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Evaluation of a domestic wastewater treatment plant at an intermediate city in Cochabamba, Bolivia

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Abstract

This study aims to determine the seasonal variability in the performance of a medium size population wastewater treatment plant (WWTP) in Bolivia. The semi-arid area where the WWTP is located is characterized as agricultural land, with an annual rainfall of 500 mm and a mean temperature of 17 °C. The WWTP is built up of five modules, each one comprising two treatment trains composed of an upflow anaerobic sludge blanket (UASB) reactor and horizontal gravel filter. The performance of the full process has been determined based on water quantity and quality. Seven monitoring campaigns of chemical and physical wastewater characteristics were performed from March to December 2017. The measured effluent showed average removal efficiencies of 83 ± 8% and 37 ± 60% for total chemical oxygen demand (COD) and total suspended solids (TSS), respectively. The treatment system has proven to be efficient to remove organic matter and TSS, despite the occurrence of high COD and total solids (TS) influent concentrations, the accumulation of solids at all the processes and the variability of flow and temperature inside the UASB reactors. In order to improve further this efficiency, it is recommended to implement a primary sedimentation unit as a pretreatment for the UASB system that would help to homogenize both the flow and the quality of the influent.

Key words: Bolivia, compact treatment technologies, municipal wastewater, semi-arid, UASB, WWTP evaluation

INTRODUCTION

In September 2015, countries of the world adopted the 2030 Agenda for Sustainable Development. As part of this agenda, Sustainable Development Goal no. 6 calls for ‘Ensuring access to water and sanitation for all’ and target 6.3 specifically expects that, by 2030, countries should improve water quality by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally (CEPAL 2016). By 2025, 1.8 billion people are expected to be living in countries or regions with absolute water scarcity, and two-thirds of the world’s population could be under water stress conditions (UNESCO 2017). Under this scenario, domestic wastewater is attracting more attention as a reliable alternative source of water for crop irrigation, forestry and urban embellishment. In this sense, wastewater should not be seen as a problem, and rather as a water resource that can be used for the benefit of the society.

Within the European Union, legislation on urban wastewater treatment for large populations defines discharge limits for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) and total suspended solids (TSS) for WWTPs, while for smaller populations it only states that an appropriate treatment must be implemented (EEC 1991). Bolivian environmental legislation establishes the maximum values for the following parameters: BOD_5 80 mg/L, COD 250 mg/L, TSS 60 mg/L, sulfur 2 mg/L and coliforms 1,000 MPN/100 mL (Ministerio de Desarrollo Sostenible y Medio Ambiente 1995). However, when it comes to nutrient concentrations, limitations for total phosphorus (TP) and nitrogen (TN) are not specified for general discharges.

In developing countries, more than 95% of wastewater is discharged into the environment without any treatment and the availability of information needed to implement technologies adequate to legal requirements is a constant difficulty (UNESCO 2017). Considering the requirements imposed for the treated effluent, the applied treatment process should accomplish several objectives: relatively low capital and operating expenses, reduced energy consumption and enhanced potential to reuse water.

Several authors have studied different processes for wastewater treatment such as septic tanks, anaerobic reactors, biofilm processes, constructed wetlands and different combinations of these processes. One of the most common and efficient treatment schemes found for wastewater treatment in small communities is an upflow anaerobic sludge blanket (UASB) reactor followed by constructed wetlands (Álvarez *et al.* 2008; Barros *et al.* 2008).

The UASB reactor can be described as a tank where the wastewater enters from the bottom of the reactor and flows up through a granulated sludge bed, where bacteria convert undissolved material into dissolved compounds; then, organic matter contained in the wastewater degrade and finally they transform into biogas. As UASB reactors aren't designed to remove nutrients and to achieve a complete removal of organic matter, some form of post treatment is usually necessary (Chernicharo 2007). Anaerobic filters can be used as polishing units to improve the quality of the effluent of a preceding anaerobic unit. They are, in fact, more suitable to perform as polishing units since when fed with the treated effluent of a preceding unit they are less bound to be clogged by inorganic suspended solids (Libhaber & Orozco-Jaramillo 2012). CWs also offer effective wastewater treatment in a simple and inexpensive manner. Some advantages of this process are that their operation requires low external energy input, and they achieve high levels of treatment with little or no maintenance, making them especially appropriate in locations where no infrastructure support exists (Green *et al.* 2006; Sundaravadivel & Vigneswaran 2001). Their main disadvantages include the large area needed and the careful operation required when starting the wetland (Jácome *et al.* 2016). Nevertheless, it is still an attractive treatment for small communities.

