Reduction of scum production in a modified UASB reactor treating domestic sewage

J. O. Pereira, J. M. Rocha, W. B. C. C. Pinto and C. T. S. Moreira

ABSTRACT

The scum accumulation inside gas–solid–liquid separators (GSL) is one of the main limitations of upflow anaerobic sequencing batch (UASB) reactors during treatment of domestic sewage. Although this type of reactor can be equipped with devices that periodically remove scum, this solution has been proved to be very expensive in addition to being inefficient when discharging procedures are not correctly performed. The main goal of this study was to investigate the performance of a modified UASB reactor concept with a GSL separator which promotes continuous scum discharge to the settling compartment. Furthermore, this proposal was compared with a conventional UASB reactor which was used as control. Both reactors in demo-scale were fed with domestic wastewater and scum production was measured. The results demonstrated volumetric reduction of 50%, and 75% reduction in the mass of total solids in the modified reactor. Additionally, the amount of biogas recovered from the modified reactor was higher than the amount that the control reactor recovered. Therefore, the proposed modification has been proved to be effective, bringing new possibilities to the GSL project.

Key words | anaerobic digestion, domestic wastewater, modified UASB reactor, scum

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INTRODUCTION

Upflow anaerobic sequencing batch (UASB) reactors are the main technology currently in use in Brazil for domestic sewage treatment due to the clear advantages in comparison with other systems. However, continuous improvements are still demanded to handle problems of solids washout, losses of dissolved gases and scum accumulation.

The technical community has reached a consensus on the seriousness of scum accumulation in UASB reactors treating domestic sewage. Since the latter half of the last decade, when the first researches and papers about this subject were developed and published (Souza *et al.* 2006; Pereira *et al.* 2009). Since then, scum accumulation on the surface of the settler compartment has been dealt with by discontinuing the use of scum baffles, and allowing the discharge of its constituents in the effluent. Therefore, this could be achieved because of the low rates of scum production rate, making it possible that such material could be discharged within the effluent, in addition to avoiding relevant deterioration of effluent quality (Van Haandel & Lettinga 1994; Souza *et al.* 2006; Lobato *et al.* 2018). On the other hand, triphasic separators adopted the periodic removal of scum as a solution, implying that this is the biggest operational limitation in most full-scale plants (Ribeiro *et al.* 2017).

The accumulation of scum in that part of the reactor may block the gas release interface and could eventually result in the detour of biogas to the settler compartment. Therefore, a deterioration of effluent quality is expected as well as uncontrolled emissions of greenhouse gases (CH_4 and CO_2), and the emission of bad odors (H_2S). Furthermore, there will be an increase of dissolved methane concentrations in the liquid phase (supersaturation), leading to higher losses of energy usage and even the disruption of separators made of fibreglass, as reported (Van Lier *et al.* 2011; Chernicharo *et al.* 2015; Glória *et al.* 2016).

The scum production rate is greatly affected by influent characteristics, efficiency of preliminary treatment stage, sludge floating and operational conditions (Ribeiro *et al.* 2017). Contribution of uncontrolled industrial effluents to the sewer, such as from dairy products, slaughterhouse, refrigerators and septic tank sludge, might increase the concentration of lipids (Lobato *et al.* 2018). As a consequence, it results in the increase of floating sludge probability because of adsorption of these components into the biomass (Wang *et al.* 2018). In the case of the preliminary treatment stage, unsuitable design of grids, meshes and strainers might result in a high amount of floating rubbish (dental floss,

doi: 10.2166/wst.2019.155

swabs, cigarette butts, plastics, condoms, among others) at the reactor inlet, which tends to float into the reactor and pile up on the scum layer of the triphasic separator (Chernicharo et al. 2015; LOBATO et al. 2018).

With regards to operational conditions, both temperature and sludge age (sludge retention time) affect the lipids conversion rate and the potential for floating and formation of sludge (Halalsheh et al. 2005; Wang et al. 2018). Halalsheh et al. (2005) performed studies in order to verify the effect of these two parameters. In their work, they observed that the increase of temperature from 15 °C to 25 °C, for the same sludge age (30 days), corresponded to the increase of lipids from 20% to 80%, in addition to reducing scum height from 8 to 5 mm. Regarding the hydrodynamics of UASB reactors applied for domestic sewage, the condition of incipient mixtures, which are caused by low accessional velocities and limited biogas production, might raise scum production because of both imprisonment of biogas bubbles into sludge and layered (block) scum floating (Van Haandel & Lettinga 1994; Wang et al. 2018). Furthermore, an excessive increase of scum production is also expected when hydraulic overcharge occurs (because of operational problems or design errors), whereby a big amount of sludge moves to the separator. This means the scum looks like layered floating sludge (Ribeiro et al. 2017; Lobato et al. 2018). This problem might also be aggravated by the sludge discharge being carried out less frequently than it should be in both these cases. (Chernicharo et al. 2015). In addition, the scum layer tends to evolve with the compound aggregation, thickness and viscosity because the inner part of the triphasic separator contains the largest stagnated zone of the reactor (Peña et al. 2006).

