Technological improvements in compact UASB/SBTF systems for decentralized sewage treatment in developing countries

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Abstract
This paper discusses current technological improvements related to a compact system comprised by UASB reactor and sponge-bed trickling filter (SBTF) as a potential alternative for decentralized sewage treatment systems in developing countries. The proposed improvements deal with some inherent constraints of the anaerobic treatment and seek to improve the design and operational strategies focusing on UASB/SBTF effluent quality, scum control and gaseous emissions.

Keywords
Compact UASB/SBTF; technological improvements; decentralized sewage treatment; sponge bed, scum control, waste gas treatment

Introduction

UASB reactors are considered a consolidated technology for sewage treatment in Latin America. A recent survey estimates that around 40% of the sewage treatment plants (STP) implemented in small municipalities in Brazil (less than 10,000 inhabitants) use the anaerobic technology as the first stage of the treatment (Chernicharo *et al., submitted*). Despite the wide use of UASB reactors in Brazil, there are some constraints that still need to be solved: residual carbon, ammonia and pathogens in the effluent, scum management and emission of corrosive, odorant and greenhouse waste gases.

Regarding the improvements in terms of effluent quality, the use of sponge-bed trickling filters post-UASB reactors has shown a remarkable potential for application in developing countries (Almeida *et al.*, 2009; Okubo *et al.*, 2015). In this case, the entrapment of the biomass within the sponge increases the hydraulic and solids retention time which is associated with very low effluent concentrations of BOD, COD and TSS, with overall removals around 95%, 85-90% and 70-90%, respectively (Tandukar *et al.*, 2007; Okubo *et al.*, 2015). Such a condition could support the elimination of secondary settlers, an important advancement towards the simplification of the system. Nevertheless, to the best of our knowledge the conditions for UASB/SBTF operating without secondary settlers is not fully established, and further investigation is needed to assess the reliability of UASB/SBTF systems without clarifiers. Previous investigation indicates that the organic loading applied to the SBTFs could be similar or even higher than those recommended to provide the activity of nitrifiers in trickling filters as a post-treatment step (Almeida *et al.*, 2009; Ribeiro, 2015).

In terms of scum management, a major operational limitation reported in most full-scale plants is the removal of scum that accumulates inside the three-phase separators. The floating material could block the natural passage of gas, hence impairing its collection, and thus imposing hurdles for energy recovery (Chernicharo *et al.*, 2015). In some cases, the scum accumulation also tends to decrease the effluent quality. The rate of scum accumulation vary in a broad range and is dependent on factors such as sewage composition, type of preliminary treatment and inherent differences in terms of design and operation of UASB reactors (Ross, 2015; Díaz, 2016). The lack of procedures for scum management has been indicated as one of the main aspects leading to operational problems related to UASB reactors (Rosa *et al.*, 2012). Frequency and strategies of scum discharge are usually inappropriate, resulting in high operational costs and health risk for personnel (Ross, 2015; Díaz, 2016).

Another constraint is related to the emission of dissolved gases (e.g. hydrogen sulphide - H_2S and methane - CH_4) present in the effluent of UASB reactors, which if not properly managed may restrain the acceptance of the anaerobic sewage treatment technology in the coming years. These gases comprise the so-called 'waste gas', which contributes to diffuse emissions of corrosive, odorant and greenhouse gases after the release from the bulk liquid. In quiescent layers of the UASB reactor settlers, the emission rates of H_2S and CH_4 are reported to range from 0.21 to 0.37 $gS.m^{-2}.d^{-1}$ and from 11.0 to 17.8 $gCH_4.m^{-2}.d^{-1}$ (Souza *et al.*, 2012), which could compromise the structure of concrete walls exposed to H_2S and also reduce the potential for energy recovery from UASB reactors.

This paper aims to present a compact sewage treatment system that incorporates technological improvements matching all afore-mentioned constraints. The work discusses: *i)* effluent quality improvements with the use of high rate settlers in the anaerobic step followed by sponge-bed tricking filters; *ii)* procedures for scum management using a hydrostatic removal device; and *iii)* the use of a cost-effective biofilter for the treatment of waste-gas in decentralized sewage treatment systems.

