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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 an up-flow anaerobic sludge blanket (UASB) reactor and sponge-bed trickling filters (SBTFs) as a potential alternative for decentralized sewage treatment systems in developing countries. The topics addressed are related to design features and operational strategies that intend to solve some inherent constraints currently observed in UASB-based sewage treatment plants, that is, effluent quality, scum control and diffuse gaseous emissions. The results showed that the use of a high rate settler improved the effluent quality of the UASB reactor, by attaining 30% lower concentration of suspended solids when compared with the conventional UASB settler. Moreover, the scum removal device installed in the three-phase separator, associated with a proper discharge routine, provided a reduction of the discharge volumes being handled. For the waste gas management, the use of a desorption chamber followed by a biofilter packed with composted leaves and expanded vermiculite allowed a decrease of 95% in the methane emissions to the atmosphere. The compact UASB/SBTF system operating without secondary settlers exhibited a high potential for removal of organic matter (89%), suspended solids (88%) and total coliforms (4.2 log units), and the use of a innovative sponge-based packing media is a factor for the effluent quality improvements. Therefore, the compact system demonstrated a high potential for its implementation; however, future research on total nitrogen removal strategies and waste gas treatment may further improve its performance.

Keywords: Compact UASB/SBTF; Decentralized sewage treatment; Sponge-based packing media; Scum control; Waste gas treatment

1. Introduction

Up-flow anaerobic sludge blanket (UASB) reactors are considered a consolidated technology for sewage treatment in Latin America. A recent survey estimated that around 40% of the sewage treatment plants (STPs) implemented in small municipalities in Brazil (<10,000 inhabitants) use anaerobic technology as the first stage in the treatment process [1]. Despite the wide use of UASB reactors in Brazil, there are some constraints that still need to be solved for improving its performance, such as the presence of residual carbon, ammonia and pathogens in the effluent; scum management and emission of corrosive, odourant and greenhouse waste gases.

Regarding the improvements in terms of effluent quality, the use of sponge-bed trickling filters (SBTFs) post-UASB

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reactors have shown a remarkable potential for application in developing countries [2,3]. According to the literature, the increase in solids retention time (SRT) provided by the sponge media leads to high levels of endogenous respiration rate, which contributes to a low total suspended solids (TSSs) concentration in the effluent [4]. In fact, overall TSS removals in full-scale plants were reported around 70%–90% [3]. Moreover, such condition could support the elimination of secondary settlers, an important advancement towards the simplification of decentralized UASB/SBTF systems. By operating the system without a secondary clarifier, previous investigations indicated that the organic loading applied to SBTFs post-UASB reactors could be similar (or even higher) than those recommended to improve the activity of nitrifiers in trickling filters (TFs) [2,5]. Nevertheless, to the best of our knowledge, the conditions for UASB/SBTF operating without secondary settlers is not yet fully established. Further investigation is needed to assess the reliability of the proposed flowsheet, in which the advantages regarding anaerobic sludge management is clearly an attractive aspect. In this case, the design for aerobic sludge digestion and thickening is not required.

In terms of scum management in full-scale UASB reactors, a major limitation reported is the removal of scum from the inner part of three-phase separators (TPSs). The floating material tends to block the natural passage of gas, imposing hurdles to its collection, and thus, energy recovery [6]. In some cases, the scum accumulation also tends to decrease the UASB effluent quality. The rate of scum accumulation varies in a broad range and is dependent on many factors, such as sewage composition, type of preliminary treatment, and reactor design and operation [7]. The lack of procedures for scum management has been indicated as one of the main aspects leading to operational problems related to UASB reactors [8]. Frequency and strategies of scum discharge are usually inappropriate, resulting in high operational costs and health risk for personnel [7].

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, the so-called "waste gas". Due to its potential contribution to corrosion, as well as to emissions of odourant and greenhouse gases, the emission of waste gas may restrain the acceptance of the anaerobic sewage treatment technology in the coming years, if not properly managed. 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}, respectively [9]. These values could induce corrosion of concrete and steel-made components 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 the aforementioned constraints. To this aim, the main issues addressed are: (i) the use of high rate (HR) settlers in the anaerobic reactor and post-treatment SBTF for effluent quality improvement; (ii) the procedures for scum management using a hydrostatic removal device and (iii) the treatment of waste gas by means of a simplified and cost-effective biofilter.