Some of the considerable options to solve these problems are: (i) usage of primary settlers; (ii) improvement of the preliminary treatment; (iii) the addition of enzymes to hydrolyze oils and greases; (iv) the improvement of the reactor design; (v) periodical scum removal. Despite primary settlers being a simple and effective solution, these units have a high cost that is equivalent to the reactor cost. And for that reason, such a solution has not been implemented in tropical conditions. Improving the effectiveness of preliminary treatment with the usage of fine grids (2–6 mm) or static screens is an important way to reduce the amount of detritus and, consequently, the mass of scum (Chernicharo et al. 2015; Rosa et al. 2017). Due to its low cost this improvement should always be recommended. The enzymatic hydrolysis is still under testing phase (Santos 2014), but the cost of enzymes may also be viewed as a constraint.

With regard to optimization of reactor design, it might be said that innovations are often applied for reactors that treat complex industrial effluent (Haridas et al. 2005), in addition to those found in patented technologies databases (Espacenet, Patentscop, and others). For UASB reactors applied for domestic sewage, innovations are even rarer; the major effort is led by Brazil, especially by Professor Carlos Chernicharo's research group. For example, a recent innovation of this group is the triphasic modular separator Etsus-1000, which is presented by Lobato et al. (2018). The product is still in the final stages of development and, for that reason, more details about this technology are not available. Another example is the UASB reactor with a double-stage biogas collector, which was developed by one of the present authors (Pereira et al. 2009). The main goal of this reactor is to control the scum accumulation in the triphasic separator. In this pneumatic reactor, the biogas is captured in the bottom of the reactor and used as the driving force in order to remove the scum from inside the triphasic separator to the decanter. It is important to highlight that this is possible because of orifices in the upper triphasic separator (or double-stage biogas collector). In this case, the results revealed a decrease of scum production higher than 90%, in comparison with a conventional reactor. Nevertheless, the possible increase of related cost and higher concentration of solids into effluent show that this configuration needs to be improved. In the end, the most applied solution is the periodical removal by gutters, pipes and/or sluice discharges installed in the separator (Ribeiro et al. 2017; Rosa et al. 2017). However, this solution may be very costly and ineffective if the scum viscosity is not maintained under conditions that are suitable for the scum to flow through the discharges devices. When this condition is not verified, the use a cesspool cleaning truck in the operational procedure will often be necessary. According to Chernicharo et al. (2015), this frequency is around 15 days, even though each case must individually be evaluated.

Considering that researches have not been focusing on the reactor design, this work proposes to investigate the reduction of scum production in the GSL separator using a modified concept to promote a continuous scum release to the settler compartment and after to the effluent (Figure 1). For that, the triphasic separator was designed in such a way that sewage flow preferably occurs inside the triphasic separator, eliminating the dead zone of this area besides reducing the possibility of layer scum aggregation. This is probable because the sewage flow can remove part of the material that was supposed to pile up on the scum layer, by acting on the lower layer, capturing and

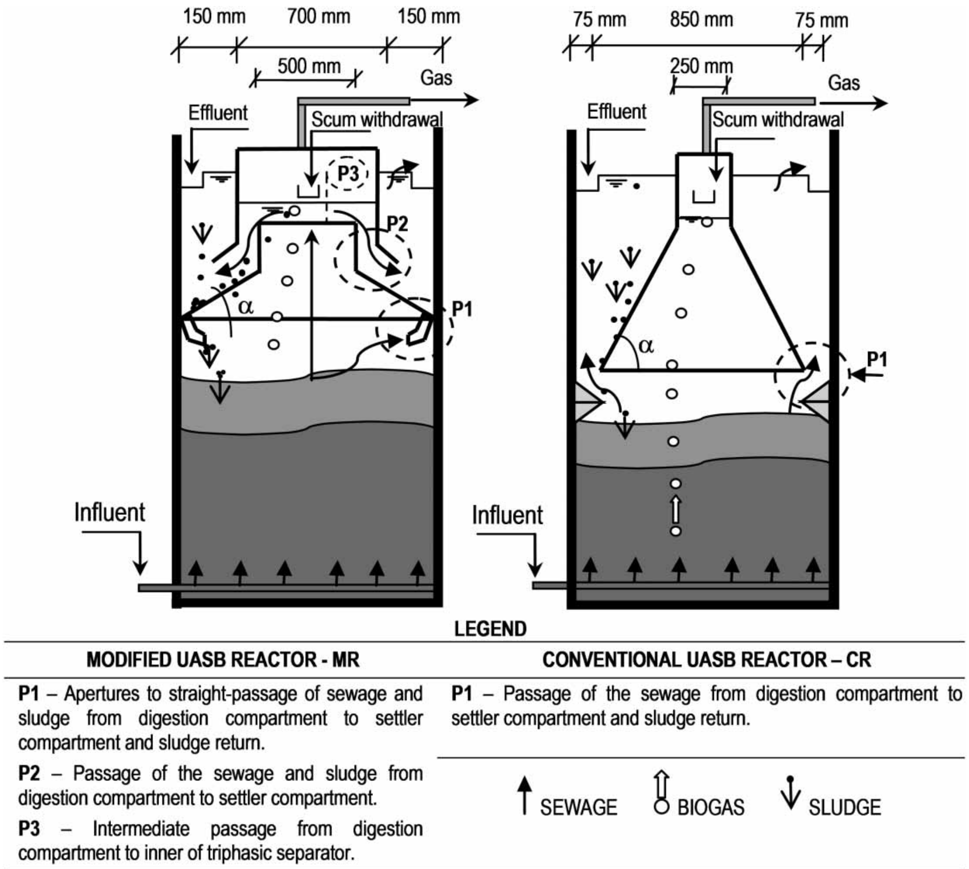

Figure 1 | Schematic configuration of the experimental reactors.

moving this material from separator to decanter. Thus, the decrease of scum production is expected in addition to the formation of a scum layer with higher fluidity.