Materials and methods

UASB/SBTF system

The proposed compact sewage treatment system is comprised by a rectangular UASB reactor followed by two sponge-bed trickling filters (SBTF) in parallel, placed at both sides of the UASB reactor. Figure 1 shows a flow-sheet of the system, which has an area requirement of less than 0.03 $m^2.inhabitant^{-1}$. The system was designed to treat domestic wastewater of approximately 500 inhabitants. The inclusion of a dissipation chamber and a biofilter for collection and treatment of the waste gas do not significantly change the footprint of the system. The area required for the dissipation chamber and the biofilter are about 0.06 $m^2.1,000inhabitant^{-1}$ and 0.4 $m^2.1,000inhabitant^{-1}$. Table 1 presents the main characteristics of the compact UASB/SBTF system, and the proposed technological improvements.

The concept of the compact UASB/SBTF system was based on the results from several studies carried out by our research group at the Centre for Research and Training in Sanitation of the Federal University of Minas Gerais – CePTS (Brazil). The practical experiences from full-scale STP in Brazil were also taken into account to assess the effectiveness of the technological improvements related to the UASB/SBTF system. The compact UASB/SBTF system was operated under a typical full-scale STP flow regime without the use of secondary settlers.

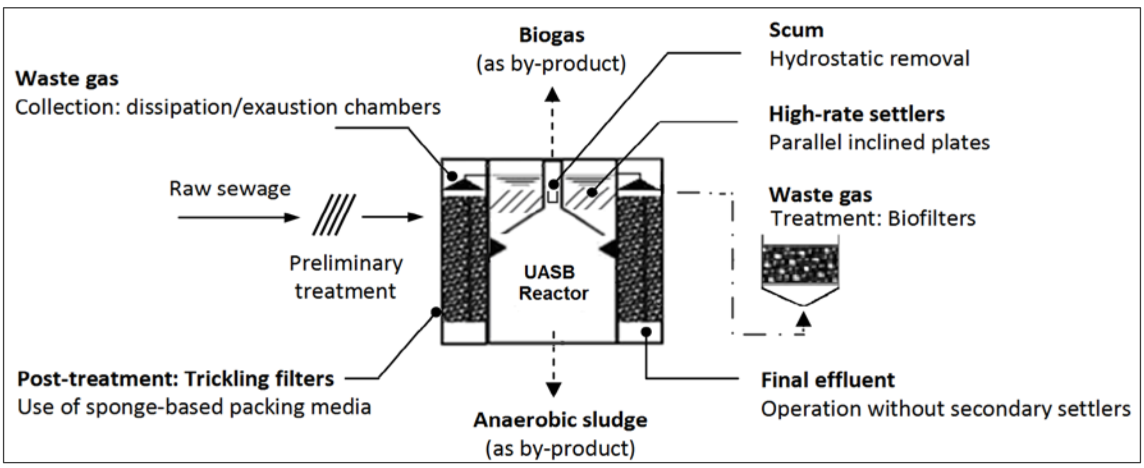

Figure 1. Compact UASB/SBTF system for sewage treatment in developing countries. The continuous lines indicate the proposed improvements for the technology.

Table 1. Summary of the main characteristics of the compact UASB/SBTF system.

Characteristics	unit	UASB reactor[1]	SBTF[1]	Dissipation chamber	Biofilter
Average flow	$m^3.d^{-1}$	45.7	13.8	45.7	0.3 - 1.5[3]
Useful height	m	4.5	3.5	1.0	1.0
Useful volume	m^3	16.8	4.4[2]	0.008	0.008
Organic loading rate	$kgCOD.m^{-3}.d^{-1}$	1.4	0.8	-	-
Hydraulic loading rate	$m^3.m^{-2}.d^{-1}$	13.0	11.5	1448.3	- [4]
Retention time	h	8.6	3.0	-	0.12 – 0,71

[1] Operative temperature of the UASB/SBTF system: 21-27°C;
[2] The sponges occupied 40% of the TF volume (0.40 $m^3.m^{-3}{}_{reactor}$);
[3] Gas flow;
[4] Superficial velocity of the synthetic waste gas: 33.6 - 196.8 $m.d^{-1}$.

Improvements for the treatment of the liquid phase: UASB and TF effluent quality

To assess the improvements in terms of the anaerobic effluent quality a high rate settler (lamella plates) was placed in one of the settler compartments of the UASB reactor. The structure was comprised by inclined (60°) glass fiber plates, spaced 12 cm apart. The high rate (HR) settler was designed to retain particles with a sedimentation velocity higher than or equal to 70% of the average upflow liquid velocity (0.68 $m.h^{-1}$).

For the post-treatment step, a sponge-based packing media developed by our research group was used to fill the trickling filters. The packing media was comprised by polyurethane sheets confined in vertical layered plastic-made structures (Ribeiro, 2015). Because of the large SRT within the SBTF post-UASB reactor (100-120 days), the use of the secondary settlers was not considered in the flow-sheet. In this case, it is not necessary to return the secondary sludge produced in the SBTF for thickening and digestion in the UASB reactor.

Improvements for the treatment of the solid phase: scum management

A hydrostatic scum removal device (Chernicharo *et al.*, 2009) was installed inside the three-phase separator (TPS) of the UASB reactor. The working principle of this device is based on scum level control inside the TPS, by increasing or decreasing the pressure in the gas line situated between the TPS and a hydraulic seal located outside the reactor. The control of the scum level within the gas chamber enables the scum seepage through the weirs installed inside of the biogas chamber, routing the material to disposal. A complete description of the hydrostatic removal system and the units related to scum disposal is presented in Chernicharo *et al.* (2009) and Rosa *et al.* (2012).

In order to establish appropriate discharge routines, four different arrangements were experimented, considering the following aspects: level of scum maintained below the edge of the collection weir (between 0 to 2 cm and 2 to 5 cm), frequency of discharge (2 and 5 $days.week^{-1}$), number of stages and duration of discharge operation (e.g.: two stages of 10 seconds each). The best operational routine would be the one with highest withdrawal of scum (coarse floating material) associated with lower amount of liquid fraction. The scum removal efficiency was calculated based on the ratio between the mass of discharged scum and the mass of accumulated scum in terms of total solids (gTS) for each discharge routine tested.

Gas phase: waste gas treatment

The experiments aimed to waste gas treatment were previously conducted by Brandt *et al.* (2016) using three biofilters packed with mixtures of 60% of composted leaves and 40% of three different non-organic materials (on a volumetric basis): *i)* Biobob®, a material consisting of polyethylene rings filled with polyurethane sponges (BioProject, Brazil); *ii)* crushed and sieved blast furnace slag; and *iii)* expanded vermiculite (a lamellar clay composed of hydrated aluminium silicate previously subjected to sudden heating, above 700 °C. This material has a highly porous structure due to abrupt evaporation of its structural water, and can be easily found in the insulating materials market). Aiming its further application to decentralized UASB/SBTF systems, the results presented in this paper are focused on the biofilter packed with composted leaves and expanded vermiculite, the one that exhibited the best performance for the treatment of diffuse CH_4 emissions. The research was focused on the treatment of air stream synthetically added with CH_4. The biofilters were fed from the bottom, and the gas flow was adjusted by valves and measured by flow meters. For the start-up, inocula enriched from activated sludge sample and sieved composted leaves (in mineral salt medium and $10\%_{v/v}$ CH_4 atmosphere for two months) were added on the top of the packing media and then the bioreactors were operated for 95 days until a steady-state condition was reached.

The results were subsequently extrapolated with the use of a model to predict the CH_4 removal from the waste gas. The model considered a wide range of operational conditions when connecting the biofilters to the desorption chamber of the UASB/SBTF. A complete description of the methods and results can be found in Brandt *et al.* (2016).

In the proposed flow-sheet (Figure 1), after the release of waste gas from the UASB effluent in the desorption chamber (Glória *et al.*, 2016), the gas is forwarded to biofilters consisted of columns (h = 1.2 m) packed with 60% (on a volumetric basis) of sieved composted leaves (2.0 to 6.3 mm) and 40% (on a volumetric basis) of expanded vermiculite (4.0 to 6.0 mm) completely mixed and prepared to a working bed height of 1.0 m.

Monitoring

For the liquid phase, composite samples were taken two or three times per week. The analytical methods to determine COD, BOD, TSS, Settleable solids, $N\text{-}NH_4^+$, DO and *Escherichia coli* were performed according to APHA (2012), as well as the total solids related to the scum removed from the three-phase separator. Additionally, biogas losses during scum removal procedures were estimated based on biogas measurements ($NL.min^{-1}$), considering the correspondent time to restart biogas production after each scum discharge event. A Ritter TG 05 gas meter was used to measure the amount of biogas produced in the UASB reactor. Tedlar® bags were used to collect the samples in the inlets and outlets of each biofilter. $CH_{4(g)}$ were determined in a gas chromatograph coupled to a flame ionization detector (FID).