Compared to aerobic treatment, the UASB process has several advantages, such as low operating costs, high solids retention time and very low hydraulic residence time, tolerance to high organic loads, application at both small and large scale, high efficiency with high strength wastewaters, simplicity, flexibility, low requirements for space, energy and chemicals as well as reduced sludge production, which results in lower maintenance costs for the plant. In addition, anaerobic treatment produces biogas, which can be used as fuel (Chernicharo 2007). However, there are still some disadvantages of the anaerobic processes, such us: anaerobic microorganism are susceptible to inhibition by a large number of compounds; process start-up can be slow in the absence of adapted seed sludge; some form of post treatment is usually necessary; the biochemistry and microbiology of anaerobic digestion are complex and still require further studies; possible generation of bad odors occurs, although they are controllable; and there exists an unsatisfactory removal of nitrogen, phosphorus and pathogens (Chernicharo 2007).

Environmental conditions play an important role when it concerns wastewater. Temperature is one of the variables that most influences the process, whose efficiency decreases below 15 °C due to the low activity of anaerobic microorganisms when the depuration is mainly due to sedimentation, while above 15 °C the biodegradation increases. The temperature affects the activity of the microorganisms, determines the amount of net energy produced, and influences the pH-alkalinity ratio. At low temperatures, the reactor is not able to provide sufficient gas mixing to completely avoid the formation of dead zones (Singh *et al.* 1999). It is also important to consider the concentration of dissolved methane in the anaerobic effluent since low temperature raises methane solubility, which promotes its release into the environment (Cookney *et al.* 2012). Anaerobic environments in relation to temperature can be subdivided into three categories: psychrophilic (0–20 °C), mesophilic (20–40 °C) and thermophilic (45–65 °C). These anaerobic reactors are commonly operated under mesophilic or thermophilic conditions (McKeown *et al.* 2012). Temperature changes in the mesophilic interval can normally be tolerated. If the temperature range in the reactor changes, it is necessary to start the reactor again. In the mesophilic range, the activity and growth of the bacteria decreases by half for every 7 °C of descent below 35 °C (Libhaber & Orozco-Jaramillo 2012). The unfeasibility of heating the reactors makes anaerobic treatment of domestic sewage becomes much more attractive for tropical and subtropical-climate countries (Chernicharo 2007).

Many researchers have investigated the performance of UASB reactors under low temperatures, with a large amount of research being done with laboratory scale reactors and some with full-scale operating reactors (Gandarillas *et al.* 2017; Uemura & Harada 2000). Although there have been some performance studies of full scale UASB reactors operating under low temperatures, there is a clear lack of reports concerning the performance of a treatment train that includes UASB reactors combined with horizontal gravel filters operating at elevated altitudes where environment temperatures can decrease drastically.

The main objective of this research is to determine the seasonal variability in the performance of the medium size population wastewater treatment plant (WWTP) of Cliza, located in the High Valley of Cochabamba (Bolivia). The performance has been determined by measuring key parameters that influence the COD removal in UASB reactors and determining the removal efficiencies of control parameters.

METHODOLOGY

Description of the WWTP at Cliza

The coverage of drinking water through network pipes in the municipality of Cliza reached between 66 and 77% in 2012, while the coverage of the sewage system reached between 68 and 95% (INE 2012). In this area, there are private wells as a source of drinking water. The urban area has a population of 11,108 inhabitants and the rural area has a population of 10,635 inhabitants (INE 2012) that count on provision of networked water and sanitation services.

The municipality of Cliza has currently five wastewater treatment plants: four Imhoff tanks and one UASB type reactor, which is the one studied in this paper. The WWTP has been designed for an equivalent population of 9,225 inhabitants (AGUATUYA 2013).