METHODS

Experimental apparatus

Two UASB reactors called, conventional reactor (CR) and modified reactor (MR) in demo-scale were installed in the wastewater treatment plant (WWTP at Ouro Branco, Brazil (population served of 35,000), and fed with domestic wastewater after preliminary treatment. Schematic configurations of both reactors are presented in Figure 1. Following, details of different configurations and operating principles are presented.

The MR has an uncoupled gas compartment to the inclined wall in order to eliminate the dead zone in the GSL separator that causes scum accumulation. Therefore, an intermediate passage of sewage through the inner part of the triphasic separator (P3) was created, allowing the contact with the scum which eventually piles up in this area. Another passage was also created (P2) in order to achieve a decanter zone. Due to the fact that P2 area is larger than P1, the biggest amount of effluent flows from the digestion compartment to the settler compartment through the separator (81%) causing scum release. Moreover, the minor part of the sewage flows through P1, facilitating the sludge return from the settler compartment to the digester zone. P1 devices consist of 31 elbows (PVC – 50 mm – 45°) which were installed along the inclined walls and distanced 51 mm from each other. As the inclined walls have a 45 degree angle, biogas cannot access the settler compartment through P1, only effluent and solids washout can. The same happens with the conventional reactor. It is important to highlight that we have tested different dimensions of gas compartment, apertures of passage from the digestion compartment to inside the GSL separator, elbows, angles of inclined walls, and other parameters. All other features of the reactor are described in Table 1, together with the values that are given in standard NBR 12.209 of the Brazilian Technical Standards Association NBR 12.209 (ABNT 2011). Furthermore, special attention should be given to the major gas compartment area in this reactor because it is important for the results of scum production, as will be discussed later in this work.

Operational conditions

Both reactors' operations were fed by the same wastewater for more than 2 years before the beginning of this study (sludge already had adapted to the effluent) and worked with a flow hydrograph influent in order to simulate real operational conditions in a full-scale WWTP (Figure 2). For this, two timers were associated with a frequency inverter. The overflows applied during 24 hours were 1.15 (0.53 $m^3.h^{-1}$), 1.30 (0.60 $m^3.h^{-1}$) and 1.50 (0.69 $m^3.h^{-1}$) from the project flow of the reactors (0.46 $m^3.h^{-1}$). Moreover, due to the fact that the sewage system contains three pump installations, an hour-counter was installed in the devices to register the real time of operation and all the necessary parameters were rectified (organic loading rate; hydraulic retention time; time of scum production).

Table 2 summarizes the other reactor operation parameters in addition to the main characteristics of raw sewage influent in accordance with the hydrograph application which was presented in Figure 2. It is important to highlight that these values are different from the ones adopted by reactor design.

Monitoring

Samples of influent and effluent from both reactors were collected with a peristaltic pump twice a week during 24 hours and analyzed for total and filtered chemical oxygen demand (COD), total suspended solids (TSS) and VSS according to *Standard Methods for the Examination of Water and Wastewater* (APHA 2017). Scum layers were kept under collector gutters and fully removed from the three-phased separator with depressurization of the gas compartment in intervals ranging from 7 to15 days. Scum was separated from the sampled liquid by means of a sieve and the volume of the resulting concentrated scum sample was then measured and taken to the laboratory and analyzed for COD, total solids (TS) and TVS. Gas production was measured by means of wet gas meters installed in the experimental apparatus (LAO/G1) at intervals of 24 hours.

RESULTS AND DISCUSSION

Scum production

In addition to results of volumetric production of scum, which were obtained from five samples collected from both reactors and related to different measurement units,

Table 1 | Main characteristics of the reactors and values standardized by NBR 12.209

Compartment	Characteristic	NBR 12.209	Reactor CR	Reactor MR
Digestion + settler	Flow rate ($m^3.h^{-1}$)	–	0.46	0.46
	Useful volume (m^3)	–	3.69	3.69
	Mean temperature of sewage (18 °C – 21 °C)[a]	8.00	8.00	8.00
	Total useful depth (m)	4.00–6.00	4.65	4.65
	Gas compartment area (m^2)	–	0.05	**0.38**
Digestion	Volume (m^3)	–	2.77	3.02
	HRT mean (h)	–	6.00	6.54
	Minimum depth (m)	2.50	3.15	3.60
	Upflow velocity to mean flow rate ($m.h^{-1}$)	≤0.70	0.59	0.59
	Upflow velocity to maximum flow rate ($m.h^{-1}$)	≤1.20	0.87	0.87
Settler	Volume (m^3)	–	0.92	0.67
	HRT mean (h)	≥1.50	2.00	**1.46**
	HRT minimum (h)	≥1.00	1.33	**0.97**
	Useful depth (m)	1.50	1.50	**1.05**
	Superficial loading rate to maximum flow rate ($m^3.m^{-2}.h^{-1}$)	≤1.20	0.94	**1.72**
	Angle of inclined walls α (°)	≥50	70	**45**

[a]Mean temperature in the coldest month of year.

