Potential of resource recovery in UASB/trickling filter systems treating domestic sewage in developing countries


ABSTRACT

This paper aims to present perspectives for energy (thermal and electric) and nutrient (N and S) recovery in domestic sewage treatment systems comprised of upflow anaerobic sludge blanket (UASB) reactors followed by sponge-bed trickling filters (SBTF) in developing countries. The resource recovery potential was characterized, taking into account 114 countries and a corresponding population of 968.9 million inhabitants living in the tropical world, which were grouped into three desired ranges in terms of cities’ size. For each of these clusters, a technological arrangement flow-sheet was proposed, depending on their technical and economic viability from our best experience. Considering the population living in cities over 100,000 inhabitants, the potential of energy and nutrient recovery via the sewage treatment scheme would be sufficient to generate electricity for approximately 3.2 million residents, as well as thermal energy for drying purposes that could result in a 24% volume reduction of sludge to be transported and disposed of in landfills. The results show that UASB/SBTF systems can play a very important role in the sanitation and environmental sector towards more sustainable sewage treatment plants.

Key words | energy recovery, nutrient recovery, sewage treatment, sponge-bed trickling filters, UASB reactors

INTRODUCTION

Currently, only 20% of the globally produced wastewater receives proper treatment, and almost one billion people still practice open defecation (UN-Water 2015). The huge public health and environmental concerns arising from this affect mainly developing countries, which lack sewer systems. As has been seen in the Latin American region, the construction of sewerage systems follows urban growth without planning for proper disposal of the collected urban wastewaters (Chernicharo et al. 2015). Thus, the lack of integrated planning and selection of proper sanitation technologies seems to be a major obstacle.

Considering that most developing countries are in the tropical climate zone, there is an enormous potential to adopt anaerobic sewage treatment systems in these countries, following the example of other tropical countries such as Brazil and India, where anaerobic treatment is already considered a consolidated technology, especially considering the use of upflow anaerobic sludge blanket (UASB) reactors as a first treatment step. A recent survey carried out in Brazil estimates that around 40% of the sewage treatment plants (STPs) implemented in the most populated states use the anaerobic technology (Chernicharo et al. submitted). Indeed, the adoption of anaerobic treatment technologies for future STPs in developing countries would accomplish low capital investment and reduced operational costs, compared to conventional full aerobic options.

The main advantage of UASB technology is the very low or even zero energy demand, leading to an up to 10-fold drop in operational costs compared to activated sludge (Chernicharo et al. 2015). As a central player, the UASB reactors allow renewable energy recovery via methane production, while preserving nutrients. Furthermore, the possible recovery of solid by-products (sludge and scum) as an energy or nutrient source could generate economic
and environmental benefits such as reduction of sludge transportation to landfills and consequently emissions of greenhouse gases.

In a post-treatment step, sponge-bed trickling filters (SBTFs) have shown outstanding prospects in terms of proper effluent quality. Remarkable residual organic carbon and pathogen abatement have been observed, as well as nitrification-denitrification (in the latter case solely when nutrient recovery is not of interest) (Almeida et al. 2015). The system comprised of a UASB reactor followed by SBTFs seems to be a cost-effective integrated anaerobic-aerobic system, with the additional benefit of reducing sludge management via elimination of secondary settlers.

Therefore, this paper aims to present perspectives for energy (thermal and electric) and nutrient (N and S) recovery in integrated UASB/SBTFs systems treating domestic sewage in developing countries, taking into account an estimation of the overall potential for resource recovery in the tropical climate zone. The work addresses the results obtained in several studies carried out in pilot and full-scale STPs in Brazil. It is also important since it presents the most appropriate technology arrangement for different scales of municipalities, considering the reality of developing countries.

