and fed-batch mode during 50% and 75% of the cycle, evidencing operational flexibility. However, the fed-batch process has a great advantage, as it improves process flexibility in the case when wastewater is not continuously available, i.e., when availability of the effluent to be treated is intermittent. In these cases even when reactor filling occurs over a longer period than conventionally used in the batch process, the current study has shown that there will be no significant decrease in process efficiency.

It should be pointed out that despite the fact that the AnSBBR and ASBR present similar behavior under the assessed fed-batch conditions, the AnSBBR has an advantage over the ASBR in relation to sensitivity of the biomass exposed to external agents, conferring increased robustness in the presence of eventual toxic and/or shock loads, as well as regarding eventual failure in the automation system, which could result in loss of biomass. However, the ASBR is safer regarding eventual clogging of the bed by high solids content in the influent.

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