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Behaviour of the solids retention time in relation to the operative variables in a hybrid moving bed membrane bioreactor treating urban wastewater

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ABSTRACT

The present research studies the influence of the operative variable of a hybrid moving bed biofilm reactor–membrane bioreactor (hybrid MBBR–MBR) in the attached biomass, and analyses the effect of the variables on the evolution of solids retention time (SRT) treating real urban wastewater in a pilot-scale experimental plant. This was operated under mixed liquor suspended solids (MLSSs) between 2,414 ± 166 and 4,594 ± 47 mg/L, the temperature ranged between 5.00 ± 1.58 and 27.88 ± 1.52°C and the regimes of 10 and 24 h HRT with 20, 35 and 50% of the filling ratio. The biofilm density changes between 2,618 ± 272 and 6,991 ± 843 mg/L of the carrier show statistically significant differences in relation to the operative variables, so it depends mainly on MLSS and temperature, and is not dependent on the filling ratio under the condition studied. The multivariable analysis showed that the most influential operative variables in the SRT were MLSS and temperature, so two models have been proposed to consider these effects. The SRT can be modelled in relation to the HRT and MLSS throughout the F/M rate with the hyperbola $5.469 \times (F/M)^{-0.833}$; $2.1976 \times (F/M)^{-1.181}$; $2.2831 \times (F/M)^{-1.207}$ for 20, 35 and 50% of the filling ratio, respectively. In relation to the temperature, the SRT increases linearly with it between approximately 5 and 30°C with linear coefficients that also increase with the filling ratio presenting the values of 0.2825, 0.3438 and 0.4615 d/°C to 20, 35 and 50% of the filling ratio, respectively.

Keywords: Hybrid moving bed; Membrane bioreactor; Solids retention time; Temperature; *F*/*M* rate

1. Introduction

The higher pollution of wastewater, the increase of the consumption and the more demanding regulation about the environmental impact of polluting discharges require a more advanced technology to preserve water quality [1,2]. Although biological processes such as conventional activated sludge (CAS) are a cost-effective and environmentally friendly alternative to the chemical treatment of wastewater [3], these treatments result in continuous production of waste activated sludge mainly disposed inside the treatment plant premises or a landfill [4]. Therefore, it is necessary to find alternatives what have the advantages of

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the activated sludge process without its disadvantages and to try to improve their efficiency. The biomass in the bioreactor also can be fixed on a carrier, forming a biofilm; the processes that used this biomass have proven to be reliable for organic carbon and nutrient removal without some of the problems of CAS [5,6].

Moving bed biofilm reactor (MBBR) consists of a process tank in which plastic carriers with slightly lower density than water are submerged and gradually colonised by the attached biomass on the protected surface on the inside. Two main configurations are frequently used as only secondary treatment or in combination with other configurations: pure MBBR in which the biomass only grows on carriers and no sludge recycling is needed; and hybrid MBBR that presents both biofilm and suspended activated sludge in the same tank requiring sludge recycling [7]. To transport the substrates to the biofilm and to maintain a low thickness of the biofilm by shearing forces is important for the movement in the reactor [8] caused by aeration in an aerobic system or by a mixer in anoxic and anaerobic processes. This process presents the following advantages: low head loss, no filter channelling and no need of periodic backwashing [9]; simple in operation, low risk of biomass loss and less temperature dependent [10]; a process inherently stable and resistant to organic and hydraulic shock loadings [11]; efficient mass transfer and elimination of the risks of liquid short circuiting and clogging [12]; flexible changing the filling ratio subject to preferences [8]; in the hybrid MBBR, the attached biomass on the support increases the total amount of biomass inside the system, but without a significant increase in the solid load to the final settling tank [13]; the biofilm on the support increases the solids retention time (SRT) of the system [14].