MATERIAL AND METHODS

In order to evaluate the potential for energy and nutrient recovery using UASB/SBTFs systems in the tropical climate zone, 114 countries (in the Americas, Africa, Asia and Oceania) were surveyed. For countries whose areas go beyond the tropics, only the cities inside the region of interest were considered. The population data were obtained from official government agencies when possible (i.e. Brazilian Institute of Geography and Statistics), as well as through the online portal City Population (http://www.citypopulation.de/). After listing all tropical countries, by continent, the city populations were grouped into three desired ranges: less than 10,000 (scenario 1), between 10,000 and 100,000 (scenario 2), and more than 100,000 inhabitants (scenario 3). The three different proposed scenarios with UASB/SBTFs systems were made considering the results obtained in several studies carried out at the Centre for Research and Training in Sanitation of the Federal University of Minas Gerais – CePTS (Brazil) (Borges et al. 2005; Souza et al. 2006; Almeida et al. 2013; Gutierrez 2014; Garcia et al. 2015) and also taking into account the information obtained in full-scale STPs in Brazil (Chernicharo & Almeida 2011; Lobato et al. 2012; Santos 2014; Rosenfeldt et al. 2015; Valente 2015; Rosa et al. 2016). The most suitable technological arrangement was assumed for each scenario according to our experience. Therefore, the liquid, solid and gaseous by-products generated in the STPs operation were estimated using the parameters depicted in Table 1.

The potential for thermal and electric energy recovery, fertilizer production (as nitrogen), and elemental sulphur recovery was estimated for each scenario, assuming the following:

- The minimum feasible STP scale for biogas energy use to electricity generation seems to be 100,000 inhabitants of population equivalent (Rosenfeldt et al. 2015; Valente 2015).
- Direct reuse of nitrogen in agriculture can be performed by applying fertigation with effluent from the SBTFs. In this case, the aspects regarding soil salinity were not taken into account.
- Elemental sulphur can be produced by partial biological oxidation of sulphide present in the effluent from the UASB reactors (Garcia et al. 2015).
- The UASB reactor is operated without a scum retention device at the settler compartment, since the impact on the effluent quality is negligible (Souza et al. 2006). There is only scum accumulation inside the three-phase separator.

The main equations used to perform the energy calculations are as follows:

\[ \text{Prod-CH}_4 = P \times \text{p-COD} \times n \cdot \text{UASB} \times Y\cdot\text{CH}_4 \] (1)

\[ E\cdot\text{avl} = \text{Prod-CH}_4 \times \text{NCV-CH}_4 \] (2)

\[ \text{Th-ep} = E\cdot\text{avl} \times n\cdot\text{th} \] (3)

\[ \text{El-ep} = E\cdot\text{avl} \times n\cdot\text{el} \] (4)