2. Materials and methods

2.1. UASB/SBTF system

The proposed compact sewage treatment system was comprised of a rectangular UASB reactor followed by two SBTF in parallel, laterally placed at both sides of the UASB reactor (Fig. 1). The system had an area requirement of <0.03 m^2 $inhabitant^{-1}$ and was designed to treat domestic wastewater of approximately 400 inhabitants. The inclusion of a desorption chamber and a biofilter for collection and treatment of the waste gas did not change the footprint of the system (desorption chamber + biofilter: 0.06 m^2 × 1,000 $inhabitant^{-1}$ and 0.4 m^2 × 1,000 $inhabitant^{-1}$, respectively). The main characteristics of the compact UASB/SBTF system are shown in Table 1. The system was operated during 90 d, nevertheless, the UASB reactor was in operation before the beginning of this systematic operational period, having achieved steady-state conditions.

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).

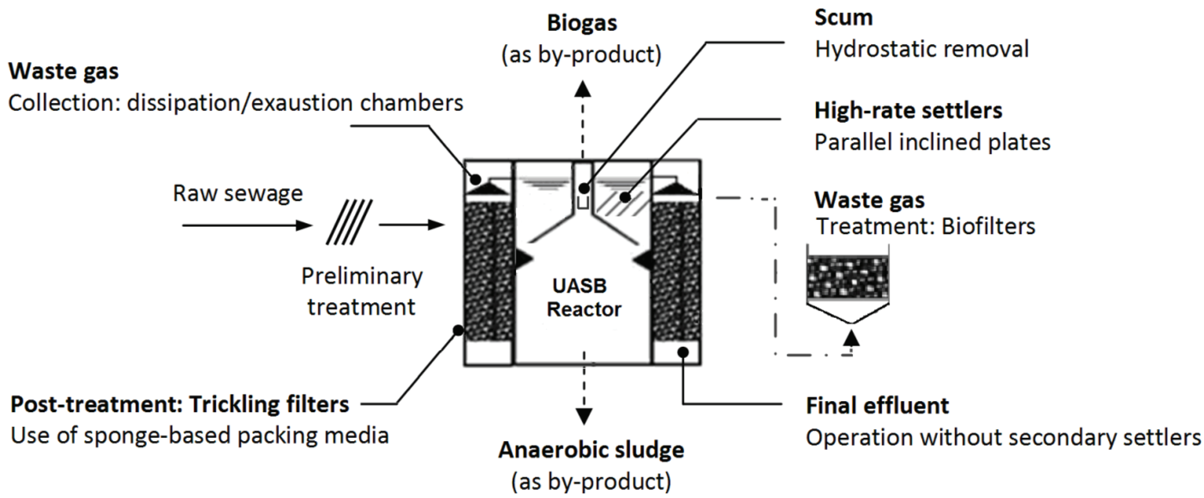

Fig. 1. Compact UASB/SBTF system for sewage treatment.

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

Characteristics	Unit	UASB reactor[a]	SBTF[a]	Desorption chamber	Biofilter
Average flow	$m^3\ d^{-1}$	45.7	13.8	45.7	0.3–1.5[d]
Useful height	m	4.5	3.5	1.0	1.0
Useful volume	m^3	16.8	4.4[b]	0.008	0.008
Organic loading rate	$kgCOD\ m^{-3}\ d^{-1}$	1.4	2.2[c]	–	–
Hydraulic loading rate	$m^3\ m^{-2}\ d^{-1}$	13.0	11.5	1,448.3	–[e]
Hydraulic retention time	h	8.6	3.0	–	0.12–0.71[f]
pH	–	7.2	8.1	–	–
Dissolved oxygen	$mg\ L^{-1}$	0.5	6.4	–	–

[a]Operative temperature of the UASB/SBTF system: 16°C–27°C (liquid temperature: 21°C–27°C).
[b]The sponges occupied 40% of the TF volume (0.40 $m^3\ m^{-3}_{reactor}$).
[c]OLR in terms of sponge volume ($kgCOD\ m^{-3}_{sponge}\ d^{-1}$).
[d]Gas flow (20°C; approximately 1 atm).
[e]Superficial velocity of the waste gas within the biofilter: 33.6–196.8 $m\ d^{-1}$.
[f]Empty bed residence time (EBRT).