Results

Technological improvements regarding UASB reactors. The use of high rate settlers (parallel inclined plates in the settling compartment of the UASB reactor) is an alternative to reduce the concentration of particulate organic matter washed out with the UASB effluent. Figure 2 depicts the observed effluent solids concentration for the conventional UASB reactor and with the use of high rate settlers. The TSS_{UASB} effluent concentrations was 30% lower with the use of high rate settlers. Additionally, smaller data variability with the use of high rate settlers was observed, even operating the system under a typical full-scale STP flow regime.

This reduction in effluent solids concentration also resulted in 12% decrease of total COD effluent concentration (*Spearman correlation - α = 5 %)*. The improvement of the UASB effluent quality propitiates a better operation of the post-treatment step and could also reinforce the possibility of simplification of the UASB/SBTF flow-sheet, as discussed ahead.

From the anaerobic sludge profiles (data not shown), the effectiveness of using high rate settlers was strictly related to the anaerobic sludge mass at the upper layers of the digestion compartment (Ribeiro, 2015). Thus, anaerobic sludge management seems to be a key factor for lowering UASB effluent solids concentration with the use of high rate settlers. In our experiment, the total solids concentration at the upper layers of the UASB digestion compartment was kept below 1.5 % when the results depicted in Figure 2 were obtained.

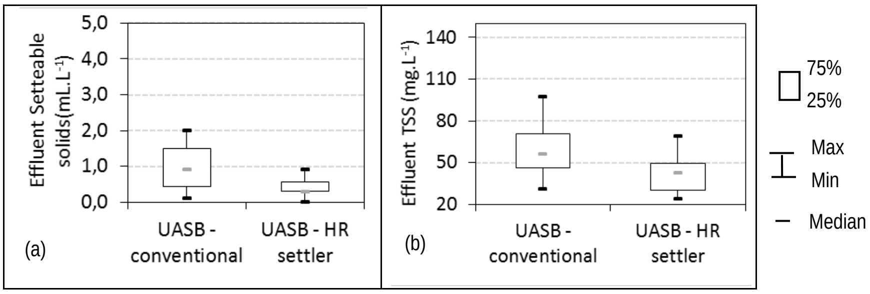

Figure 2. Effluent setteable solids (a) and effluent TSS (b) concentrations from the conventional UASB reactor and from the UASB reactor equipped with the high rate settler.

Regarding the scum accumulation within the UASB three-phase separator, the accumulation coefficient varied between 5.0 and 12.3 $gTS.kgCOD^{-1}{}_{applied.}$ The wide variation observed seems to be correlated with the sludge concentration at the upper layers of the digestion compartment (*Spearman test - α = 5 %*). Therefore, it reinforces the importance of a proper sludge management in order to reduce scum accumulation rates, as well as maintaining the effectiveness of high rate settlers.

Advances have been made to reduce the scum accumulation within three-phase separators with the use of a hydrostatic removal device, which is based on the biogas pressure control within the biogas chamber (Chernicharo *et al.*, 2015). By controlling the water level in the hydraulic seal, it is possible to provide proper conditions to remove the excess of scum through a weir located inside the three-phase separator. The four tested discharge routines resulted in scum removal efficiencies higher than 75%. Nevertheless, the best condition was obtained with a frequency of discharge of 5 $days.week^{-1}$, adopting a level of scum between 2 and 5 cm below the edge of the collection weir. This condition led to a 3.2-fold volume reduction of the liquid fraction discharged together with the coarse floating material, as compared to the other evaluated routines. This reflects the importance of establishing an efficient routine, not only in terms of scum removal, but also in terms of the liquid fraction that is simultaneously discharged with the scum itself, since it is essential to reduce the running costs and to minimize environmental impacts associated with the final disposal of this material. In addition, more frequent discharge tends to avoid the increase of the scum layer in thickness and viscosity.

Considering the above mentioned discharge routine, the removed scum volume corresponded to only 0.05% of the sewage volume treated during two consecutive operations of scum discharge. This estimation is lower than the value (0.12%) reported by Ross *et al.* (2012) for the evaluation of full-scale STPs in the South of Brazil. The biogas losses during the scum removal procedure accounted for only 0.07% of the biogas volume produced in the period, which is a negligible amount decreasing the potential of the system for energy recovery.

As related to waste gas treatment (and consequently the reduction of the dissolved methane in the effluent), Figure 3 shows the contour plots for the interpolation of the CH_4 removal efficiencies obtained in the biofilter packed with composted leaves and expanded vermiculite, as a function of the CH_4 concentration in the waste gas and the empty bed residence time (EBRT). The CH_4 conversions decreased gradually (from above 90% to below 10%) with the increase of the CH_4 inlet concentration and decrease of the EBRT. The EBRT proved to be a more important parameter, although the CH_4 in the waste gas was also important, especially for higher EBRT.

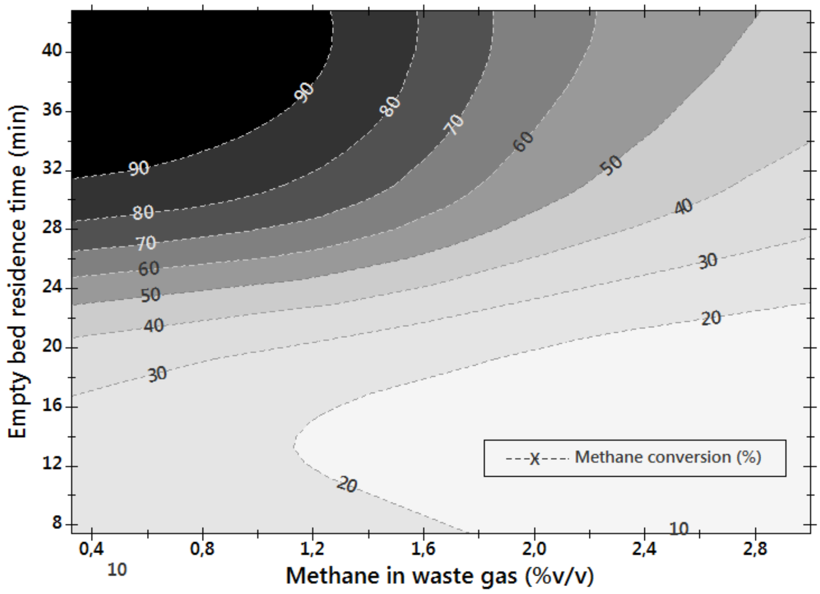

Figure 3. Contour plots showing the effect of the CH_4 in waste gas and the empty bed residence time on CH_4 abatement in biofilters packed with composted leaves (60%$_{v/v}$) and expanded vermiculite (40%$_{v/v}$).

Comparing the CH_4 conversions usually achieved in studies with biofilters packed with mixtures of composted materials and non-organic materials (e.g.: expanded perlite and zeolite), as reported by Pawłowska *et al.* (2011) and Melse and van der Werf (2005), the results obtained in our study showed a much better performance. This finding calls attention for the potential use of composted leaves and expanded vermiculite for the treatment of waste gas from UASB reactors treating domestic sewage. If we consider the use of these biofilters to treat the CH_4 released from the effluent of full-scale UASB reactors currently in operation in Brazil, this could potentially prevent the emission of approximately 1.28 $tCO_{2,equiv}.d^{-1}$. This estimation was based on the following premises: *i)* the wastewater from approximately 22.9 million people is currently treated by anaerobic reactors in Brazil (42.8 $m^3 \cdot s^{-1}$) (Chenicharo *et al.*, *submitted*); *ii)* the concentration of dissolved CH_4 in the effluent of UASB reactors is close to 20 $mg.L^{-1}$ (Souza *et al.*, 2011); *iii)* desorption chambers can transfer around 73% of the dissolved CH_4 to the waste gas (Glória *et al.*, 2016); *iv)* the biofilter can oxidise 95% of the CH_4 contained in the waste gas (best performance as shown in Figure 3).