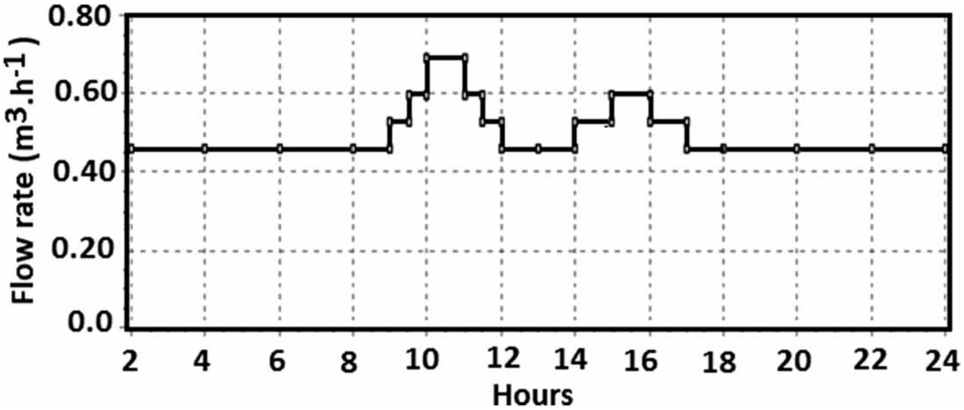

Figure 2 | Hydrograph of sewage influent of the experimental reactors.

Table 2 | Operational parameters

Parameter	Influent	Conventional UASB reactor	Modified UASB reactor
pH[a]	7.32	7.09	7.08
Temperature (°C)[a]	24.6	24.2	24.5
Median of volumetric organic loading rate (kgCOD. $m^3.d^{-1}$)	2.29	2.29	2.29
Flow rate ($m^3.d^{-1}$)[b]	11.76	11.76	11.76
HRT effective (h)[b]	–	7.53	7.53
Upflow velocity to mean flow rate ($m.h^{-1}$)[b]	–	0.62	0.62
P1 – Min. upflow velocity ($m.h^{-1}$)	–	2.12	1.40
P1 – Max. upflow velocity ($m.h^{-1}$)	–	3.18	2.10
P2 – Min. upflow velocity ($m.h^{-1}$)	–	–	1.22
P2 – Max. upflow velocity ($m.h^{-1}$)	–	–	1.83
P3 – Min. upflow velocity ($m.h^{-1}$)	–	–	1.90
P3 – Max. upflow velocity ($m.h^{-1}$)	–	–	2.86

[a]Mean parameter value of field measurement obtained between 9 a.m. and 11 a.m.
[b]Value calculated according to hydrograph of Figure 2.

Table 3 presents organic loading rate (OLR), time of accumulation (theoretical and corrected for real time of feed), and some descriptive statistics parameters. This table shows that the median of volumetric rates of scum, reading across the columns, were 0.90 L; 0.06 $L.d^{-1}$; 2.34 $L.m^{-2}$; 0.17 $L.m^{-2}.d^{-1}$; and 9.21 $mL.kgCOD^{-1}_{applied}$, in the MR, while for CR the values were 2.00 L; 0.19 $L.d^{-1}$; 40.73 $L.m^{-2}$; 3.78 $L.m^{-2}.d^{-1}$; and 21.01 $mL.kgCOD_{applied}.^{-1}$.

In comparison with CR, MR presented a perceptible reduction in volumetric scum production, varying between 40 and 65% (Figure 3(a)). This might happen because of the continuous scum release to the settler compartment, which is caused by the flow of the major part of the effluent through the separator (81%). Moreover, the high percentage of scum production reduction (94%), for the specific accumulation rate ($L.m^{-2}.d^{-1}$) (or scum layer equivalent – mm) and compared to volumetric production, indicates that a larger dimension of gas compartment (700 mm of diameter) improved scum control in MR. It has also resulted in a significant higher volume of recovered biogas, as will be discussed further. Scum yield was higher than observed by Santos (2014) and Rosa *et al.* (2017) who reported an average of scum yield which varied in the range 6.79–10.33 mL and 6.8–14.6 mL per kg COD applied in full-scale UASB reactors treating domestic sewage in Brazil (Laboreaux sewage treatment plant, designed and constructed for a population equivalent of 70,000 inhabitants). These differences, especially compared to CR (21.01 $mL.kgCOD^{-1}_{appied}$), probably were caused by the high hydraulic retention time (HRT) (>14 h) and the lower OLR used in those studies.

Table 3 | Volumetric scum production rates related to different measurement units