Location

The WWTP is located in the municipality of Cliza in the High Valley of Cochabamba, Bolivia, at 2,718 m.a.s.l. and the coordinates of the treatment plant are 17° 36′ S; 65° 57′ 24″ W. The municipality of Cliza is characterized by a dry winter with precipitation between 2 and 20 mm per month (April to October) and a hot and rainy summer with precipitations between 20 and 130 mm per month (November to March), an average annual temperature of 16.6 °C and annual rainfall of approximately 494 mm.

Treatment sequence

The WWTP consists of five modules, each one comprising two treatment trains simultaneously operated (Figure 1), making a total of 10 treatment trains, comprising one UASB reactor and one

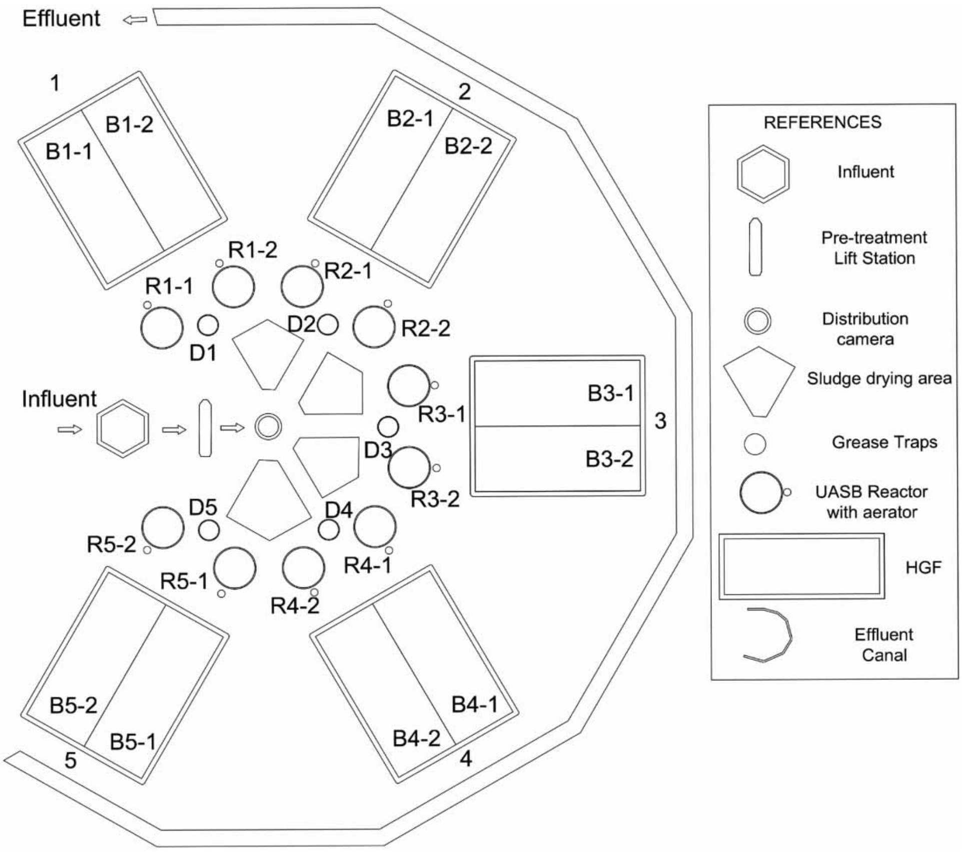

Figure 1 | Sketch of the wastewater treatment plant with the five modules and 10 treatment trains.

horizontal gravel filter (HGF) each. The scheme of the flow direction in the treatment process can be seen in Figure 2. This whole process is designed for a flow of 568.24 m^3/d and to have a hydraulic retention time (HRT) of 31.5 h: 0.8 h at the pretreatment and grease trap, 9.1 h at the UASB reactors and 21.6 h at the horizontal gravel filters. The treatment train is composed of:

- A mechanized pretreatment unit equipped with aerated grit basin and 6 mm screen (AGUATUYA 2013).
- