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A modified upflow anaerobic sludge blanket reactor as an alternative for decentralized domestic wastewater treatment in developing countries

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Abstract

The aim of this paper was to evaluate the performance of two modified upflow anaerobic reactor (RAns) as a decentralized technology for the treatment of high-strength domestic wastewater. Two full-scale anaerobic reactors (Ran_1 and Ran_2) with the same configuration and total volume of 14.6 m^3, total height of 2.57 m, and constructed from fibreglass reinforced plastics were operated with a 16-hour hydraulic retention time and submitted to a volumetric organic load less than 2.7 kg chemical oxygen demand $(COD)\cdot m^{-3}\cdot d^{-1}$. The RAns were monitored for 10 consecutive months and showed the capability to support the fluctuations of organic loading and volumetric rates. The compact anaerobic reactors proved to be effective in removing organic matter (biological oxygen demand removal efficiencies greater than 70% and the average soluble COD removal efficiencies greater than 57.4%). The solids profile in the reactor ranged from very dense particles with good settleability close to the bottom (sludge bed) to a more dispersed and light sludge close to the top of the reactor (sludge blanket), similar to conventional UASB reactors.

Key words: anaerobic process, decentralized treatment, domestic wastewater, sludge blanket reactor

INTRODUCTION

During the last decade, the trend in urban sanitation in most developing countries has been to collect and transport domestic wastewater through large sewer systems from the generation site to a central wastewater treatment plant (WWTP). However, this approach requires massive investments during the installation step and presents high operational costs, and all the inhabitants of a city are not guaranteed to benefit from it. Therefore, there has been increased interest in the installation of decentralized wastewater treatment systems that employ a combination of onsite and/or cluster systems both in peri-urban and rural areas of small and medium-sized municipalities (Massoud *et al.* 2009; Singh *et al.* 2014; Chernicharo *et al.* 2015). Abbassi *et al.* (2018) state that in the USA alone, around 60 million people are connected to on-site wastewater treatment systems.

Regarding the technology used in decentralized wastewater treatment, the anaerobic process has been well established due to some characteristics, such as good cost-benefit relationship; compactness; low electricity demand; low sludge production; and reduced installation, operation and maintenance costs (Moussavi *et al.* 2010; Singh *et al.* 2014; Capodaglio *et al.* 2017). High-rate anaerobic reactors, mainly upflow anaerobic sludge blanket (UASB) reactors and modified versions, have been widely used in developing countries such as India, Vietnam, Colombia, Mexico and Brazil (Noyola *et al.* 2012; Chernicharo *et al.* 2015; von Sperling 2016).

Despite the increasing adoption of the anaerobic process in small and decentralized wastewater treatment, a stable and reliable full-scale operation is still a challenge. Some studies performed in experimental-scale showed a good potential for decentralized anaerobic treatment, mainly regarding the results of organic matter and solids removal. However, the experimental scale data and results are not always similar to those found during a full-scale operation, which is subject to operational and maintenance problems in addition to the variations of hydraulic and organic loads that occur every day. Therefore, the aim of this work was to evaluate the full-scale performance of two decentralized, compact and modified upflow anaerobic sludge blanket reactors (RAns) with the same configuration and designed for treating high-strength wastewater generated by an educational centre. Additionally, the impacts of hydraulic and organic load variation on process performance, quantity and quality of anaerobic sludge were evaluated.

METHODS

The most important principles that govern the operation of the conventional UASB reactors are the upward flow that assures maximum contact between the biomass and the substrate and the installation of a three-phase separator in the upper part of the reactor, capable of suitably separating the biogas, liquid and solids, releasing the first two and allowing the retention of the last (von Sperling & Chernicharo 2005). Table 1 shows the main characteristics of RAns (Figure 1) and highlights the differences between them and the conventional UASB reactors.

Ran1 and 2 have the same design and operational configuration. The RAns (Figure 1) have a conical shape, total volume of 14.6 m^3, total height of 2.57 m and were constructed from fibreglass reinforced plastics (FRP) which makes them very light (190 kg) and easy to transport to remote regions. The total installation time for these modified anaerobic reactors is less than one week and does not require highly specialized workers. The depths of the digestion and settling compartments are 1.60 and 0.75 m, respectively. Each of the anaerobic reactors was sized to receive an average flow rate of 1.7 $m^3 \cdot h^{-1}$ and a maximum flow rate of 2.9 $m^3 \cdot h^{-1}$ and has been in continuous operation for over three years.

Before reaching the RAns, the influent wastewater is subjected to a preliminary treatment for the removal of oils, grease, coarse solids and sand. After this step, the wastewater is pumped to a flow distribution tank with two triangular weirs installed to deliver equal flow to both anaerobic reactors. In this way, the two RAns receive flow from the same source. The reactors have an influent distribution device located in the upper part of the reactor (see Figure 1(b)) which transports the influent to two 100 mm diameter distribution tubes. These distribution tubes transport the wastewater to the reactor bottom.