Sample	Accumulation time (days)		Influent OLR ($kgCOD.d^{-1}$)	Volume (L)		Volumetric rate ($L.d^{-1}$)		Specific volume ($L.m^{-2}$)[a] or equivalent scum layer thickness (mm)		Specific accumulation rate ($L.m^{-2}.d^{-1}$)		Scum yield coefficient ($mL.kgCOD_{app}^{-1}$)	
	Theoretical	Real		MR	CR	MR	CR	MR	CR	MR	CR	MR	CR
1	10	10.0	9.52	1.20	2.00	0.12	0.20	3.12	40.73	0.31	4.07	12.6	21.0
2	14	14.0	6.98	0.90	2.60	0.06	0.19	2.34	52.95	0.17	3.78	9.2	26.6
3	16	15.0	8.17	0.80	1.50	0.05	0.10	2.08	30.55	0.14	2.04	6.5	12.2
4	16	16.0	8.12	1.00	2.10	0.06	0.13	2.60	42.77	0.16	2.67	7.7	16.2
5	14	9.1	5.40	0.70	1.80	0.08	0.20	1.82	36.66	0.20	4.02	14.2	36.5
Mean			7.64	0.92	2.00	0.08	0.16	2.39	40.73	0.20	3.32	10.05	22.51
Median			8.12	0.90	2.00	0.06	0.19	2.34	40.73	0.17	3.78	9.21	21.01
Standard deviation			1.54	0.19	0.41	0.03	0,04	0.50	8.27	0.07	0.91	3.26	9.51
Coeff. of variation (%)			18.98	21.37	20.31	40.92	24.14	21.37	20.31	40.92	24.14	35.38	45.27

[a]Production related to area of gas compartment (see Table 1).

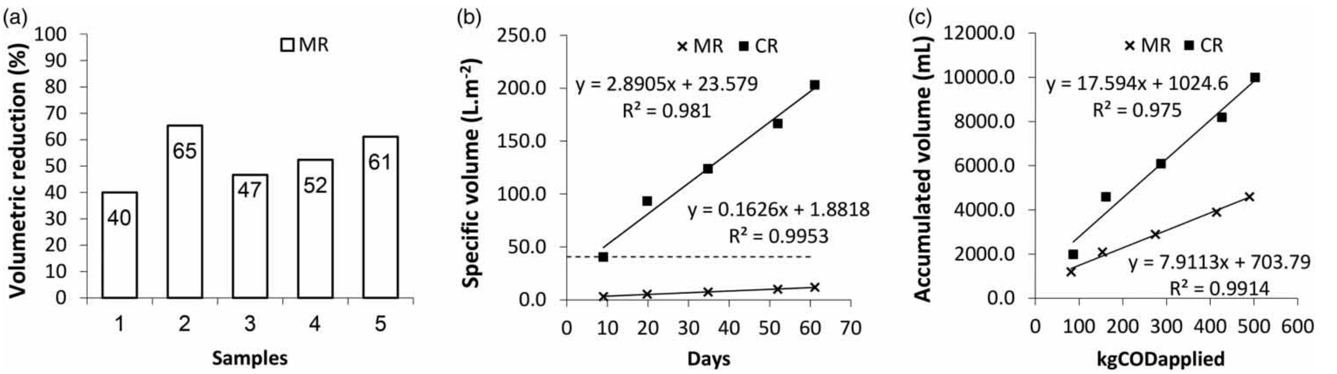

Figure 3 | (a) Volumetric reduction of scum production in the MR; (b) volumetric scum production accumulated as a function of accumulated days ($L.d^{-1}$); (c) volumetric scum production accumulated as a function of accumulated $kgCOD_{applied}$.

Figure 3(b) and 3(c) present the correlation between values of specific volumetric and accumulated scum production ($L.m^{-2}$) as a function of accumulated time (days) and accumulated OLR applied ($mL.kgCOD_{applied}^{-1}$) in order to indicate the production for a long-term or higher OLR. Although a simple sum of results from each collected sample does not represent the real situation, this figure express a reasonable overview about the differences between the scum accumulation in both reactors, in addition to bringing useful information for the prediction of volumetric scum production. It is interesting to notice that the rates of 0.16 $L.m^{-2}.d^{-1}$ and 7.91 $mL.kgCOD_{applied}^{-1}$, in MR, and 2.89 $L.m^{-2}.d^{-1}$ and 17.59 $mL.kgCOD_{applied}^{-1}$, in CR, are in the same order of magnitude, according to the median data in Table 3. As cause of the low specific accumulation rate ($L.m^{-2}.d^{-1}$), around 94%, even after 60 days, MR could not show a specific volume like the one observed in CR during only 10 days. Finally, this contrasts with the criterion of minimum rates of biogas release (Souza 1986) which is widely used in UASB reactor design in Brazil, and leads to reduction of gas compartment dimensions and consequently higher specific volume (or scum layer thickness equivalent).

Table 4 summarizes results of scum yield coefficient in terms of mass (COD, TS, volatile total solids (VTS)) per COD applied. As occurred with volumetric production, it can be noticed that in 100% of studied cases, values from MR were lower than CR, confirming the better performance of MR. Median values of these coefficients were 1.26 $gCOD.COD_{applied}^{-1}$, 0.86 $gTS.COD_{applied}^{-1}$ and

Table 4 | Mass scum production rates in terms of COD, TS and VTS

	Accumulation time (days)			Y_{Scum} – Scum yield coefficient					
				$gCOD.kgCOD^{-1}_{applied}$		$gTS.kgCOD^{-1}_{applied}$		$gVTS.kgCOD^{-1}_{applied}$	
Sample	Theoretical	Real	Influent OLR $kgCOD.d^{-1}$	MR	CR	MR	CR	MR	CR
1	10	10.0	9.52	1.53	3.74	1.67	6.86	1.49	6.56
2	14	14.0	6.98	1.26	5.22	0.95	6.02	0.81	5.66
3	16	15.0	8.17	0.89	1.89	0.74	1.50	0.64	1.40
4	16	16.0	8.12	1.10	2.83	0.70	2.13	0.53	1.88
5	14	9.1	5.40	1.96	5.56	0.86	2.96	0.67	2.15
Mean			7.64	1.35	3.85	0.99	3.89	0.83	3.53
Median			8.12	1.26	3.74	0.86	2.96	0.67	2.15
Standard deviation			1.54	0.41	1.56	0.40	2.40	0.38	2.39
Coeff. of variation (%)			18.98	32.63	41.63	46.15	81.15	57.23	111.51