where: \( \text{Prod-CH}_4 = \) methane production (Nm\(^3\).d\(^{-1}\)); \( P = \) population in each scenario (million inhabitants); \( \text{p-COD} = \) per capita contribution of COD (kgCOD.inhab\(^{-1}\).day\(^{-1}\)); \( n\cdot\text{UASB} = \) UASB reactor COD removal efficiency (%); \( Y\cdot\text{CH}_4 = \) specific methane yield (LCH\(_4\)kgCOD\(_{removed}\)); \( E\cdot\text{avl} = \) energy available in biogas (MWh.d\(^{-1}\)); \( \text{NCV-CH}_4 = \) net calorific value of methane (kWh.m\(^{-3}\)); \( \text{Th-ep} = \) thermal efficiency
Table 1 | Summary of the main parameters used to perform the evaluations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population served by sewage network and treatment</td>
<td>%</td>
<td>20</td>
<td>UN-Water (2015)</td>
</tr>
<tr>
<td>Per capita sewage generation</td>
<td>L.inhab⁻¹.day⁻¹</td>
<td>170</td>
<td>von Sperling (2007)</td>
</tr>
<tr>
<td>Per capita chemical oxygen demand (COD) contribution</td>
<td>gCOD.inhab⁻¹.day⁻¹</td>
<td>100</td>
<td>von Sperling (2007)</td>
</tr>
<tr>
<td>Typical UASB reactor COD removal efficiency</td>
<td>%</td>
<td>65</td>
<td>Chernicharo (2007)</td>
</tr>
<tr>
<td>Unitary methane yield*</td>
<td>LCH₄.kgCOD₉removed</td>
<td>158.3</td>
<td>Lobato et al. (2012)</td>
</tr>
<tr>
<td>Unitary biogas yield*</td>
<td>NLbiogas.inhab⁻¹.d⁻¹</td>
<td>13.6</td>
<td>Lobato et al. (2012)</td>
</tr>
<tr>
<td>Net calorific value for methane</td>
<td>kWh.m⁻³CH₄</td>
<td>9.97</td>
<td>Moran et al. (2010)</td>
</tr>
<tr>
<td>Electric efficiency conversion</td>
<td>%</td>
<td>30</td>
<td>USEPA (2005)</td>
</tr>
<tr>
<td>Thermal efficiency conversion</td>
<td>%</td>
<td>40</td>
<td>USEPA (2005)</td>
</tr>
<tr>
<td>Methane emission conversion factor</td>
<td>tCO₂equivalent</td>
<td>0.01693</td>
<td>USEPA (2016)</td>
</tr>
<tr>
<td>Monthly electricity consumption by households (Brazil’s base)</td>
<td>kWh.month⁻¹</td>
<td>170</td>
<td>EPE (2016)</td>
</tr>
<tr>
<td>Per capita sludge generation (UASB reactor)</td>
<td>L.inhab⁻¹.day⁻¹</td>
<td>0.45</td>
<td>Chernicharo (2007)</td>
</tr>
<tr>
<td>Per capita dried sludge generation (UASB reactor) – drying beds</td>
<td>L.inhab⁻¹.day⁻¹</td>
<td>0.05</td>
<td>Andreoli et al. (2001)</td>
</tr>
<tr>
<td>Per capita dried sludge generation (UASB reactor) – centrifuge</td>
<td>L.inhab⁻¹.day⁻¹</td>
<td>0.11</td>
<td>Andreoli et al. (2001)</td>
</tr>
<tr>
<td>Humidity content of dewatered sludge</td>
<td>% (centrifuge)</td>
<td>75</td>
<td>Chernicharo (2007)</td>
</tr>
<tr>
<td></td>
<td>% (drying beds)</td>
<td>65</td>
<td>Chernicharo (2007)</td>
</tr>
<tr>
<td>Thermal energy for water evaporation</td>
<td>kJ.L⁻¹</td>
<td>5,588</td>
<td>Moran et al. (2010)</td>
</tr>
<tr>
<td>Arbitary distance between STP and landfill</td>
<td>km</td>
<td>19</td>
<td>Gutierrez (2014)</td>
</tr>
<tr>
<td>Truck transport capacity</td>
<td>t</td>
<td>7.5</td>
<td>Gutierrez (2014)</td>
</tr>
<tr>
<td>Sulphur generated in biological sulphide oxidation system</td>
<td>gS.m₉treated sewage</td>
<td>3.2</td>
<td>Garcia et al. (2015)</td>
</tr>
<tr>
<td>Scum accumulation coefficient</td>
<td>mLscum.kgCOD₉applied</td>
<td>8.56</td>
<td>Santos (2014)</td>
</tr>
<tr>
<td>Scum methane yield</td>
<td>LCH₄.kgVS⁻¹</td>
<td>507</td>
<td>Santos (2014)</td>
</tr>
<tr>
<td>Scum volatile solids (VS)</td>
<td>gVS.L⁻¹</td>
<td>114.8</td>
<td>Santos (2014)</td>
</tr>
<tr>
<td>Scum energetic density</td>
<td>MJ.kg⁻¹</td>
<td>5.8</td>
<td>Santos (2014)</td>
</tr>
<tr>
<td>Nitrogen conc. in SBTF effluent</td>
<td>mgN.L⁻¹</td>
<td>30</td>
<td>Almeida et al. (2013)</td>
</tr>
<tr>
<td>Nitrogen consumption in agriculture (Brazil’s base)</td>
<td>kgN.ha⁻¹.ano⁻¹</td>
<td>10</td>
<td>FAO (2008)</td>
</tr>
<tr>
<td>Nitrogen content in UASB reactor dried excess sludge</td>
<td>%</td>
<td>2.22</td>
<td>Andreoli et al. (2001)</td>
</tr>
<tr>
<td>Exhaust gases generation</td>
<td>Kg.m⁻³biogas</td>
<td>3.22</td>
<td>Rosa et al. (2016)</td>
</tr>
<tr>
<td>Thermal energy content of exhaust gases</td>
<td>MJ.kg⁻¹</td>
<td>2.59</td>
<td>Rosa et al. (2016)</td>
</tr>
<tr>
<td>Efficiency of the exhaust gas dryer</td>
<td>%</td>
<td>85</td>
<td>Rosa et al. (2016)</td>
</tr>
</tbody>
</table>

* Methane yield can significantly increase if dissolved methane is recovered and rainwater contribution in the sewerage network is avoided.