In comparison with CAS, membrane bioreactors (MBRs) represent a treatment technology that produces a high-quality effluent at a lower surface demand [15]. The use of hybrid MBBR–MBR consists of the use of a hybrid system in which a hybrid MBBR coupled with a MBR is used for the biodegradation of soluble organic matter. In this combined technology, the biofilm presented in the system may reduce the concentration of mixed liquor suspended solids (MLSS) [16], providing optional strategies for minimising the problem of fouling [17]. A hybrid MBBR–MBR has the potential to combine the best characteristics of biofilm processes and membrane separation [18]. Using this technology, the addition of carriers inside the bioreactor reduces the concentration of suspended solids thus limiting the extent of membrane fouling, and reducing the effect of membrane fouling caused by high biomass concentrations inside the membrane bioreactors [19]. In comparison to the MBR, the hybrid MBBR–MBR has the advantages of being even more compact, operating with higher fluxes and having better energy efficiencies and higher control of membrane fouling; thus this technology provides optional strategies for minimising the problem of fouling [17].

The SRT is related to a better acclimatisation of the biomass to the contaminants due to a longer residence time of the sludge, and also to the presence of slower growing species [20]. The attached biomass contributes significantly to the total amounts of biomass maintained in the hybrid MBBR process, providing longer SRT and resulting in higher nitrification in the system [14]. The high SRT values of biofilm lead to a favourable environment for the growth of nitrifying bacteria [21]. Therefore, a hybrid MBBR process can be a suitable alternative for biological nitrogen removal, and a cost-effective option for retrofitting wastewater treatment plants (WWTPs) to sustain nitrification under low temperatures [22]. Operating conditions of the system play an important role, and these seem to be critical for hybrid MBBR–MBR process; when the system operates at lower SRT and MLSS, the removal rates achieved are much lower, being higher MLSS and SRT necessary to achieve higher removal rates [20,23]. The fractions of denitrification in the aerobic zone increase proportionally with the suspended SRT maintained in the systems [14]. Moreover, higher MLSS is related to lower feed/mass (F/M) ratios, which may induce micro-organisms to metabolise poorly degradable compounds due to food shortage [24].

The aim of the present research was to study the influence of the operative variables of a hybrid MBBR–MBR in the attached biomass, to analyse the effect of the variables in the evolution of SRT and to propose a model to predict the system behaviour in relation to the operative variables.

2. Material and methods

2.1. Experimental procedure

2.1.1. Description of the pilot-scale experimental plant

A hybrid MBBR–MBR pilot-scale experimental plant was used in the present research; a schematic diagram of the process used is shown in Fig. 1. The plant was fed with real urban wastewater from the effluent of the primary settler of the WWTP Puente de Los Vados WWTP in Granada (Spain) where the pilot plant was located. The experimental plant consisted of two bioreactors: the hybrid MBBR with an operative

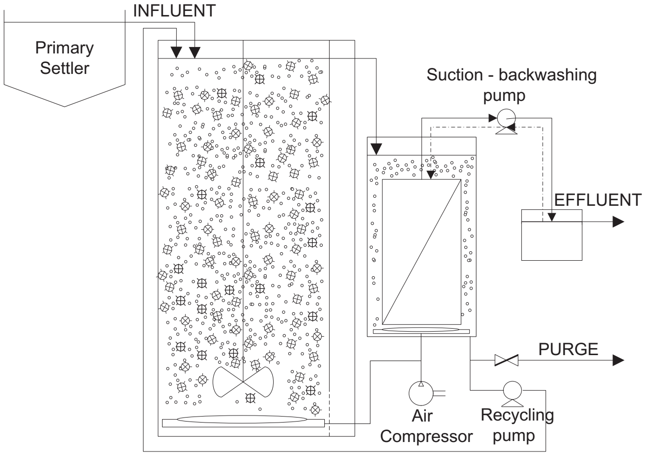

Fig. 1. Schematic diagram of the studied hybrid MBBR–MBR pilot plant.

volume of 358 L in which three different filling ratios of carriers (20, 35 and 50%) were contained; and the MBR tank with 87 L of operative volume in which three ZW-10 modules of Zenon® hollow fibre ultrafiltration were submerged. They were configured as an outside/in hollow fibre with a nominal membrane surface area of 0.93 m^2, a nominal pore size of 0.04 μm and an absolute pore size of 0.1 μm. Biodegradation took place in the hybrid MBBR, and separation occurred in the membrane reactor. In order to maintain the concentration of biomass in the hybrid MBBR in each cycle, a recycling pump was installed in the membrane tank with a constant flow, and a constant flow of sludge was extracted from the membrane tank.