0.67 $gTVS.COD^{-1}_{applied}$, for the MR. For the CR these values were found to be 3.74 $gCOD.COD^{-1}_{applied}$, 2.96 $gTS.COD^{-1}_{applied}$ and 2.15 $gTVS.COD^{-1}_{applied}$. According to the results observed in CR, the scum production reduction in MR was higher than 50% for all parameters (Figure 4(a)–4(c)). Souza *et al.* (2006) and Pereira *et al.* (2009) reported scum yield inside a GLS of 0.11–1.32 $gTS.COD^{-1}_{applied}$ for pilot- and demo-scale reactors fed with domestic sewage (average COD of 500 $mg.L^{-1}$).

The scatter charts and linear regression, presented in Figure 4, were built with the same methodology used for volumetric production, in order to show the production of scum in both reactors for a long-term or higher OLR. Based on these correlations, scum yield coefficients were found to be 1.09 $gCOD.COD^{-1}_{applied}$, 0.80 $gTS.COD^{-1}_{applied}$ and 0.65 $gTVS.COD^{-1}_{applied}$, for the MR; while for the CR these values are 2.99 $gCOD.COD^{-1}_{applied}$, 2.68 $gTS.COD^{-1}_{applied}$ and 2.38 $gTVS.COD^{-1}_{applied}$. In addition, it was also verified for volumetric production, as presented in Table 3. It also suggests that the production in MR over the long term tends to be lower than in CR, and the time of successive discharges possibly higher.

Reactors' performance

The domestic sewage from Ouro Branco is typically strong and with high concentrations of total COD (median of 778 $mg.L^{-1}$) and TSS (median of 416 $mg.L^{-1}$) as can be noticed in Figure 5(a) and 5(b). It is possible to see that reactors presented a similar performance in organic matter removal in terms of total COD and TSS with median concentrations of total COD of 189 and 202 $mg.L^{-1}$, respectively, for MR and CR; and 73 and 82 $mg.L^{-1}$, respectively, for TSS. Thus, it demonstrates that MR does not decrease organic matter performance in comparison with CR, even though its design does not follow values standardized by the Brazilian Technical Standards Association NBR 12.209 (ABNT 2011) notably in the settler compartment.

When the performance for organic matter removal is analysed from the point of view of standards related to effluent discharge in Brazil, Minas Gerais State (180 $mgCOD.L^{-1}$ or average from efficiencies observed of total COD removal major of 65%; 100 $mg.L^{-1}$ for TSS), the MR has shown suitable results. Averages of COD removal were 76% in the MR and 75% in the CR, while median values were 81% and 78%, respectively (Figure 6(a)). For TSS a similar performance was observed (Figure 6(b)). In this case, median values were seen to be 81% (MR) and 75% (CR). Considering the concentration standards for COD and TSS (Figure 6(c)), it can also be noticed that 75% of all the samples collected from MR were lower than 180 $mgCOD.L^{-1}$ and 100 $mgTSS.L^{-1}$ respectively. For the CR, these values were 65% and 60% respectively.

From these results, it is possible to confirm that the modified reactor presented a similar performance to the control reactor, notably for TSS, considering its settler compartment has been operating in overload conditions of superficial loading rate and with much lower HRT (Rocha *et al.* 2017). It could have been compensated for by the greater volume of the digestion compartment, even though the difference was small (8%) and its settler compartment was 28% lower than the control reactor.