The practical experiences from full-scale UASB-based 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 by treating real municipal sewage (post-preliminary treatment), under a typical full-scale STP flow regime without the use of secondary settlers.

2.1.1. Liquid phase: effluent quality improvement

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

For the post-treatment step, a sponge-based packing media developed by our research group was used in the TFs. The packing media was comprised by polyurethane sheets confined in vertical layered plastic-made structures [5]. The sponges occupied 40% of the SBTF volume. Due to the high SRT within the SBTF post-UASB reactor (i.e., 100–120 d) and the resulting low sludge production rate the use of the secondary settlers was not considered in the flow-sheet. Thus, the management of the secondary sludge produced in the SBTF was not needed. For the operation of the UASB/SBTF system we kept a high anaerobic sludge mass within the UASB reactor, leading to an increase in TSS_{UASB} concentrations (observed operative values: 90–130 $mg\ L^{-1}$). The objective to impose such a condition was to assess the performance of the UASB/SBTF system without secondary settlers under unfavourable conditions, in terms of particulate organic loadings applied to the SBTF.

2.1.2. Solid phase: scum management

A hydrostatic scum removal device [10] was installed inside the TPS of the UASB reactor. The working principle of this device was 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 enabled the scum seepage through the weirs installed inside the biogas chamber, routing the material to disposal. A more detailed description of the hydrostatic removal system and the units related to scum disposal is presented in Rosa et al. [8] and Chernicharo et al. [10].

In order to establish an appropriate criteria for discharge routines, different arrangements were investigated by taking into account the level of scum maintained below the edge of the collection weir (between 0–2 cm and 2–5 cm) and the frequency of discharge (each 2 or 5 operational days). The operational routine adopted was that with the highest withdrawal of scum (coarse floating material) associated with the lowest amount of liquid fraction. The scum removal efficiency was calculated based on the ratio between the average mass of discharged scum and the average mass of the remaining amount of scum within the TPS after discharge in terms of total solids (gTS).

2.1.3. Gas phase: waste gas treatment

The experiments associated to waste gas treatment were conducted by Brandt et al. [11]. To this aim, three biofilters packed with mixtures of 60% of composted leaves and 40% of three different non-organic materials (on a volumetric basis) were used: (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 at above 700°C. The latter material has a highly porous structure due to abrupt evaporation of its structural water. Lamellar clay is usually applied to thermal insulation, and can be easily found in the 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, which was the one that exhibited the best performance for the treatment of diffuse CH_4 emissions. The research 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 with the use of flow meters to perform four empty bed residence times (EBRT, in min)/superficial velocities (in m^3 m^{-2} h^{-1}): (i) 42.8/1.4; (ii) 29.5/2.0; (iii) 19.6/3.1 and (iv) 7.4/8.2. For the start-up, inoculum enriched from activated sludge sample and sieved composted leaves (in mineral salt medium and 10% v/v CH_4 atmosphere for 2 months) were added on the top of the packing media. Subsequently, bioreactors were operated for 95 d until a steady-state condition was reached.

The extrapolation of the results was subsequently studied with the use of an interpolation model to predict the CH_4 removal over the expected waste gas concentration range collected in desorption chambers installed in UASB reactors treating municipal sewage (0.3%–3.2% v/v). The model considered a wide range of operational conditions when connecting the biofilters to the desorption chamber of the UASB/SBTF (Fig. 1). A complete description of the methods and results can be found in Brandt et al. [11].

In the proposed flow-sheet (Fig. 1), after the release of waste gas from the UASB effluent in the desorption chamber [12], the gas was forwarded to biofilters. The desorption chamber was located outside the UASB reactor for establishing hydraulic energy dissipation through a controlled free-fall. To this aim, a cylindrical chamber (10 cm diameter) was operated at a 1 m drop height and controlled air exhaustion rate (12 air renovations^{-1}). In summary, the turbulence caused by the free drop height would increase the mass transfer for the liquid phase and the exhaustion of the confined atmosphere would promote the gas phase renovation. The biofilters consisted of columns (1.2 m total height) packed with 60% (on a volumetric basis) of sieved composted leaves (2.0–6.3 mm) and 40% (on a volumetric basis) of expanded vermiculite (4.0–6.0 mm) completely mixed and operated with a working bed height of 1.0 m.

2.1.4. Monitoring

For the liquid phase, composite samples were taken two or three times per week. The analytical methods to determine chemical oxygen demand (COD), biochemical oxygen demand (BOD), TSSs, settleable solids, ammonium nitrogen (NH_4^+–N), dissolved oxygen (DO) and *Escherichia coli* were performed according to APHA [13], as well as the total solids (TS) related to the scum removed from the TPS. Additionally, biogas losses during scum removal procedures were estimated based on the biogas measurements (NL min^{-1}), considering the correspondent time for the reestablishment of the gas pressure inside the TPS 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 waste gas samples in the inlets and outlets of each biofilter. $CH_{4(g)}$ was determined in a gas chromatograph coupled to a flame ionization detector (GC-FID 2014, Shimadzu).

2.1.5. Statistical analysis

Non-parametric relationship evaluations with the use of the Spearman test – α = 5% were performed in order to assess (i) the correlation between TSS_{UASB} and the decrease in COD_{UASB} concentrations and (ii) the correlation between the sludge concentration at the upper layers of the digestion compartment and the scum accumulation within the TPS. Spearman rank correlation coefficient was used due to the observed lognormal data distribution, as typically observed for UASB effluents [14].

3. Results

3.1. Technological improvements on UASB reactors

The use of parallel inclined plates as HR settlers inside the settling compartment of the UASB reactor may be an alternative to reduce the concentration of particulate organic matter washed out with the effluent. Fig. 2 depicts the observed effluent solids concentration for the conventional UASB reactor and one with the use of HR settlers. As can be noticed, the reactor compartment containing the HR settler showed 30% lower TSS concentration in the effluent compared with the conventional settler compartment. Additionally, by applying this configuration, smaller data variability was observed, even if operating the system under a typical full-scale STP flow regime. In our experiment, TS concentration at the upper layers of the UASB digestion compartment was kept below 1.5% when the results depicted in Fig. 2 were obtained.

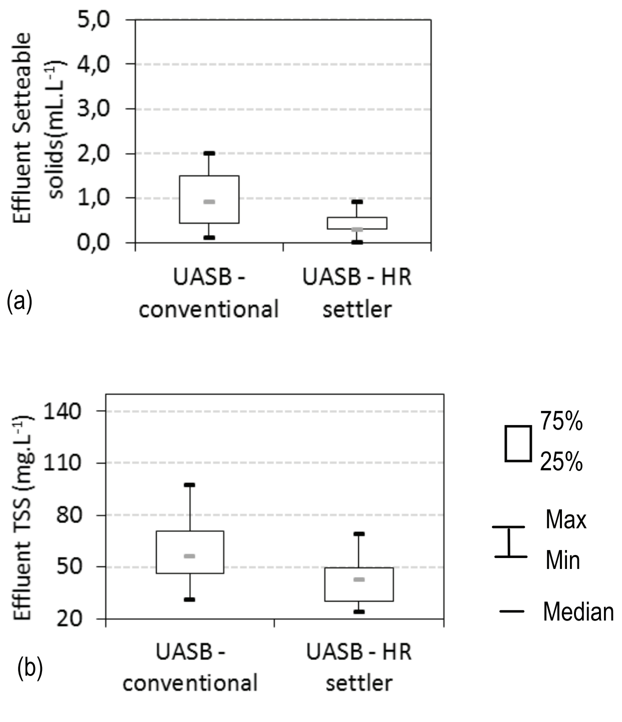

Fig. 2. (a) Settleable solids and (b) TSS effluent concentrations from the UASB reactor designed with conventional settler (UASB-conventional) and with high rate settler (UASB-HR settler).

Regarding the anaerobic sludge profiles (data not shown), the effectiveness of using HR settlers was directly related to the concentration of anaerobic sludge at the upper layers of the digestion compartment [5]. This indicates that anaerobic sludge management seems to be a key factor for decreasing the concentration of solids in the UASB effluent even with the use of HR settlers.

The lower concentration of solids in the effluent was correlated to the decrease in the total COD effluent concentration (Spearman correlation – α = 5%) ($COD_{effluent}$ decrease: 12%). The improvement of the UASB effluent quality also tends to provide a better operational condition for the post-treatment step in terms of TSS loadings, reinforcing the proposed simplification in the UASB/SBTF flow-sheet (elimination of the secondary settler unit) into a more reliable operation.

Regarding the scum accumulation within the UASB TPS, a wide range between 5.0 and 12.3 gTS $kgCOD^{-1}_{applied}$ was observed. Such a variation seems to be correlated with the sludge concentration at the upper layers of the digestion compartment (Spearman test – α = 5%). This data reinforces the importance of a proper sludge management in order to reduce scum accumulation rates, as well as maintaining the effectiveness of HR settlers.

Advances have been made to manage the scum accumulation within TPS with the use of a hydrostatic removal device, based on the biogas pressure control within the biogas chamber [6]. 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 TPS. The tested discharge routines resulted in scum removal efficiencies higher than 75% (mass of discharged scum/mass of remaining scum in gTS). The best condition was obtained with a discharge frequency of each 5 operational days, by 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 with the other evaluated routines.

The election of a proper scum frequency discharge was shown essential to avoid the increase of the scum layer in thickness and viscosity, which could impose hurdles to biogas collection from the TPS. An efficient routine also aims at reducing the amount of liquid fraction that is simultaneously discharged with the scum itself. In practice, a higher amount of liquid being discharged may result in extreme pressure losses in the gas line, which could decrease the efficiency by withdrawing coarse floating material.

Considering the abovementioned discharge routine, the removed scum volume corresponded to only 0.05% of the sewage volume treated during two consecutive scum discharge procedures. This estimation is much lower than the values previously reported in full-scale STPs in the South of Brazil (0.12%) [7]. The biogas losses during the scum removal procedure accounted for only 0.07% of the biogas volume produced during this period, which is negligible at decreasing the potential for thermal energy recovery.

Results for the waste gas treatment are shown in Fig. 3, which represents contour plots for CH_4 removals as a function of the CH_4 concentration in the waste gas and the EBRT of the gas in the biofilter. 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.

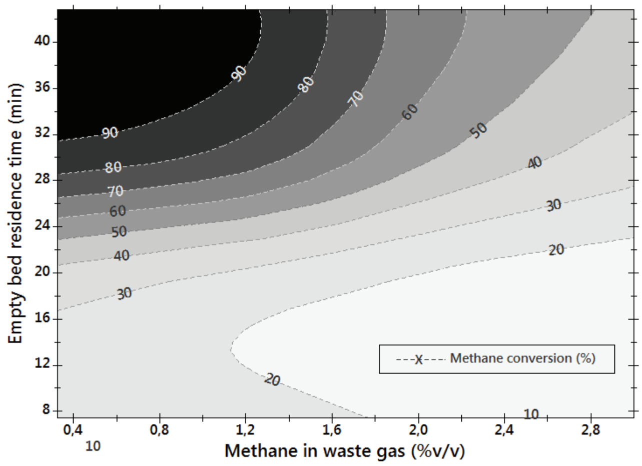

Fig. 3. Contour plots showing the effect of the CH_4 in waste gas and the empty bed residence time on CH_4 abatement in biofilters packed with composted leaves (60% v/v) and expanded vermiculite (40% v/v).

The EBRT proved to be a very important parameter, although the CH_4 in the waste gas was also important, especially for higher EBRT.

Comparing the CH_4 conversions achieved with biofilters packed with mixtures of composted materials and non-organic materials (e.g., expanded perlite and zeolite) [15,16], the results from our study showed a remarkable outlook. From Fig. 3, it is possible to estimate that biofilters packed with composted leaves-expanded vermiculite would exhibit CH_4 abatement above 95% when applying the operating conditions studied by Pawłowska et al. [15] (EBRT = 80 min and [$CH_{4,inflow}$] = 0.75 to 1.00%v/v). If such condition is compared with the removal obtained in our study, a rather similar or even higher value was observed (i.e., 80% to approximately 100%). Moreover, our biofilter could provide a superior performance for CH_4 removal when submitted to similar conditions studied by Melse and van der Werf [16], considering a volumetric load of 25 g m^{-3} h^{-1} (EBRT = 7 min and [$CH_{4,inflow}$] = 0.85%v/v), which showed CH_4 abatement <20%.

The results from our study indicated the potential of biofilters packed with composted leaves-expanded vermiculite for the treatment of waste gas from UASB reactors treating domestic sewage. The use of this system to treat the CH_4 released from full-scale UASB reactors currently in operation in Brazil could prevent the emission of approximately 1.28 $tCO_{2,equiv}$ d^{-1}. This estimation was based on the following premises: (i) wastewater from approximately 22.9 million people is currently treated by anaerobic reactors in Brazil (42.8 m^3 s^{-1}) [1]; (ii) the concentration of dissolved CH_4 in the effluent of UASB reactors is approximately 20 mg L^{-1} [17]; (iii) desorption chambers can transfer around 73% of the dissolved CH_4 to the waste gas [12] and (iv) the biofilter can oxidize 95% of the CH_4 contained in the waste gas (according to the best performance shown in Fig. 3).

In comparison with other technologies, such as membrane separation, direct combustion, catalytic oxidation, chemical scrubbers and others [18,19]; biofilters emerge as an attractive alternative for decentralized sewage treatment systems in developing countries. It is worth to mention that for a successful CH_4 abatement using biofiltration, the installation of desorption chambers for gas capture is extremely relevant [12]. The enclosed unit designed to release/strip the dissolved gases tends to enhance the capture of waste gas from the UASB effluent, also increasing its concentration in a gaseous stream. In the abovementioned study, concentrations of H_2S from 100 to 500 ppm and CH_4 from 1.00% to 4.75% v/v in the gaseous stream were reported, which is much higher than the concentrations in the settler compartment of a full-scale UASB reactor (3–26 ppm for the H_2S and 0.03%–0.34% v/v for the CH_4) [9]. In this case, a higher exhaustion rate in the desorption chamber is required to ensure lowered CH_4 concentrations (0.4%–1.2%) and higher CH_4 abatement (>95%; Fig. 3).

For the co-treatment of CH_4 and H_2S, the EBRT needed for CH_4 abatement (2–80 min) [15,16,20] was also apparently sufficient for H_2S oxidation (5–110 s) [21–24]. This indicates the possibility to remove both constituents in one single biofilter. However, inhibitory effects due to acidification caused by the oxidation of sulphur compounds, as well as the toxicity of some pollutants (e.g., free ammonia), may influence the activity of methanotrophs. Whether or not acidification and the presence of toxic compounds are relevant factors for CH_4 abatement is a matter of further research.

3.2. Technological improvements on SBTF technology as a post-treatment of UASB effluents

The use of polyurethane sponge as a support material in TFs is a potential alternative [3], but still not widely considered in feasibility studies for full-scale systems. One of the main advantages of using sponge-based packing media is to simplify the construction of the TF tank by implementing a self-structured medium. This type of sponge-based packing media is currently under development in Brazil. From the treatment process standpoint, the use of sponges allows the retention of microorganisms for longer periods at higher hydraulic retention time, when compared with rock or plastic-bed TFs [25]. 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 even additional procedures to overcome clogging issues or improving the wetting efficiency.

In our study, low average concentrations of COD, BOD, TSS and NH_4^+–N were observed when implementing this technology, that is, 83, 35, 30 and 17 mg L^{-1}, respectively (Fig. 4). The overall COD, BOD, TSS and NH_4^+–N removal efficiencies were 84%, 89%, 88% and 44%, respectively. 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 result indicated the potential to reduce the number of faecal indicators in order to comply with restricted wastewater reuse in agriculture [26].