2.1.2. Operating conditions

The 11 cycles of operation shown in Table 1 were studied in the present research in relation to the filling ratio, MLSS and HRT. These cycles were ordered in three phases according to the filling ratio: phase I with 20% (cycles from 1 to 4), phase II with 35% (cycles from 5 to 8) and phase III with 50% (cycles from 9 to 11). The start-up of the pilot plant consisted of feeding the pilot plant with urban wastewater from the primary settler of the WWTP of Los Vados in Granada (Spain), where the plant was situated. The pilot plant worked under the conditions of each cycle until the MLSS obtained the established concentration, initiating, at this point, the purge flow in order to stabilise the biomass. In each phases, two HRTs were checked with two different MLSSs. The MLSSs operated were about 2.5 g/L (cycles 1, 2, 5, 6 and 9) and about 4.5 g/L (cycles 3, 4, 7, 8, 10 and 11); the HRTs were 10 h (cycle 1, 3, 6, 7, 9 and 10) and 24 h (cycles 2, 4, 5, 8, and 11) and they operated at a flow rate of 45.5 L/h (10 h of HRT) and 18.96 L/h (24 h of HRT).

2.2. Physical and chemical determination

The samples for analytical determination were taken daily from the feed tank, biological reactor and permeate. The biological oxygen demand (BOD_5) was determined according to the American Public Health Association, the American Water Works Association and the Water Environment Federation (APHA–AWWA–WEF) method. The solids in suspension (SS) were determined by gravimetric methods [25]. The pH

Table 1
Operative conditions (filling ratio, HRT, MLSS and temperature) in the different phases and cycles checked in the main research

		Operative variables			
Phase	Cycle	Filling ratio (%)	HRT (h)	MLSS (mg/L)	Temperature (°C)
I	1	20	10	2,414 ± 166	17.99 ± 1.56
	2	20	24	2,514 ± 148	25.01 ± 3.49
	3	20	10	4,329 ± 342	14.12 ± 1.63
	4	20	24	4,397 ± 275	10.35 ± 1.91
II	7	35	24	2,798 ± 67	14.00 ± 2.60
	8	35	10	2,581 ± 127	20.51 ± 3.26
	9	35	10	4,278 ± 154	27.88 ± 1.52
	10	35	24	4,548 ± 104	22.42 ± 2.64
III	13	50	10	2,579 ± 61	14.43 ± 3.11
	14	50	10	4,524 ± 49	6.48 ± 3.74
	15	50	24	4,594 ± 47	5.00 ± 1.58

and conductivity were determined using a pH meter (Crison pH 25®) and a conductivity meter (Crison CM 35®), respectively. The biomass attached to the carriers was determined according to Martín–Pascual et al. [26], obtaining the suspended solids in the biofilm (BFSS).

2.3. Statistical analysis

The data obtained throughout this study were analysed using a computer-assisted statistics program, SPSS 20 for Windows. A least significant differences test was used to measure the differences between the SRT and feed/mass rate (F/M) for the different operational conditions studied (filling ratio, MLSS, HRT and temperature of the bioreactor). Normality tests of the data were undertaken using the Shapiro–Wilk test since the data set was smaller than 2000 elements. An analysis of variance (ANOVA) was used to assess the homogeneity of the variance, with a significance level of 5% ($p < 0.05$).

A multivariable analysis in Canoco for Windows version 4.5 was used to quantify the influence of the environmental variables (HRT, MLSS, filling ratio and temperature) on the SRT, total amount of biofilm in the reactor (biofilm concentration) and biofilm density. A Monte Carlo test of permutations (499 permutations) was performed, with a selected significance level of 0.05. The analysis represented 68.8% of accumulated variance of the species in the first axis, and 61.5% in the second one. The cumulative variance of the relationship between the species and the variables represented in the first axis was 89.5% and the totality in the second axis.