The treated effluent is collected in the upper part of the RAns, within the sedimentation compartment, through a single 150 mm diameter pipe. Sludge sampling is provided by three stainless steel ball valves installed along the height of the digestion compartment at 0.44, 0.87 and 1.30 m from the bottom of the RAns. The periodic removal of sludge occurs by means of two hydraulic gate valves. One is located close to the bottom of the reactor and another approximately 0.90 m above the bottom. The RAns are also equipped with one gate valve connected to a 100 mm diameter pipe to remove the scum that accumulates on the surface of the settler compartment.

The monitored decentralized WWTP is located at coordinates 12°56′9.23″S and 38°24′4.98″W, in Salvador city, Bahia State, Northeast region of Brazil. According to the Köppen classification system, the climate is Cwa-tropical humid, the average annual temperature is 25.2 °C and the average annual precipitation value is 1,781 mm. The WWTP occupies a total area of 81.1 m^2 and was designed to treat a flow rate of 5.8 $m^3 \cdot h^{-1}$ (about 1,582 inhabitants) in two equal anaerobic reactors (Ran_1 and RAn_2).

The RAns were monitored over 10 consecutive months. An Incontrol® ITS 2000 flow meter was installed in a Parshall flume to measure influent flow. The daily hydraulic profile was constructed

Table 1 | Physical and operational parameters of RAns and conventional UASB reactors

Parameters	RAns	Conventional UASB reactor
Useful heights	2.35 m	4.0–6.0 m
Height of settler compartment	0.75 m	1.5–2.0 m
Height of digestion compartment	1.60 m	2.5–3.5 m
Influent distribution	Upflow	Upflow
Influent distribution system	Consists of a device that divides the influent flow in two 100 mm-diameter distributing tubes.	Consists of small compartments (boxes) fed by weirs that divide the influent flow in several 75–100 mm diameter distributing tubes.
Distance between the exit mouth and the bottom of the reactor (m)	0.30 m	0.10–0.15 m
Influence area of each influent distribution tube	2.9 m^2	2.0–3.0 m^2
Three-phase separator	Installed in the upper part of the reactor.	Installed in the upper part of the reactor.
Scum removal	The scum is removed through two 100 mm-diameter pipes.	Scum baffles can be attached to the effluent collection launder (as an option).
Effluent collection system	The effluent is collected from the reactor in its upper part, within the sedimentation compartment through a 150 mm-diameter pipe, without devices.	The effluent is collected from the reactor in its upper part, within the sedimentation compartment. The devices usually used for the collection of the effluent are plates with V-notch weirs
Biogas removal system	Consists of a gas chamber (internal part of the three-phase separator) and a hydrogen sulfide filter. The biogas is released into the atmosphere.	Consists of a gas chamber (internal part of the three-phase separator) and a gas burner when the biogas is not used.
Sludge sampling system	Three pipes (50 mm-diameter each) with ball valves installed at 0.44, 0.87 and 1.30 m from the bottom of the reactor.	Consists of a series of ball valves installed along the height of the digestion compartment (spaced 50 cm from the base of the reactor) and 25–50 mm-diameter pipes for the sampling
Sludge discharge system	Two sludge discharge pipes close to the bottom of the reactor, 150 mm-diameter each.	At least two sludge withdrawal points should be planned, one close to the bottom of the reactor and another approximately 1.0–1.5 m above the bottom. Minimum diameter of 100 mm for the sludge discharge pipe.
HRT	16 hours for average flow (25.5 °C)	6 to 9 hours for average flow (wastewater temperature in the range of 20 to 26 °C)
HRT (sedimentation compartment)	4 hours (Average flow) 1.5 hours (Maximum flow)	1.5–2.0 (Average flow) >1.0 (Maximum flow)
Upflow velocities	0.2 m/h (Average flow) 0.3 m/h (Maximum flow)	0.5–0.7 m/h (Average flow) $<$ 0.9–1.1 (Maximum flow)

Notes: HRT = hydraulic retention time. Source of the data and information obtained for conventional UASB: Chernicharo (2007) and von Sperling (2016).

using the mean values of hourly flows. Composite samples of the wastewater and treated effluent were collected once a week. These samples were refrigerated and immediately sent and analysed in the Laboratory of Waste and Wastewater Treatment of the Polytechnic School, Federal University of Bahia, Brazil. The parameters monitored were: biological oxygen demand (BOD), total and soluble chemical oxygen demand (COD_{tot} and COD_{sol}), total suspended solids (TSS), volatile suspended solids (VSS), settleable solids (SS), total and ammonia nitrogen, phosphate, alkalinity, pH value, total volatile acids (TVA) and n-Hexane extractable material (fat, oil and grease – FOG). The