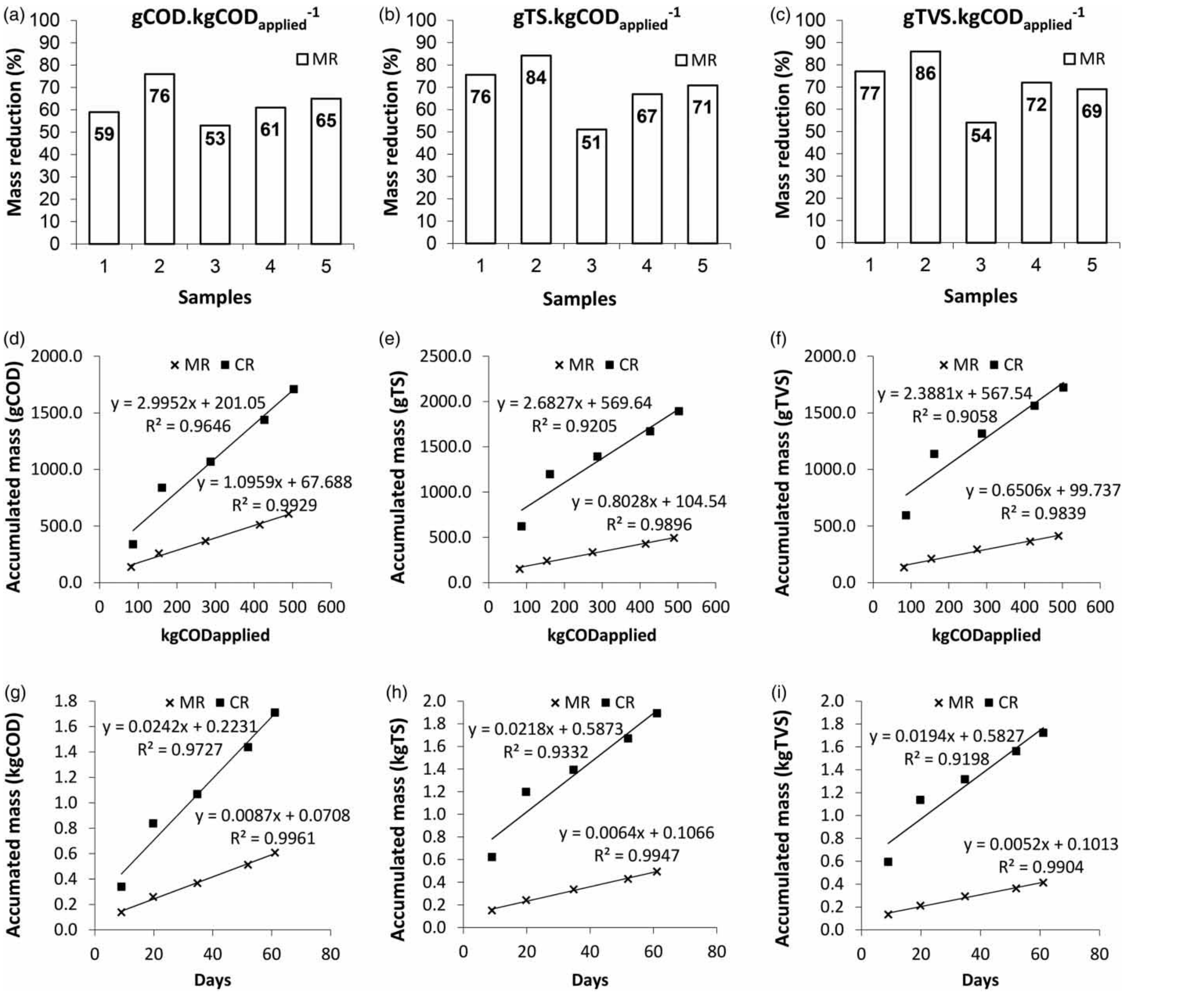

Figure 4 | Percentage of reduction on scum yield coefficient in terms of mass per COD applied: (a) gCOD.kgCOD$_{applied}^{-1}$, (b) gTS.kgCOD$_{applied}^{-1}$, (c) gTVS.kgCOD$_{applied}^{-1}$. Correlations between accumulated mass of scum and accumulated kgCOD$_{applied}$: (d) accumulated mass in terms of gCOD; (e) accumulated mass in terms of gTS; (f) accumulated mass in terms of gTVS. Correlations between accumulated mass of scum and accumulated days: (g) accumulated mass in terms of kgCOD; (h) accumulated mass in terms of kgTS; (i) accumulated mass in terms of kgTVS.

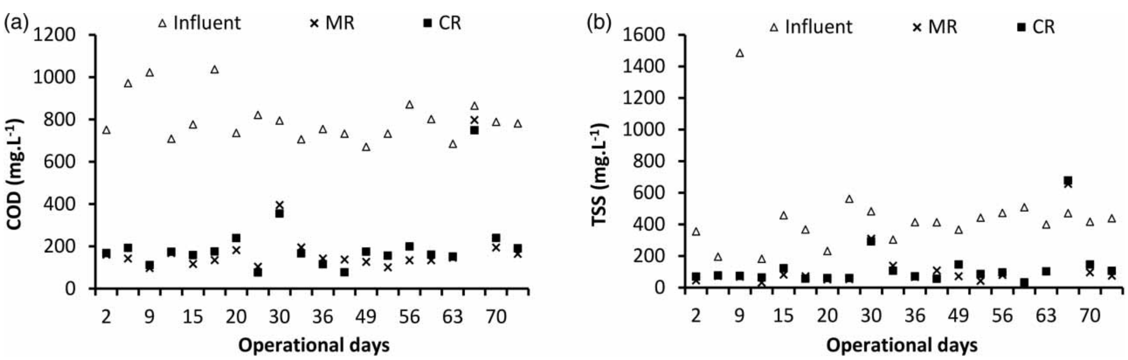

Figure 5 | Temporal series of the COD (a) and TSS (b) for influent and reactor effluents.