2.4. Solids retention times modelling

In order to relate SRT with the operative variables, several fits of the SRT were done. The F/M rate was chosen as variable in the SRT modelling because it is a parameter related to the growth and distribution of the micro-organisms [27,28], and it is a traditional parameter of operation in conventional WWTPs. The F/M rate is the relationship between the load of BOD entering the aeration plant and the available biomass in the aeration tank. Eq. (1) shows the expression used to calculate the F/M rate from the concentration of BOD_5 in the influent, the MLSS of the reactor and the HRT.

$$F/M = \frac{\text{BOD}_5}{\text{MLSS} \times \text{HRT}} \tag{1}$$

Considering that the SRT is very high under low F/M and is almost nil under a high F/M rate, the behaviour of the SRT in relation to the F/M rate has been modelled arithmetically by a hyperbola because this function presents a horizontal and vertical asymptote and is always positive in the first quadrant.

In order to consider the effect of the temperature in the evolution of SRT, a theoretical SRT ($\text{SRT}^{\text{theoretical}}$) has been defined considering the absence of the microbial metabolism. $\text{SRT}^{\text{theoretical}}$ has been calculated with Eq. (2) that was obtained from a mass balance, considering that the ultrafiltration membrane avoids the concentration of suspended solids in the effluent of the system.

$$\text{SRT}^{\text{Theoretical}} = \text{HRT}\ \frac{\text{MLSS}}{\text{SS}_{\text{influent}}} \tag{2}$$

3. Results and discussion

The average values of BFSS are shown in Table 2; the superscripts of the average values in Table 2 show the homogenous subset of Tukey's HSD of the ANOVA test undertaken with $\alpha = 0.05$. The biomass in the system is an important parameter that affects the organic matter and nitrogen removal of the process. The BFSS ranged between 2,618 ± 272 and 6,991 ± 843 mg/L of carrier, both in phase I. The ANOVA analysis of the data obtained during the research showed the existence of statistically significant differences in the biofilm and the non-presence in the characteristics of the influent (COD, BOD_5, SS) in different cycles; therefore, the biofilm depends on operational variables (HRT, filling ratio, MLSS and temperature). The parameters that can affect the formation of biofilm have been described by different authors [29–32]. The thickness of the biofilm formed depends on the organic load, temperature and concentration of dissolved oxygen [29]; this stress the importance of the organic substrate flux, the higher organic load, the higher growth of attached biomass [29,30] as well as in the relationship C/N [32] as a result of competition between autotrophic and heterotrophic bacteria by substrate available. This effect can be clearly analysed in the present research throughout the HRT, e.g. in phase I, comparing the cycles with similar MLSS concentration, BFSS is higher in the cycles with higher HRT (cycles 2 and 4). However in phase II, the effect of the MLSS is not clear as a consequence of the temperature although the HRT is higher in cycle 5, the

Table 2
Operative parameters (SRT, BFSS and *F*/*M* rate) in the different phases and cycles checked in the main research. The homogenous subset of Tukey's HSD of the ANOVA test undertaken with $\alpha = 0.05$ is shown as superscript (a, b, c, d and e)

		Operative parameters		
Phase	Cycle	SRT (d)	BFSS (mg/L of carrier)	F/M (kgBOD$_5$/(kgMLSS d))
I	1	12.71	2,618 ± 272^{a}	0.409 ± 0.074^{a}
	2	24.72	4,355 ± 457^{b,c}	0.139 ± 0.036^{b,c}
	3	22.25	5,196 ± 324^{c}	0.163 ± 0.060^{c}
	4	55.63	6,991 ± 843^{e}	0.073 ± 0.022^{d}
II	5	18.54	4,403 ± 188^{b,c}	0.134 ± 0.020^{b}
	6	8.56	5,424 ± 259^{d}	0.352 ± 0.054^{a}
	7	17.8	5,284 ± 287^{c}	0.160 ± 0.026^{c}
	8	56.53	4,594 ± 217^{b,c}	0.075 ± 0.007^{d}
III	9	13.91	5,844 ± 268^{d}	0.135 ± 0.125^{b}
	10	18.59	5,564 ± 259^{d}	0.181 ± 0.089^{e}
	11	49.44	4,604 ± 191^{b,c}	0.085 ± 0.007^{a}

BFSS is greater in cycle 6 due to the fact the temperature is lower in the first one.