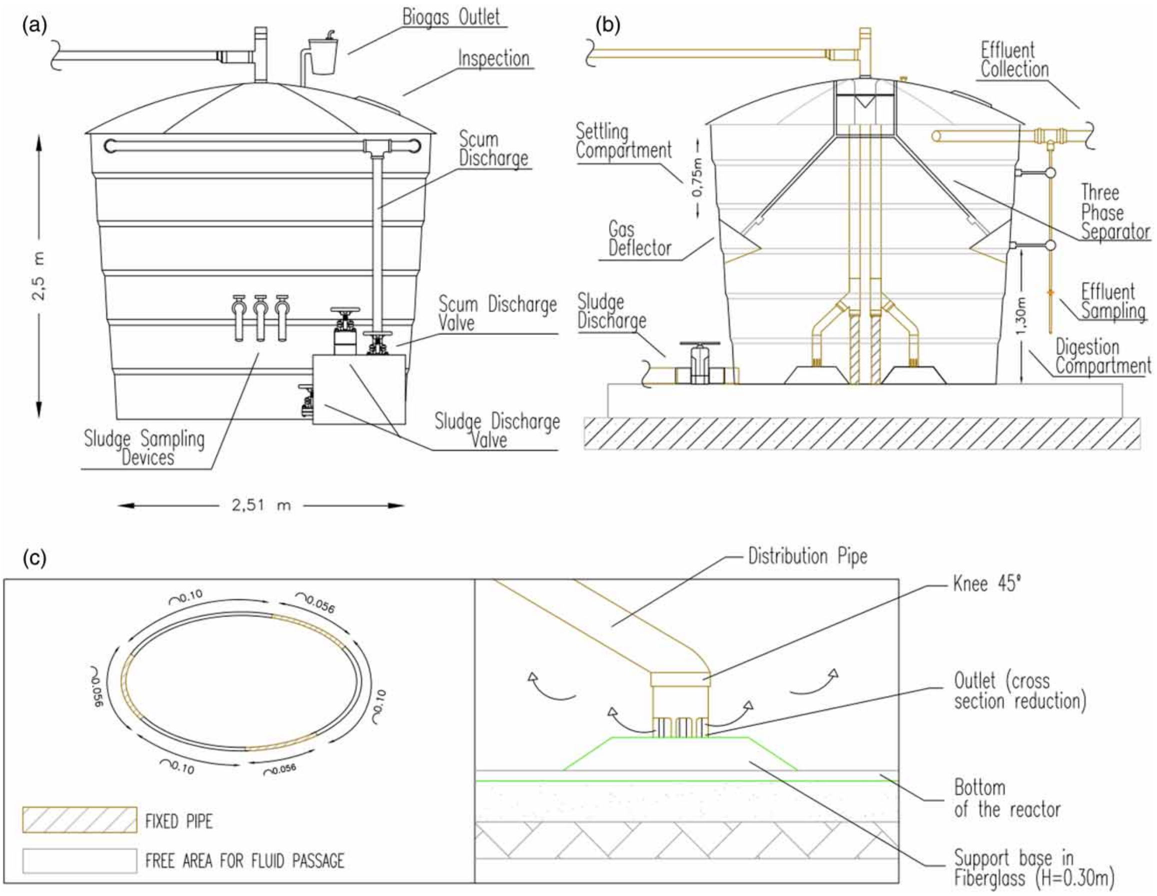

Figure 1 | Schematic drawing of the RAns. (a) External Configuration of the RAns. (b) Internal Configuration. (c) Influent distribution at the bottom of the reactor.

procedures for collecting and preserving the samples and the methods of analysis followed the recommendations of the Standard Methods (APHA; AWWA; WEF 2012). All samples were analysed in triplicate.

The influent presented pollutant concentrations from medium to high when compared with values usually typical of domestic sewage (Oliveira & von Sperling 2011). In general, the wastewater generated in educational centres is characterized by high ammonia concentrations and organic loads. Table 2 shows the main characteristics of the wastewater generated and compares the main characteristics with typical domestic wastewater treated in full-scale wastewater treatment plants operating in Brazil (Oliveira & von Sperling 2011).

Descriptive statistics (average, standard deviation, minimum, maximum) and the removal efficiencies were also calculated. Individual control charts were used to analyse the stability of the process regarding the removal of SS, TSS, COD and BOD. The control charts consist of a lower control limit (LCL), upper control limit (UCL) and a midline. The average value was used as the midline, assuming that the process average (X) is known and the data follow a Gaussian distribution.

The evaluation of the biological sludge was performed on a biweekly basis and made through the determination of the volatile solids (VS) profile. Grab samples were collected at three levels of the reactor (0.44, 0.87 and 1.30 m, from the bottom) and analysed following the recommendations of the Standard Methods (APHA; AWWA; WEF 2012). The results were expressed in terms of grams of volatile solids per litre ($gVS{\cdot}L^{-1}$). These concentration values of VS (made for each of the sludge sampling points along the reactor height), multiplied by the volumes corresponding to each sampled zone, provided the mass estimation of microorganisms along the reactor. The sum of the biomass quantities in each zone was assumed to be equal to the total solids in the reactor.