In comparison with technologies such as membrane separation, direct combustion, catalytic oxidation, chemical scrubbers, and others listed in Estrada *et al.* (2012) and Alfonsín *et al.* (2015), the biofilters emerge as an attractive alternative for decentralized sewage treatment systems in developing countries. Worth to mention that to a successful CH_4 abatement with the use of biofiltration, the installation of desorption chambers for gas capture, as proposed by Glória *et al.* (2016), is extremely relevant. The enclosed unit designed to release/strip the dissolved gases tend to increase the concentration of waste gas in a gaseous stream. In this study, concentrations of H_2S of 100 to 500 ppm and CH_4 of 1.00 to 4.75 %$_{v/v}$ in the gaseous stream were reported, which is much higher than the concentrations found in the enclosed settler compartment of a full-scale UASB reactor (3 to 26 ppm for the H_2S and 0.03 to 0.34%$_{v/v}$ for the CH_4) (Souza *et al.*, 2012).

For the co-treatment of the CH_4 and H_2S, further research is still needed. The mass-transfer limitation of CH_4 to the biofilm requires the use of a higher EBRT when compared to commonly EBRT applied in biofilters used for odour abatement. In general, EBRT of 5 to 110 seconds is needed for H_2S abatement (Kennes and Veiga, 2001; Oyarzún *et al.*, 2003; WEF, 2004; Lee *et al.*, 2006), whereas EBRT from 2 to 80 minutes is required for CH_4 abatement (Melse and van der Werf, 2005; Pawłowska *et al.*, 2011; Gomez-Cuervo *et al.*, 2016).

Technological improvements regarding SBTF. The use of polyurethane sponge as a support material in trickling filters (TF) is a potential alternative (Okubo *et al.*, 2015), but still not widely considered in feasibility studies. One of the main advantages attributed to the use of sponge-based packing media is the possibility to simplify the construction of the TF tank, if the packing media is designed to be self-structured, which is the case of the filter bed media currently developed in Brazil. As related to the treatment process, the use of sponges allows the retention of microorganisms for longer periods at higher hydraulic retention time, when compared with plastic-bed tricking filters (Almeida *et al.*, 2013). Moreover, no additional operational strategies (e.g.: recirculation of the final effluent) are needed to meet the discharge standards generally adopted in developing countries or procedures for a proper wetting efficiency of the packing media.

As shown in Figure 4, low median COD, BOD, TSS and NH_4^+-N concentrations were observed, respectively 83, 35, 30 and 17 mg.L^{-1}. The overall COD, BOD, TSS, NH_4^+-N removal efficiencies were 84%, 89%, 88% and 44%, respectively. In terms of COD, a removal rate of 1.01 kgCOD.m$^{-3}_{sponge}$.d^{-1} was obtained. The system was also able to reduce the effluent concentrations of faecal indicator organisms. The overall total coliforms and *Escherichia coli* removals were 4.3 and 3.5 log units, respectively. This finding indicates the potential to reduce the number of faecal indicators in order to comply with restricted wastewater reuse in agriculture (WHO, 2006).

During the operational period, the organic loading rate (OLR) applied to the SBTF varied between 1.5 and 2.9 kgCOD.m$^{-3}_{sponge}$.d^{-1}. However, the COD effluent concentration remained around 100 mgCOD.L^{-1}. The high solids retention time (~ 100 days) probably had an important role in this process (Tandukar *et al.,* 2007; Almeida *et al.*, 2013). Whereas the heterotrophic activity was not significantly affected by OLR increase, the apparent nitrification activity decreased approximately 25%. Nevertheless, 91% of the ammonium-N concentration data stayed below 20 mg.L^{-1}.

The results indicate that even at high organic loadings applied to the SBTF (around 2.0 kgCOD.m$^{-3}_{sponge}$.d^{-1}) the final effluent consistently met the discharge standards generally observed in developing countries (in Brazil: 180 mgCOD.L^{-1}, 60 mgBOD.L^{-1}). Moreover, the sludge yield was usually lower than 0.2 kgSS.kgCOD$^{-1}_{removed}$, without the use of final clarifier, thus eliminating the need for aerobic sludge management. The elimination of secondary settlers might be an important simplification for compact UASB/SBTF systems, thus increasing the feasibility of using the technology in regions where construction and operational expertise are limited.