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}. In terms of COD, a removal rate of 1.01 kgCOD m^{-3}_{sponge} d^{-1} was obtained, with the COD effluent concentration constantly remaining around 100 mgCOD L^{-1}, despite the OLR increase. The high SRT (~100 d) probably

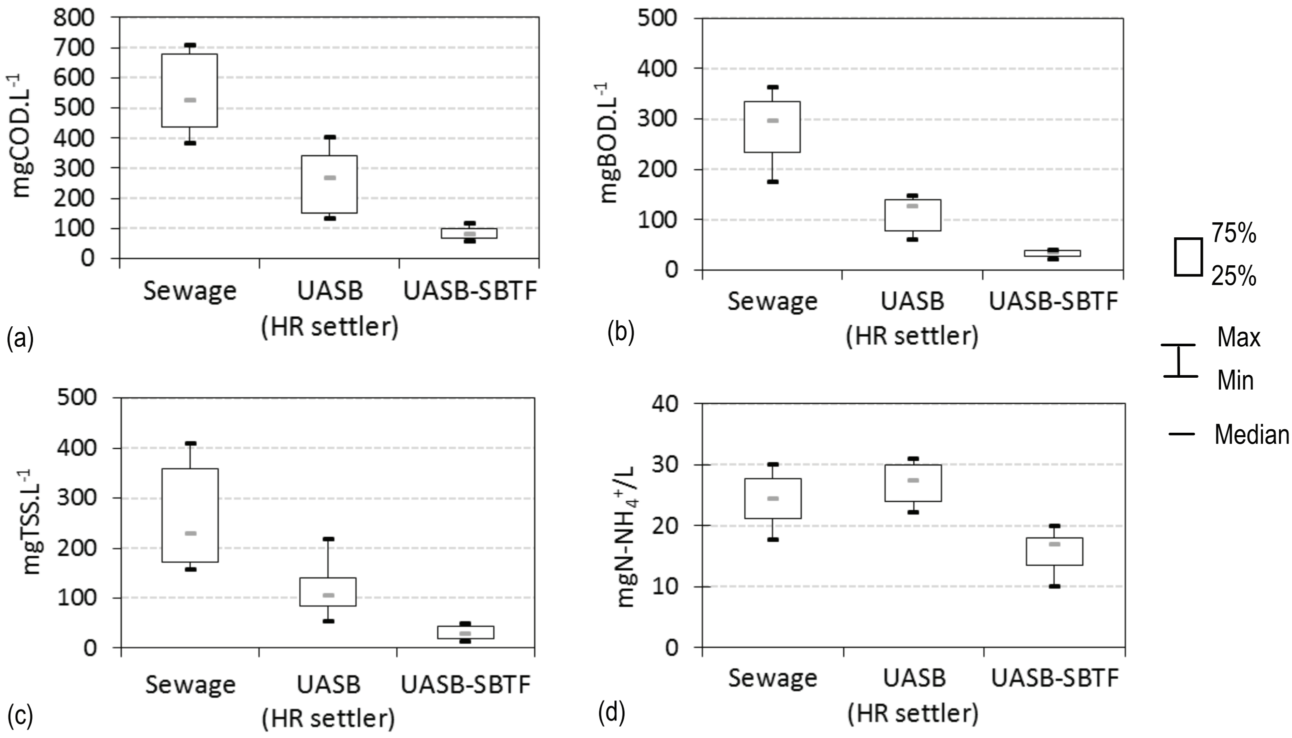

Fig. 4. Influent and effluent concentrations for (a) COD, (b) BOD, (c) TSS and (d) NH_4^+–N, considering the system with high rate settler (UASB-HR settler/SBTF) within the anaerobic step unit.

had an important role in this process [25,27]. On the other hand, NH_4^+–N removal decreased approximately 25% when OLR was increased to 2.9 kgCOD m^{-3}_{sponge} d^{-1}. Nonetheless, NH_4^+–N concentrations stayed below 20 mg L^{-1} almost during the whole period probably due to the low NH_4^+–N influent concentrations. The obtained effluent quality in terms of NH_4^+–N concentration might be in accordance with discharge standards related to developing countries. However, it should be noted that nitrification did not fully occur despite the long SRT, elevated DO, and proper pH and temperature. From previous studies performed in our research centre [25], the higher organic loadings (>1.5 kgCOD m^{-3}_{sponge} d^{-1}) was considered the main reason for low NH_4^+–N removals, favouring heterotrophic bacteria to outcompete nitrifying microorganisms, as also observed in Tandukar et al. [28]. The increase in TSS_{UASB} concentrations may also result in lower nitrification activity within the TFs, as also observed in full-scale studies [29].