Table 2 | Main characteristics of the educational centre wastewater and typical domestic wastewater

		Educational centre wastewater			Typical domestic wastewater[a]
Parameter	**Unit**	**Mean**	**Range**	**Standard deviation**	**Mean**
BOD	$mgO_2 \cdot L^{-1}$	441.1	200.0–844.0	147.9	371.0
COD	$mgO_2 \cdot L^{-1}$	925.6	550.6–1,495.6	267.7	715.0
Soluble COD	$mg \cdot L^{-1}$	478.9	227.3–850.3	131.1	–
TSS	$mg \cdot L^{-1}$	334.0	180.0–883.0	189.6	289.0
Settleable solids	$mL \cdot L^{-1}$	14.5	0.1–58.0	15.1	–
Fat, oil and grease (FOG)	$mg \cdot L^{-1}$	20.4	5.0–47.0	15.0	–
Phosphate	$mg \cdot L^{-1}$	10.5	8.4–15.8	1.5	7.0
Total nitrogen	$mg \cdot L^{-1}$	145.8	128.3–184.8	17.1	43.0
Ammonia nitrogen	$mg \cdot L^{-1}$	108.7	86.6–131.6	11.0	–
pH value	$mg \cdot L^{-1}$	7.7	6.5–8.7	0.5	–
Alkalinity	$mg \cdot L^{-1}$	367.6	220.2–447.8	49.6	–
Total volatile acids (TVA)	$mg \cdot L^{-1}$	169.0	107.5–232.1	43.7	–

Notes: Number of samples of the educational centre wastewater analysed per parameter (n): BOD (18), COD (19), Soluble COD (20), TSS (20), Settleable solids (20), pH value (20), Alkalinity (20), TVA (11), Ammonia nitrogen (16), Total nitrogen (16), Phosphate (20), FOG (20). [a]Concentration of typical domestic wastewater affluent to UASB reactors in Brazilian municipalities (Oliveira & von Sperling 2011).

RESULTS AND DISCUSSION

Technical analysis of the anaerobic reactors

The performance of the RAn was similar to those found by Oliveira & von Sperling (2011) in a conventional UASB reactor in terms of organic matter and solids removal, even with the Ran operating under low organic loading (less than $2.7\ kgCOD_{tot} \cdot m^{-3} \cdot d^{-1}$). Analysing the design criteria, the RAn was more compact than the UASB reactor, in relation to the heights of the digestion and settling compartments.

Table 3 presents a summary of the descriptive statistics of concentrations and removal efficiencies for each parameter studied. The values of pH ranged from 7.1–7.8. These values are considered adequate to achieve the stability of the anaerobic process, as mentioned by Chernicharo (2007). Furthermore, it should be noted that the concentration of alkalinity was greater in the RAn's effluent than in the influent. Considering these results, the anaerobic digestion process occurred normally and, consequently, no signs of instability or acidification were observed.

Considering the flow pattern presented in Figure 2, each reactor received an average flow rate of $22.1\ m^3 \cdot d^{-1}$, resulting in a hydraulic retention time (HRT) of 16 hours, upflow velocity of $0.2\ m \cdot h^{-1}$ and volumetric hydraulic load of $1.5\ m^3 \cdot m^{-3} \cdot d^{-1}$. The upflow velocity was far below the range recommend by von Sperling & Chernicharo (2005) ($0.5–0.7\ m \cdot h^{-1}$) to prevent sludge washout in a traditional UASB. However, the low upflow velocity was favourable to avoid preferential pathways or hydraulic short circuits in the sludge bed. Al-Shay & Mahmoud (2008) and Al-Jamal & Mahmoud (2009) also reported very low upflow velocities (0.05 and $0.02\ m.h^{-1}$) in the UASB-septic tanks (improvement of the septic tank by applying upward flow and gas/solids/liquid separation device at the top).

The removal of organic matter and solids has not been compromised, even when the RAn was receiving wastewater from 07:00 am to 09:00 pm, which demonstrates the operational flexibility of these reactors. However, the application of lower average flows than expected ($1.7\ m^3 \cdot h^{-1}$) and the absence of pronounced flow peaks, certainly contributed to this good performance.

Figure 3 shows the BOD removal in each reactor (two separate curves) and the applied organic load during the monitoring period. The average BOD removal efficiency was 79.1% and 75.8%

Table 3 | Descriptive statistics of the concentrations and removal efficiency of the parameters monitored