RESULTS

Estimated tropical world population

Figure 1(a) and 1(b) present the number of cities in the tropical world and the corresponding population, grouped into three different categories in terms of city size. Most cities (7,349) have populations between 10,000 and 100,000 inhabitants, however approximately 75% of the tropical zone population lives in towns with more than 100,000 inhabitants.

Considering the population served by the sewage network and treatment (20% - 193.8 million inhabitants), it was estimated that the following populations still lack proper sanitation infrastructure and therefore could be served by anaerobic-based treatment systems: (i) 12.7 million people in municipalities with up to 10,000 inhabitants; (ii) 180.1 million people in municipalities between...
10,000 and 100,000 inhabitants; and (iii) 582.3 million people in cities over 100,000 inhabitants. Hence, the total corresponding raw sewage flow currently discharged into the environment in the tropical world was estimated in 131.8 million m³.d⁻¹. The proposed resource recovery scenarios encompass the treatment to this total currently unserved population.

**Proposed resource recovery scenarios**

The three different population scenarios led to different resource recovery flow-sheet proposals, depending on their technical and economic viability (Figures 2–4), as follows.

**Scenario 1 (up to 10,000 inhabitants)**

This scenario (Figure 2) applies to an estimated population of 12,695,895 inhabitants, living in 3,786 tropical climate cities. For treatment systems applied to municipalities with up to 10,000 inhabitants, direct biogas combustion with thermal energy recovery seems to be the simplest and highest cost-benefit alternative (Lobato et al. 2012). The potential thermal energy generation from biogas burning (190,755 MWh.year⁻¹) could be used in the STP vicinity to heat boilers to produce steam or hot water, for cooking or to directly sanitize the excess sludge generated in the UASB reactors. In this case, drying beds would be used only when the sludge sanitizer was out of operation. The sanitized sludge (about 1.6 Mtdry sludge .year⁻¹), which passes through a previous densification stage with a volume reduction of 35% (Borges et al. 2008), can represent an important source of nitrogen (0.016 MtN.year⁻¹) that could be used for agricultural purposes. Another source of nitrogen could be obtained from direct application of the SBTF effluent for fertigation (0.024 MtN.year⁻¹). Considering both sources (sludge and effluent) and the need for

![Figure 2](https://iwaponline.com/wst/article-pdf/75/7/1659/453425/wst075071659.pdf)
nitrogen in agriculture (10 kgN.ha\(^{-1}\).year\(^{-1}\) – FAO 2015), the proposed resource recovery flow-sheet could sustain around 4 Mha of crops (about 16% of the United Kingdom land). According to our experience, the biological sulphide oxidation system for sulphur recovery does not appear as an attractive alternative for small STPs.

Scenario 2 (10,000 to 100,000 inhabitants)

This scenario (Figure 3) applies to an estimated population of 180,105,925 inhabitants, living in 7,349 tropical climate cities. For this scenario, the potential thermal energy generation from biogas (2,706,075 MWh.year\(^{-1}\)) could be used for further drying the excess UASB reactors sludge, after centrifugation. This would allow 24% volume reduction of sludge to be transported and dispose of. In this case, two main benefits could be achieved: reduction of transportation costs and the associated greenhouse gas emissions. Considering the arbitrary distance between STP and landfill (19 km) as well as a CO\(_2\) emission factor (2.75 kgCO\(_2\)/km – based on diesel stoichiometric oxidation), it would be possible to avoid the emission of approximately 12,145 MtCO\(_2\).year\(^{-1}\). Another alternative regarding the solid by-product management would be the valuation of the dry sludge as fuel, however it requires additional mechanical processing (pelleting, briquetting) that we still consider challenging for such STP scale (between 10,000 and 100,000 population equivalent).
Substantial nitrogen recovery could be attained from the final effluent (0.355 MtN.year\(^{-1}\)) and that could be sufficient to sustain around 33.5 Mha of crops (about one and a half of the United Kingdom land). The biological sulphide oxidation systems designed to receive the effluent from UASB reactors could be able to produce about 0.056 Mt of elemental sulphur per year.