The average values of solids retention time (SRT) are shown in Table 2. This increases with the HRT because an increase in HRT implies a decrease in the substrate available for micro-organisms and so less biomass can be formed. The values of SRT obtained were slightly higher than those obtained by de la Torre et al. [20] operating under 13 h of HRT and MLSS in the same order; this could be due to the higher filling ratio used. Comparing cycles of this research with similar MLSS (cycle 1 and 2; 3 and 4; 5 and 6; 7 and 8; and 10 and 11), it is observed that SRT increases approximately twice from HRT from 10 to 24 h. In a similar way, an increase of MLSS for the same HRT implies that the micro-organisms have less substrate available, and therefore, less generated matter to purge, and the SRT increases as well.

The effect of the filling ratio in the evolution of the BFSS in the present research was not clear; this is a consequence of the other variables that could soften its effect, e.g. similar values of biofilm density have been obtained under similar MLSS and HRT in cycles 8 (4,594 ± 217 mg/l of carrier) and 11 (4,604 ± 191 mg/L of carrier) with 35 and 50% of filling ratio, respectively; this could be a consequence of the low temperature of the cycle 11 or of the effect of filling ratio. The global amount of biofilm in the system increased with the filling ratio to the same substrate; thus micro-organisms had less substrate and therefore less matter to purge. However, the crashes of the carrier were higher with high filling ratio, generating an increase in biofilm detachment, and therefore, an increased SRT. Various studies have exposed a possible relationship between the filling ratio and the biofilm density and its thickness [33–35]. The thickness of the biofilm under high filling ratios presents greater activity indicating an increased rate of removal of organic matter and nutrients per unit biofilm [36–38]. However, with a high filling ratio, the detachment of the micro-organisms of the biofilm is favoured assuming a decline in biomass attached in the bioreactor [39]; moreover, the fluidisation of the carriers requiring a greater flow of air to suspend them implies a cost overrun of the process [6].

The temperature affects microbial activity, which increases with the temperature and generates a greater consumption of substrate, and therefore, an increase in the SRT. The effect of variable temperature is cushioned by other more influential variables; however, an important variation of temperature can affect the SRT. In cycles 2 and 5 under similar MLSS and HRT, a reduction of 11 degrees in the temperature produced a reduction about 7 d of SRT.

A multivariate analysis to study the combined effect of the different variables and the relationships between the different species was done. The biplot diagram of analysis of redundancy is shown in Fig. 2. The Monte Carlo test showed that the filling ratio and MLSS were statistically significant variables in the system (*p*-value of 0.050 and 0.002, respectively) and therefore the most influential variables on the variability of the system under the conditions studied. The most influential variable in the biofilm density was the MLSS; it affected positively, the higher MLSS was, the higher biofilm density was observed. Temperature showed a strongly positive correlation with SRT and BFSS, when the biofilm density increases with the temperature caused by the higher microbial activity under medium temperatures. The HRT showed a slightly positive influence on the biofilm density and SRT. Moreover, the multivariable statistical analysis showed that the filling ratio did not influence the biofilm density under the conditions studied. However, the total amount of biofilm in the bioreactor obviously presented a positive correlation with the filling ratio. The MLSS presented a positive correlation with the biofilm concentration and the effect of HRT was much lower in the system than expected (p-value of 0.718) and the temperature was not relevant in the biofilm concentration.

Given the influence of the HRT and MLSS in the SRT, an empirical relationship between SRT and F/M rate was designed. The values of F/M rate are also shown in Table 2. These values ranged between 0.05 and 0.5 $\text{kgBOD}_5/(\text{kgMLSS d})$, as a consequence of the operated HRT and MLSS. Fig. 3 shows the values of SRT in relation to the average values of the F/M rate in the different cycles of each phase of the present research and the empirical fit for a hyperbola done.

The fit equations are shown in Eqs. (3)–(5) for the filling ratio of 20, 35 and 50%, respectively. The correlation rate (R^2) was 0.947, 0.936 and 0.784 to 20, 35 and 50%, respectively. These equations predict the SRT in relation to the HRT and MLSS under each filling ratio tested.