		RAn$_1$		RAn$_2$	
Parameters	**Statistic**	**Conc. (mg·L^{-1})**	**Effic. (%)**	**Conc. (mg·L^{-1})**	**Effic. (%)**
BOD	Mean	91.5	78.2	99.0	76.5
	Range	42.7–150.0	54.3–91.3	52–152	61.7–86.3
	Standard deviation	33.5	8.3	33.1	7.2
COD$_{tot}$	Mean	280.4	67.8	263.9	68.5
	Range	234.0–380.7	52.7–82.0	199.7–376.9	56.9–81.0
	Standard deviation	36.3	8.1	40.8	6.4
COD$_{sol}$	Mean	198.1	57.5	182.0	61.1
	Range	125.7–334.3	37.4–70.0	117.1–345.4	48.5–61.2
	Standard deviation	52.8	9.0	49.6	7.0
TSS	Mean	66.8	75.9	57.8	79.4
	Range	50.5–80.3	61.1–92.0	46.0–77.0	67.6–93.0
	Standard deviation	9.0	9.2	9.4	7.4
VSS	Mean	58.7	76.6	50.6	79.6
	Range	41.3–68.5	61.6–90.9	39.1–68.5	67.2–91.8
	Standard deviation	7.6	8.5	8.5	6.9
Settleable solids (mL·L^{-1})	Mean	0.6	87.7	0.3	96.3
	Range	0.1–1.8	37.5–100.0	0.0–0.9	82.0–100.0
	Standard deviation	0.5	16.8	0.3	5.2
pH	Mean	7.4	–	7.4	–
	Range	7.1–7.8	–	7.1–7.7	–
	Standard deviation	0.2	–	0.1	–
Alkalinity	Mean	520.5	–	525.0	–
	Range	440.0–661.1	–	450.6–662.2	–
	Standard deviation	59.9	–	58.2	–
TVA	Mean	50.5	–	49.6	–
	Range	22.0–73.9	–	35.7–72.1	–
	Standard deviation	13.4	–	10.9	–
Ammonia nitrogen	Mean	125.3	–	126.8	–
	Range	109.4–142.7	–	108.5–154.1	–
	Standard deviation	10.5	–	10.1	–
Total nitrogen	Mean	141.0	2.9	138.6	4.5
	Range	116.7–173,4	0.0–17.5	117.3–172.7	0.0–22.1
	Standard deviation	16.6	8.9	14.9	8.7
Phosphate	Mean	10.8	–	10.5	–
	Range	7.9–13.6	–	7.9–12.8	–
	Standard deviation	1.6	–	1.4	–
FOG	Mean	6.5	48.1	6.2	47.9
	Range	5.0–16.0	0.0–89.0	5.0–12.0	0.0–89.0
	Standard deviation	3.2	33.7	2.3	38.0

Notes: Number of samples per parameter at each sampling point (n): BOD (18), CODtot (19), CODsol (20), TSS (20), settleable solids (20), pH (20), Alkalinity (20), TVA (11), ammonia nitrogen (16), total nitrogen (16), phosphate (20), FOG (20).

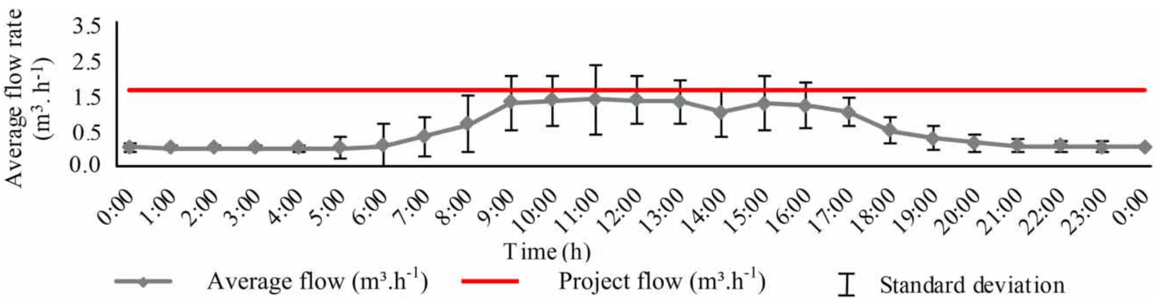

Figure 2 | Flow pattern constructed with the average flows observed during the monitored period in each reactor.

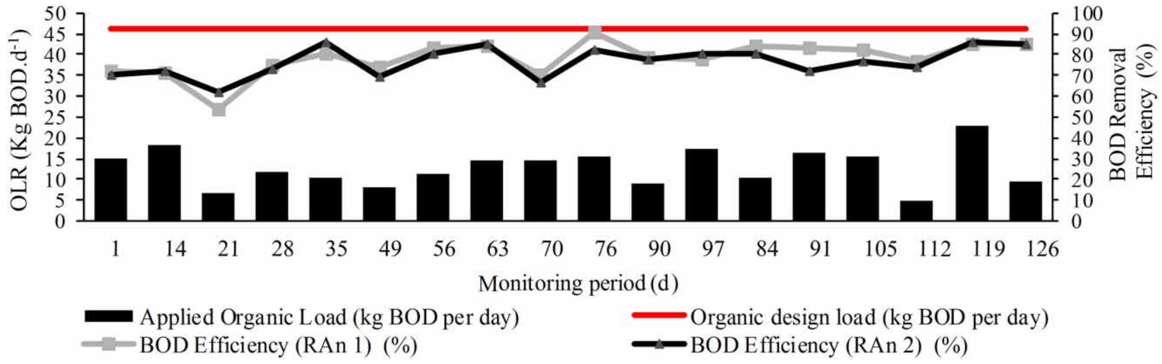

Figure 3 | Removal profiles of BOD as a function of applied organic load (kgBOD.d^{-1}).

respectively, for RAn1 and 2. Despite the variations of organic load (5.1–23.1 kgBOD·d^{-1}), the removal efficiencies can be considered satisfactory when compared to the typical efficiencies of UASB reactors (60–70%) (von Sperling 2016), demonstrating, therefore, that the RAns are reliable.

The BOD removal efficiencies were probably associated with the adequate organic load applied to each reactor. Therefore, considering the safety factor, it was confirmed that the minimum detention time (16 hours) and the maximum applied organic load (20.0 kgBOD.d^{-1}) guarantee BOD removal efficiencies superior to 70%. The average COD$_{sol}$ removal efficiency (57.4% RAn$_1$ and 61.2% RAn$_2$) was slightly lower than the COD$_{tot}$ removal efficiency (67.8% RAn$_1$ and 68.5% RAn$_2$). Considering the operational conditions, this result leads to the conclusion that the anaerobic process was not significantly affected by the reduction of the digestion compartment height.