**Scenario 3 (over 100,000 inhabitants)**

This scenario (Figure 4) applies to an estimated population of 582,327,513 inhabitants, living in 1,606 tropical climate cities. For this scenario, the total energy available in the biogas could be used for generation of electricity (6,559,278 MWh.year\(^{-1}\)) or thermal energy (8,745,704 MWh.year\(^{-1}\)). In this case, the electricity could supply approximately 3.2 million households, taking into account the average monthly electricity consumption in Brazil. On the other hand, the total use of generated biogas for thermal energy for drying purposes could result in 24% volume reduction of sludge to be transported and disposed of in landfills. Alternatively, it could be used for the production of energetic biosolids if it is possible to achieve a final moisture content of 10%, as suggested by Rosa et al. (2016).

For this scenario, an important technological alternative is to use the total energy available in the biogas for co-generation of electricity (6,559,278 MWh.year\(^{-1}\)) and thermal energy as heat from the engine exhaust gases (5,686,197 MWh.year\(^{-1}\)). Such thermal energy could be used for drying purposes, resulting in approximately 16% volume reduction of sludge to be transported and disposed of in landfills. Although co-generation of heat and electricity is challenging in small and medium size STPs, it can be technically and economically feasible in large plants (population equivalent over 100,000 inhabitants).

The scum generated in the UASB reactors (181,865 m\(^3\).year\(^{-1}\)) could be used as an extra source of energy (42,232 MWh.year\(^{-1}\)), since it could be treated in anaerobic digesters before disposal in landfill. In a year, the scum treatment can prevent the emission of around 0.179 Mt of CO\(_2\),equiv. to the atmosphere. Regarding the nitrogen content in SBTFs effluents (1.08 MtN.year\(^{-1}\)) it is sufficient to attend to the needs of around 108.4 Mha of agricultural crops (about five times larger than the territory of the United Kingdom). In such a scenario, the biological sulphide oxidation systems designed to receive the effluent from the UASB reactors could be able to produce around 0.116 Mt of elemental sulphur per year.

**General limitations and constraints**

Although there is technical and economic feasibility for the proposed technological set-ups, some limitations and constraints need to be addressed. The UASB/SBTF system has very low or even zero energy demand, nevertheless, the use of pumping stations (particularly in hilly areas) and mechanized sludge dewatering could exert important energy requirements, especially in large scale systems. The electric energy generation potential might be sufficient to meet these demands, however local assessments should be carried out. The existence of irregular connections and contributions of storm water to the sewerage system cause very high sewage dilutions, sharply reducing the net biogas production during rainy seasons (Chernicharo et al. 2015).

The aforementioned proposed scenarios were conceived for the treatment of exclusively domestic sewage. This implies that high concentrations of inorganic substances (e.g. metals) are not expected. In fact, practical full-scale experiences of soil amendment with sewage sludge in Brazil have shown that metal accumulation was not a limiting factor in agronomic recommendations (Bittencourt et al. 2014). Notwithstanding, it can be noticed that the possible cumulative impacts of these substances in the soil demands a well-established monitoring programme. In terms of soil salinization, it tends to be a concern in regions with back-salinity conditions (Bittencourt 2014), nevertheless saline and sodic soils are restricted to relatively small geographic areas. In Brazil, restrictions of this nature would represent only 2% of the vast Brazilian territory (Ribeiro et al. 2005). This does not exclude the need to monitor the soil salt content during the period of biosolids application.

It is worth mentioning that during rainy seasons or fallow soil periods, storage tanks may be required to accommodate the continuous generation of biosolids or liquid for fertigation. This could be a concern regarding infrastructure and operational aspects.

**CONCLUSION**

The results show that anaerobic-based sewage treatment systems can play an important role in the sanitation and environmental sector in developing countries, as demonstrated by its enormous potential for resource recovery in warm climate regions. Overall, for the three population scenarios evaluated, the nitrogen contained in the treated effluent and in the biosolids would be sufficient to fertilize around 142 million hectares of land, and the energy
recovered from the biogas could generate around 11,646 GWh.year\(^{-1}\) of thermal energy and 6,562 GWh. year\(^{-1}\) of electricity. Besides, the biological oxidation of hydrogen sulphide contained in the anaerobic effluent could produce around 151 thousand tons of elemental sulphur per year. The outlined tendencies still need further research and practical improvement in order to better tailor resource recovery potentials to the need for expanding sanitation access in developing countries.

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