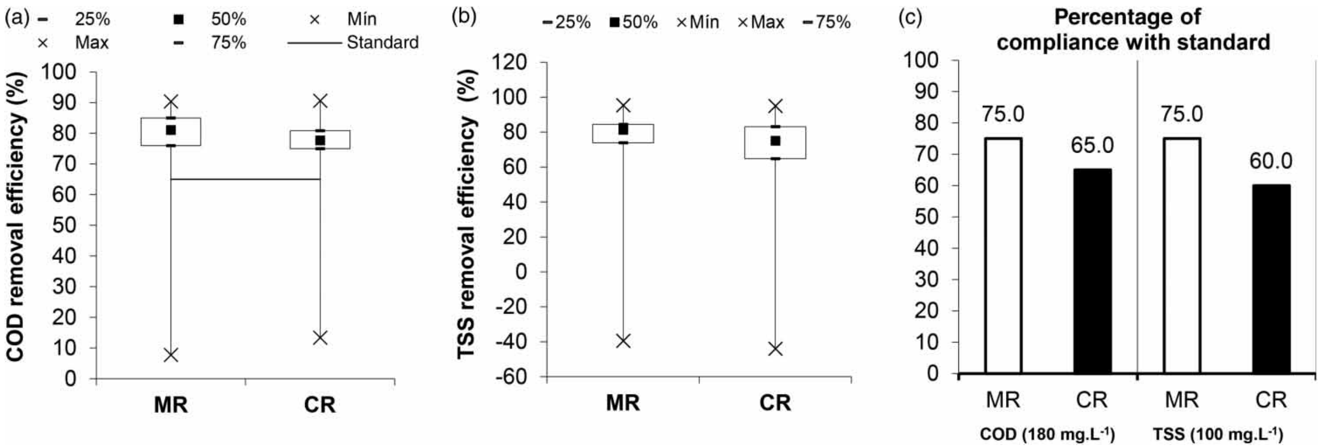

Figure 6 | Box-plot of total COD removal efficiency (a) and TSS (b); perceptual of compliance with standard (c).

The results show (Figure 7(a)) that median values for biogas production were 1.31 $m^3.d^{-1}$ (MR) and 0.86 $m^3.d^{-1}$ (CR), and a far higher biogas production was achieved in the modified reactor (52%). This might prove that the decrease of scum production in the separator and less concentrated scum formation might facilitate the biogas release in liquid phase. That effect has also been observed by Pereira *et al.* (2009), who obtained higher biogas regeneration in the reactor with a double-stage biogas collector. It is also possible that the detachment of methane which is dissolved into effluent may have occurred, whereas the sewage flow inside the separator generates higher shaking, favouring the biogas release from the liquid phase (Souza *et al.* 2012). In this way, besides small scum production allowing its easy removal from separator, small scum production also presents higher biogas recovery as an advantage. On the other hand, the larger gas compartment area might also play an important role in the process, whereas the generated layer thickness would be reduced in comparison with a conventional UASB. Thus, this could have contributed to the continuous separator scum removal, and consequent biogas separation in liquid phase. It must be also highlighted that the effects of other different gas compartment dimensions and sewage velocities through separator (P3) on dissolved gas detachment have been investigated for the proposed new GSL separator.

Finally, Figure 7(b) exhibits that the rate of biogas release was much lower than the minimum recommended by Souza (1986) for UASB reactor projects (1.0 $m^3.m^{-2}.h^{-1}$). As mentioned before, this criterion leads to reduced dimensions in the gas compartment, which could jeopardize the accessibility for maintenance and even scum removal by cesspool cleaning trucks. Additionally, such a criterion assumes that scum fluidity would be ensured only by biogas passage (contrasting with MR). However, Van Haandel & Lettinga (1994) indicates that conventional reactors applied to treat domestic sewage struggle to reach this minimum rate of biogas release.

CONCLUSIONS

The decrease of volumetric scum production in the modified reactor has shown average values of 50%, confirming that the proposed design is more efficient in comparison to the

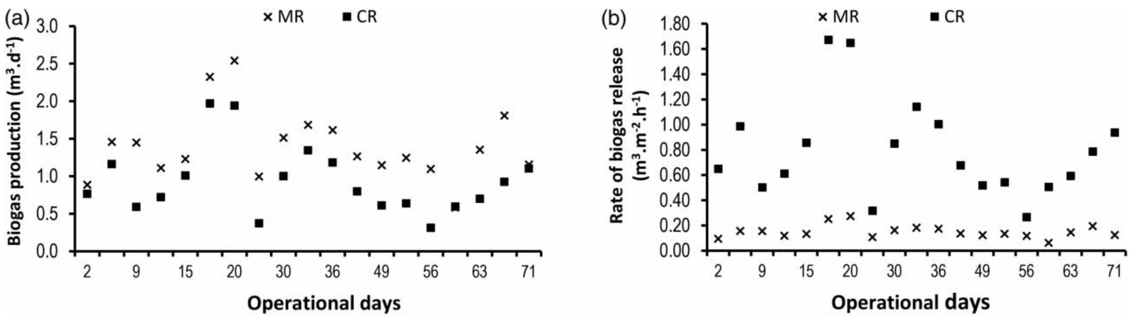

Figure 7 | (a) Biogas production; (b) rate of biogas release.

control reactor. It has also confirmed that the effectiveness of the continuous scum release mechanism to the settler compartment was caused by the flow of the biggest amount of effluent through the separator. The much larger gas compartment dimensions provided a reduced scum layer thickness, or specific scum production per unit of area, 93% lower in the modified reactor than in the control reactor. The combined effects can also improve the amount of gas regeneration in the modified reactor. In this case, MR presented a production 52% higher than that of CR. Therefore, the design of a gas compartment with larger dimensions has proved to be a suitable strategy for UASB reactors applied to treat domestic sewage.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support obtained from the following institutions: Brazilian Scientific and Technological Development Council – CNPq; Sanitation Company of Minas Gerais– COPASA; Minas Gerais Research Foundation – FAPEMIG.

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First received 28 December 2018; accepted in revised form 23 April 2019. Available online 2 May 2019