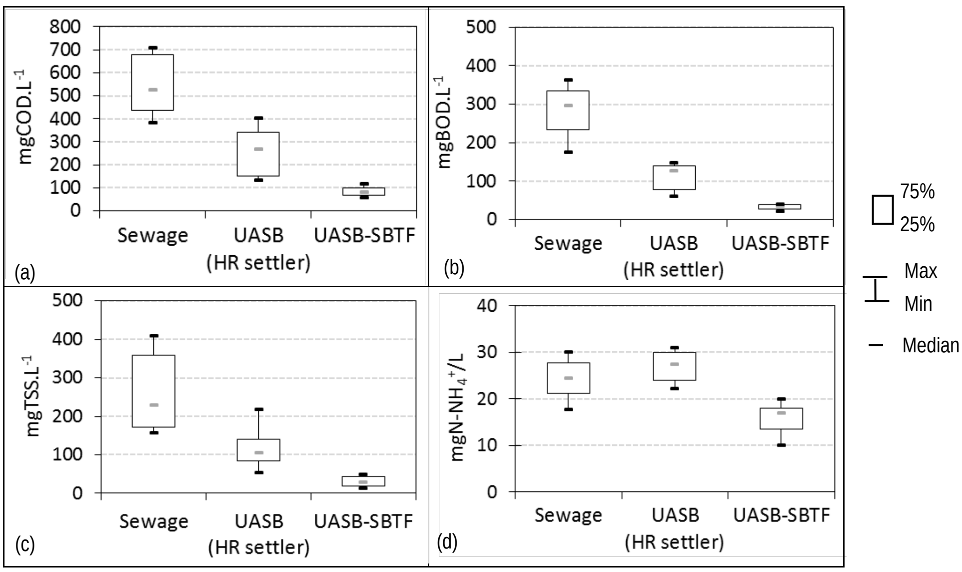

Figure 4. (a-d) Box plot of the system effluent concentrations for COD, BOD, TSS and NH_4^+-N.

Summary of the technological improvements for compact UASB/SBTF systems

Table 2 shows a summary of inherent constraints and technological improvements regarding to compact UASB/SBTF systems for decentralized sewage treatment in developing countries.

Table 2. Summary of inherent constraints and technological improvements to UASB/SBTF systems.

Matter of concern	Inherent constraints	Technological improvement
UASB effluent solids concentration and final effluent quality	Particulate organic matter from UASB reactor influences a proper operation of sponge-bed trickling filters as a post-treatment step, compromising the final effluent quality.	• Use of high rate settlers within the clarifier compartment for a better UASB effluent quality and a more reliable operation of the UASB/SBTF without secondary settlers.
	The use of plastic-based packing media usually requires additional operational strategies (e.g.: effluent recirculation) to increase the hydraulic retention time and wetting efficiency. In this case, secondary settlers are usually needed.	• Use of sponge-based packing media aiming to increase the hydraulic and sludge retention time in the post-treatment step. The use of sponge as a packing material also increases the reliability of the UASB/SBTF system, allowing its operation without secondary settlers.
Scum accumulation inside the three-phase separator	Scum accumulation causes serious operational hurdles and tends to reduce the potential for energy recovery from UASB reactors. In some cases can also impact the UASB effluent quality.	• Use of hydrostatic scum removal device and proper discharge routine can avoid the increase of the scum layer in thickness and viscosity, and reduction of volumes for final disposal.
Release of waste gas in UASB reactors	The release of waste gas from the UASB bulk liquid contributes to diffuse emission of corrosive, odorant and greenhouse gases.	• Use of desorption chamber followed by a biofilter filled with composted leaves and expanded vermiculite allows expressive reduction of methane emissions to the atmosphere. • For the co-treatment of the CH_4 and H_2S, further research is still needed.

Conclusions

The proposed technological improvements presented in this paper seek to attribute operational simplicity to the UASB/TF technology when applied as a decentralized treatment system. The operation of the UASB reactor with high rate settlers and the use of a sponge-bed trickling filter without final clarifier post-UASB reactor can lead to the production of a final effluent that can consistently comply with the discharge standards adopted in developing countries. The use of a hydrostatic scum removal device has shown promising and effective results, requiring a minimal level of operation and expertise. The use of desorption chambers followed by biofilters for collection and treatment of dissolved gases present in the effluent of UASB reactors seems to be appropriate for a decentralized system applied to developing countries, although further research is needed for the simultaneous treatment of relevant constituents present in the waste gas. Considering the proposed technological improvements, a successful operation of UASB/SBTF systems is highly associated with a proper anaerobic sludge management.

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