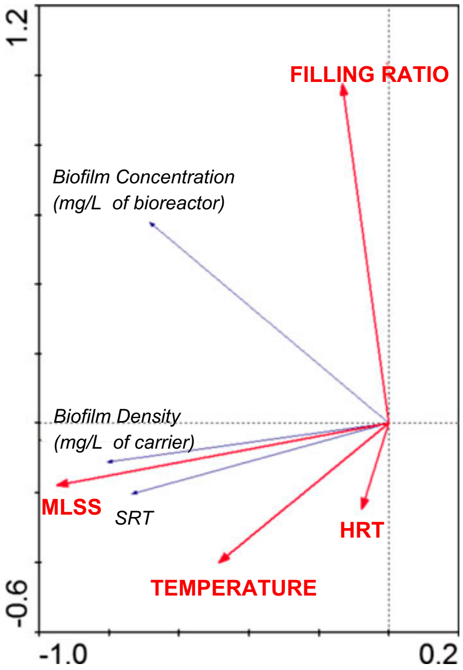

Fig. 2. Graph of the results from the multivariable analysis used to study the relationship between HRT, temperature, MLSS and filling ratio as variables, and biofilm measured per volume of carrier (density) and per volume of bioreactor (concentration) and SRT as species for the conditions tested.

$$\text{SRT}^{20\%}\ (\text{d}) = 5.469 \times (F/M)^{-0.833} \tag{3}$$

$$\text{SRT}^{35\%}\ (\text{d}) = 2.1976 \times (F/M)^{-1.181} \tag{4}$$

$$\text{SRT}^{50\%}\ (\text{d}) = 2.2831 \times (F/M)^{-1.207} \tag{5}$$

Temperature is an important parameter that influences the microbial community, biological activity rate and sludge morphology [15]. The effects of the temperature on the biological process have been widely studied including, for example, on the growth of wastewater bacteria [40], on the treatment efficiency, solids discharges, sludge physicochemical properties and microbiology [41] or under aerobic and anoxic conditions [42]. Although in this research the temperature did not show a statistically significant difference in the SRT, its effect has been analysed in order to include it in the model. This has been considered comparing the difference between the real SRT (ΔSRT) and the $\text{SRT}^{\text{theoretical}}$ supposing an absence of microbial activity. The values of temperature, $\text{SRT}^{\text{theoretical}}$, SRT and ΔSRT are shown in Table 3.

The values of ΔSRT in each cycle are shown in Fig. 4. Independently of the filling ratio, these values increase with the temperature as a consequence of the increase of the microbial activity. The fits obtained for 20, 35 and 50% of filling ratio, whose correlations (R^2) were 0.9864, 0.8192 and 0.9954, respectively, are shown in Eqs. (6)–(8).

$$\Delta\text{SRT}_{20\%}\ (\text{d}) = 0.2825T - 0.0058 \tag{6}$$

$$\Delta\text{SRT}_{35\%}\ (\text{d}) = 0.3438T - 1.7796 \tag{7}$$

$$\Delta\text{SRT}_{50\%}\ (\text{d}) = 0.4615T - 1.6005 \tag{8}$$

According to the definition of ΔSRT considered, SRT of the system can be estimated in relation to HRT, MLSS and SS of the influent. Eqs. (9)–(11) show the fit obtained for 20, 35 and 50% of filling ratio, respectively.

$$\text{SRT}_{20\%}\ (\text{d}) = \text{HRT}\ \frac{\text{MLSS}}{\text{SS}_{\text{influent}}} + 0.2825T - 0.0058 \tag{9}$$

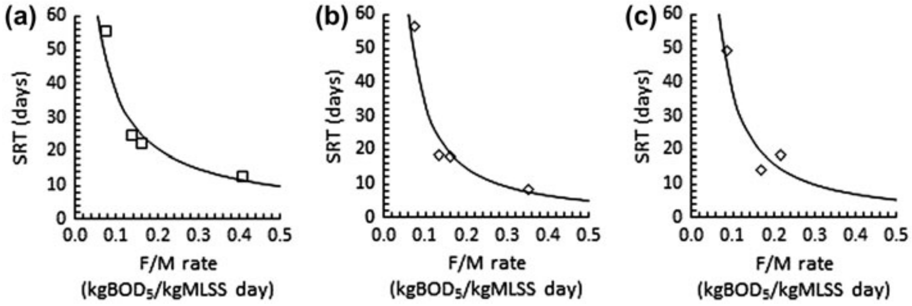

Fig. 3. Evolution of SRT in relation to the *F*/*M* rate under each of the different filling ratios tested in the present research: 20% (a), 35% (b) and 50% (c).