The mean value of the TSS concentration for the anaerobic reactor influent (334.0 mg·L^{-1}) was reduced to 66.8 and 57.8 mg·L^{-1} for RAn$_1$ and RAn$_2$, respectively, resulting in removal efficiencies of 75.9% and 79.4%. The mean TSS efficiencies were very similar to the range indicated by von Sperling (2016) (60–80%) for traditional UASB reactors. Certainly, the excellent results of solids removal were favoured by the high HRT in the sedimentation compartment (4.0 h).

Giraldo *et al.* (2007) and Chernicharo *et al.* (2015) found that the maximum removal efficiencies achieved in full-scale UASBs operating in Latin America for BOD, COD and SS reached 75–85%, 70–80% and 70–80%, respectively. Thus, the performance of the modified UASB reactor observed in this study was similar to those found in full-scale UASB reactors, although the former operates under low load organic rate conditions (less than 2.7 kgCOD·m^{-3}·h^{-1}). For this reason, the modified RAn could be an interesting treatment technology for decentralized wastewater management in small-scale applications with low organic loads.

The FOG removal efficiency of both reactors (48%) was due to the fact that floating material, such as grease and oil, tend to have a lower density than the surrounding liquid and therefore rise to the surface of the sedimentation compartment contributing to the formation of a thick scum layer, as shown in Figure 4.

During the monitoring period, the scum removal was performed manually through the inspection opening. The scum removal device (a 100 mm-diameter pipe on the surface of the settler compartment and one gate valve) proved to be inadequate. The failure of this device was due to the encrustation of floating material mainly inside the 100 mm pipe. Chernicharo *et al.* (2015) recommended the use of a scum baffle on the surface of the settling compartment and the use of a peripheral channel with triangular weirs for the removal of scum. In addition, it is also advisable to install inspection points and devices for the removal of accumulated scum inside the three-phase separator.

Ammonia nitrogen and phosphorus removal efficiencies were insignificant. The reason for the low nutrient removal is that during the anaerobic process, organic nitrogen and phosphorous are hydrolysed to ammonia and phosphate, which are not removed from the system; thus, their concentration increases in the liquid phase (Khan *et al.* 2011). The mean ammonia nitrogen concentrations were

Figure 4 | Formation of a thick scum layer at the settler compartment surface.

125.3 mg·L^{-1} (RAn$_1$) and 126.8 mg·L^{-1} (RAn$_2$). The concentration of ammonia nitrogen in anaerobically treated municipal wastewater has been reported to range from 30–50 mg·L^{-1}. These high concentrations of treated effluent ammonia nitrogen from the RAns are related to the fact that a school does not produce the same type of domestic wastewater. In general, we characterize school sewage by many toilet flushes. This results in high concentrations of ammonia in school wastewater. The mean phosphorus concentrations were 10.8 mg·L^{-1} (RAn$_1$) and 10.5 mg·L^{-1} (RAn$_2$).

As mentioned by Chernicharo (2007), when the purpose is biological nitrogen and phosphorus removal, the use of anaerobic reactors is not advisable. Therefore, the effluent should be directed to a complementary treatment system to meet the standards of the Brazilian legislation for effluent disposal in aquatic environments. However, the effluent presents the potential for water reuse in agriculture but is necessary to include a disinfection step after the RAn.

In order to evaluate the stability of the anaerobic reactors for the removal of organic matter and solids, quality control charts of the RAn$_2$ effluent were studied (Figure 5). The upper specification