The TSS_{UASB} effluent concentrations were kept around 100 mgTSS L^{-1} (Fig. 4(c)). From our experience, a proper anaerobic sludge management provides an effluent concentration below 100 mgTSS L^{-1}, even under a typical full-scale STP flow regime. This observation is also supported by other full-scale studies performed in developing countries [3], which tends to allow the use of higher OLR applied to the SBTF post-UASB reactors (around 3.0 kgCOD m^{-3}_{sponge} d^{-1}). However, to the best of our knowledge the effect of particulates on nitrification when sponge-based packing media is used is not reported in the literature, which could be a matter of future research.

The results indicated that even when applying high OLR to the SBTF (around 2.0 kgCOD m^{-3}_{sponge} d^{-1}), the final effluent consistently met discharge standards in developing countries (in Brazil: 180 mgCOD L^{-1}, 60 mgBOD L^{-1}). SBTF sludge yield (usually lower than 0.2 kgSS $kgCOD^{-1}_{removed}$) is one of the main reasons obtaining a good effluent quality with a simplified UASB/SBTF flow-sheet. The operation of UASB/SBTF systems without a secondary settler might be an important simplification for compact UASB/SBTF systems, thus (i) eliminating the need for aerobic sludge management and (ii) increasing the feasibility of UASB/SBTF systems in regions where construction and operational expertize are limited.

3.3. Summary of the technological improvements for compact UASB/SBTF systems

The inherent constraints and technological improvements regarding the compact UASB/SBTF systems for decentralized sewage treatment in developing countries are summarized in Table 2.

3.4. Future efforts for UASB/SBTF technology improvements

Future efforts aiming to improve the UASB/SBTF technology involves the simultaneous removal of odourous gases and methane in a simple and reliable system, and the implementation of a protocol for the design and operation of hydrostatic scum removal devices. In terms of effluent quality, autotrophic nitrogen removal in the post-treatment step seems to be an achievable possibility. Since the sponges tend to increase the SRT within the SBTF at more than 100 d, the use of anammox process might be an alternative, if the interplay of heterotrophic and autotrophic microorganisms

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

Matter of concern	Inherent constraints	Technological improvements
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 settler
	The use of rock or 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, it 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 provide a 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, odourant and greenhouse gases	Use of desorption chamber followed by a biofilter packed with leaves-expanded vermiculite allows expressive reduction of methane emissions to the atmosphere. However, for the co-treatment of the CH_4 and H_2S, further research is still needed

can be managed by simply controlling the oxygen supply within the SBTF. Recent studies indicated the cultivation of anammox bacteria [30] and autotrophic nitrogen removal over nitrite in SBTFs [31,32] as a proven of concept. From another perspective, heterotrophic denitrification could also be a relevant strategy, and proper operational conditions are being currently planned for future research efforts. Finally, the effect of the anaerobic sludge management on NH_4^+–N removals in SBTFs post-UASB reactors is also an important topic to be elucidated.

4. Conclusions

The present study aimed at proposing technological improvements for compact sewage treatment systems comprised by UASB reactor followed by SBTFs. The operational simplicity of such system allied to its efficiency in meeting the discharge standards adopted in developing countries reinforce its potential for application as a decentralized sewage treatment system. To this aim, possible solutions related to the main bottlenecks associated with both technologies were addressed, that is, effluent quality improvement, scum control and abatement of gaseous emissions. The use of HR settlers in the UASB reactor decreased by 30% the concentration of suspended solids in the effluent, compared with the conventional settler compartment. Moreover, the use of a hydrostatic scum removal device has shown promising and effective results, requiring a minimal level of operation and expertize. Regarding the solutions for gaseous emissions management, a high potential for methane abatement was demonstrated, together with a possible H_2S oxidation in the same biofilter due to the high EBRT in the biofilter. The post-treatment system also showed remarkable removal efficiencies for organic matter (89%), suspended solids (88%), ammonia (44%) and total coliforms (4.2 log units) at higher organic loadings. These results were associated to the high SRT within the SBTF. Considering the proposed technological improvements, a successful operation of UASB/SBTF system was highly associated with a proper anaerobic sludge management. Finally, to move a step forward at improving this compact system, further research should consider a simultaneous removal of odourous gases and methane as well as an increase in nitrogen removal by means of anammox process.

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