Table 3
Influence of the temperature in the SRT during the different cycles of the research

			SRT (d)		
Phase	Cycle	Temperature (℃)	Theoretical	Real	ΔSRT
I	1	17.99	7.80	12.71	4.91
	2	25.01	17.65	24.72	7.07
	3	14.12	17.98	22.25	4.27
	4	10.35	52.85	55.63	2.78
II	5	14.00	15.02	18.54	3.52
	6	20.51	4.66	8.56	3.90
	7	27.88	9.72	17.80	8.08
	18	22.42	50.00	56.53	6.53
III	9	14.43	8.83	13.91	5.08
	10	6.80	17.37	18.59	1.22
	11	5.00	48.59	49.44	0.85

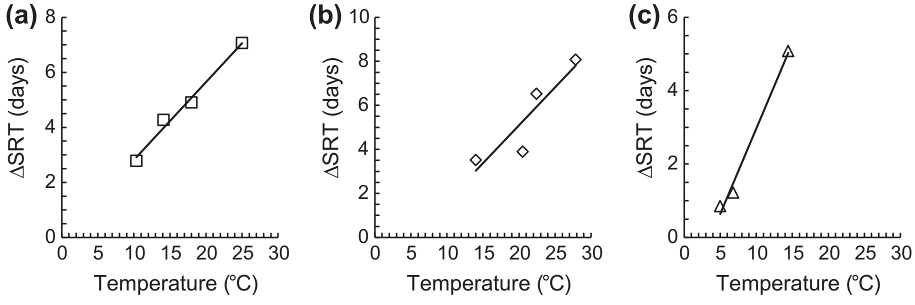

Fig. 4. Average value of ΔSRT during the different cycles of the phase I (a), phase II (b) and phase III (c) in relation to the different temperatures tested.

$$\mathrm{SRT}_{35\%}\ (\mathrm{d}) = \mathrm{HRT}\ \frac{\mathrm{MLSS}}{\mathrm{SS}_{\mathrm{influent}}} + 0.3438T - 1.7796 \qquad (10)$$

$$\mathrm{SRT}_{50\%}\ (\mathrm{d}) = \mathrm{HRT}\ \frac{\mathrm{MLSS}}{\mathrm{SS}_{\mathrm{influent}}} + 0.4615T - 1.6005 \qquad (11)$$

The linear coefficient of the increase of the SRT with respect to the temperature increases with the filling ratio as a consequence of the higher global concentration of biomass; thus, the sludge from the system is digested more when the filling ratio is higher.

4. Conclusions

Given the results obtained under MLSSs between 2,414 ± 166 and 4,594 ± 47 mg/L, temperature ranged between 5.00 ± 1.58 and 27.88 ± 1.52°C and the regimes of 10 and 24 h HRT in a hybrid moving bed biofilm reactor–membrane bioreactor with 20, 35 and 50% of the filling ratio, the following conclusions were drawn:

(1) The most influential operative variables in the behaviour of SRT and biofilm density were MLSS and temperature.
(2) An increase in micro-organisms (*M*) with respect to organic load (*F*) produce a higher sludge removal asymptotically, so the SRT can be modelled in relation to the HRT and MLSS throughout the *F*/*M* rate with the hyperbola $5.469 \times (F/M)^{-0.833}$; $2.1976 \times (F/M)^{-1.181}$; $2.2831 \times (F/M)^{-1.207}$ for 20, 35 and 50% of the filling ratio, respectively. This SRT increased linearly with the temperature between approximately 5 and 30°C with coefficients of 0.2825, 0.3438 and 0.4615 d/°C.

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