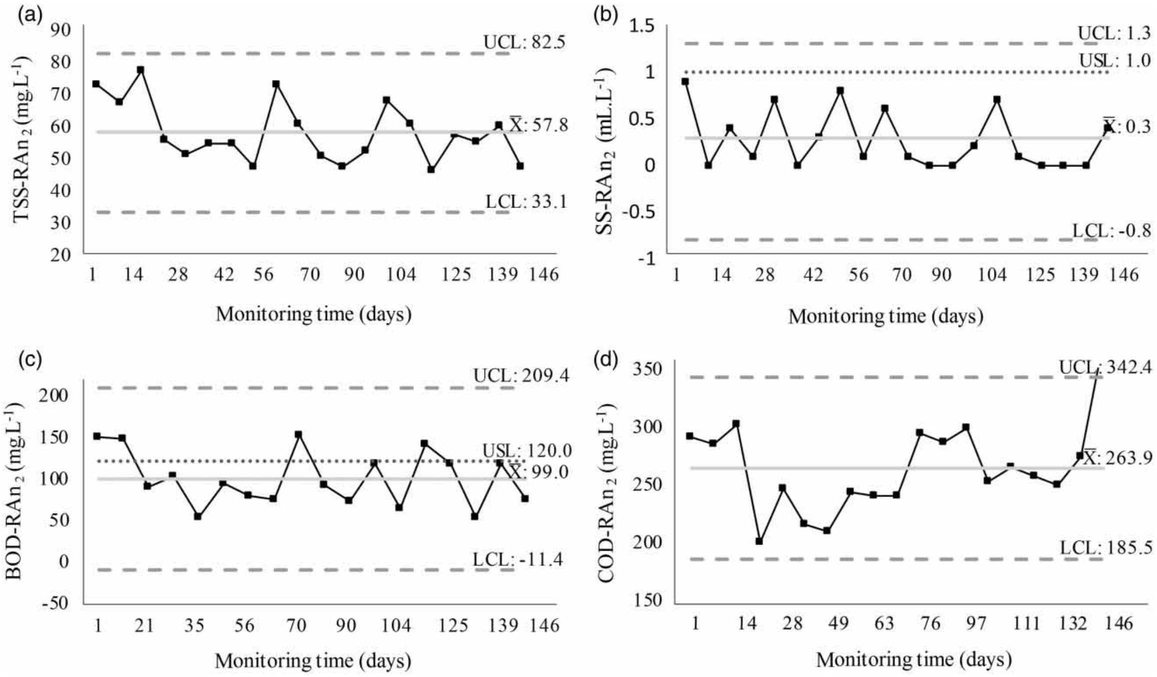

Figure 5 | Individual control charts of the RAn$_2$ effluent for total suspended solids (a), settleable solids (b), BOD (c) and COD (d).

limits (USL) for BOD and SS represent the Brazilian directives from Resolution 430/2011, published by the Brazilian Environmental Council (CONAMA), related to the specification of quality standards for effluent discharge into receiving water bodies. Figures 5(a) and 5(b) show that the values of the SS and TSS parameters are inside the limits of statistical control. Therefore, the reactor presented satisfactory performance in the removal of solids throughout the monitoring period.

High variability is noted (values ranged from 119.6–376.9 $mgO_2 \cdot L^{-1}$) in the values of COD. However, only one result is above the upper control limit. This result may be related to the influent quality which presented the highest COD concentration (1,495.6 $mgO_2 \cdot L^{-1}$) during the monitoring period. Despite this very high COD concentration, the removal efficiency was still satisfactory (75.0%). A single measurement located slightly above the control limit is not necessarily a cause for concern. However, frequent violations should be investigated to have the cause determined. In addition, while analysing the BOD control chart, it was verified that the organic matter removal is under statistical control since it does not present discrepant points out of control limits.

Regarding the BOD, the Brazilian directive establishes a maximum concentration of 120 $mgO_2 \cdot L^{-1}$ or a minimum removal efficiency of 60%. Observing the data in Figure 3, all the samples presented BOD removal efficiencies above the legislation value. Therefore, the process is within statistical and environmental limits.

The evaluation of the concentration of RAn's biomass was made through the determination of the total and VS profile in the digestion compartment (Figure 6). The total solids concentration at the bottom of the reactor varied between 40–80 $gTS \cdot L^{-1}$ (P1). The total solids concentration in the sludge blanket compartment (P2 and P3) was less than 35 $gTS \cdot L^{-1}$ during the entire monitoring period. Therefore, the solids profile in the reactor ranged from very dense particles with good settleability close to the bottom (sludge bed) to a more dispersed and light sludge close to the top of the reactor (sludge blanket) similar to a conventional UASB reactor.

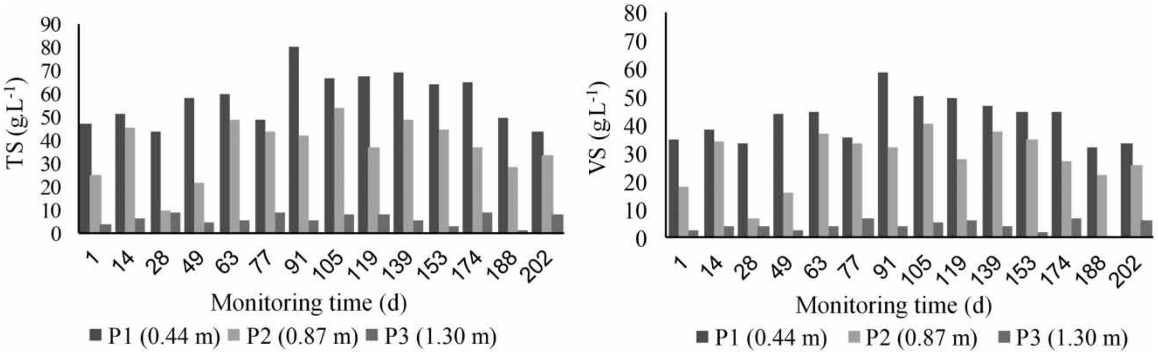

Figure 6 | Evaluation of the total and volatile solids profile in the digestion compartment of RAn_2.

The VS/TS ratio in the sludge deposited in the bottom of the reactors decreased from 0.75 to close to 0.65 after six months of monitoring, indicating digestion and stabilization of the retained solids in the RAn. This result demonstrated that this anaerobic reactor is also a sludge digester like the traditional UASB reactors. In addition, these results are in accordance with Ángel *et al.* (2018) and Al-Jamal & Mahmoud (2009) who reported a VS/TS ratio of 0.64 and 0.67, respectively in UASB-septic tank treating domestic wastewater.

The average amount of biomass accumulated inside the RAn during the operational period was 172 kg of VS, which represents an average biomass concentration of 2.0% in the digestion compartment. The sludge bed was the zone of the digestion compartment in which the greatest amount and concentration of biomass was observed. The average values were 93 kg VS and 4.2% respectively.

CONCLUSION

The compact anaerobic reactors proved to be very effective in removing organic matter (BOD: 78.2% RAn_1, 76.5% RAn_2 and COD: 67.8% RAn_1, 68.5% RAn_2) and solids (TSS: 75.9% RAn_1, 79.4% RAn_2) from high-strength wastewater. In addition, its performance was not affected by the fluctuations of the influent organic load. The VS/TS ratio in the anaerobic sludge decreased, indicating the digestion and stabilization of the retained solids in the anaerobic reactor. The low organic loading rate, which was applied daily to the reactor, resulted in moderate values of solids concentration in the sludge blanket and sludge bed.

By comparing the performance of the compact anaerobic reactors and the UASB reactor, it was shown that under low organic load conditions (less than 2.7 $kgCOD·m^{-3}·h^{-1}$) the RAn is an attractive option for decentralized wastewater treatment. Additionally, since the RAn is built with high strength and low-cost material and does not require sophisticated equipment, it is also an economical and practical alternative to face the lack of sanitation services in medium and low-income countries.

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REFERENCES

Abbassi, B. E., Abuharb, R., Ammary, B., Almanaseer, N. & Kinsley, C. 2018 Modified septic tank: innovative onsite wastewater treatment system. *Water* **10**(5), 578–589.

Al-Jamal, W. & Mahmoud, N. 2009 Community onsite treatment of cold strong sewage in a UASB-septic tank. *Bioresource Technology* **100**(3), 1061–1068.

Al-Shayah, M. & Mahmoud, N. 2008 Start-up of an UASB-septic tank for community on-site treatment of strong domestic sewage. *Bioresource Technology* **99**, 7758–7766.

Ángel L. Díaz, S., Albortante, J. G., Mónica, L. & Peláez, S. 2018 UASB-septic tank as an alternative for decentralized wastewater treatment in Mexico. *Environmental Technology*. DOI: 10.1080/09593330.2018.1430170

APHA/AWWA/WEF 2012 *Standard Methods for the Examination of Water and Wastewater*, 22th edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Capodaglio, A. G., Callegari, A., Cecconet, D. & Molognoni, D. 2017 Sustainability of decentralized wastewater treatment technologies. *Water Practice & Technology* **12**(2), 463–477.

Chernicharo, C. A. L. 2007 *Anaerobic Reactors*. IWA Publishing, London.

Chernicharo, C. A. L., van Lier, J., Noyola, A. & Ribeiro, T. B. 2015 Anaerobic sewage treatment: state of the art, constraints and challenges. *Environmental Science and Bio/Technology* **14**(4), 649–679.

Giraldo, E., Pena, M., Chernicharo, C. A. L., Sandino, J. & Noyola, A. 2007 Anaerobic sewage treatment technology in Latin-America: a selection of 20 years of experiences. *Proceedings of the Water Environment Federation* **13**, 5208–5228.

Khan, A. A., Gaur, R. Z., Tyagi, V. K., Khursheed, A., Lew, B., Mehrotra, L. & Kazmi, A. A. 2011 Sustainable options of post treatment of UASB effluent treating sewage: a review. *Resources, Conservation and Recycling* **55**, 1232–1251.

Massoud, M. A., Tarhini, A. & Nasr, J. A. 2009 Decentralized approaches to wastewater treatment and management: applicability in developing countries. *Journal of Environmental Management* **90**, 652–659.

Moussavi, G., Kazembeigib, F. & Farzadkiac, M. 2010 Performance of a pilot scale up-flow septic tank for on-site decentralized treatment of residential wastewater. *Process Safety and Environmental Protection* **88**, 47–52.

Noyola, A., Padilla-Rivera, A., Morgan-Sagastume, J. M., Güereca, L. P. & Hernández-Padilla, F. 2012 Typology of municipal wastewater treatment technologies in Latin America. *Clean – Soil, Air, Water* **40**(9), 926–932.

Oliveira, S. M. A. C. & von Sperling, M. 2011 Performance evaluation of different wastewater treatment technologies operating in a developing country. *Journal of Water, Sanitation and Hygiene for Development* **1**, 37–56.

Singh, N. K., Kazmi, A. A. & Starkl, M. 2014 A review on full-scale decentralized wastewater treatment systems: techno-economical approach. *Water Science and Technology* **71**(4), 468–478.

von Sperling, M. 2016 *Urban Wastewater Treatment in Brazil*. Technical Note NW IDB-TN-970. August, 2016. Inter-American Development Bank. Water and Sanitation Division.

von Sperling, M. & Chernicharo, C. A. L. 2005 *Biological Wastewater Treatment in Warm Climate Regions*. IWA Publishing, London.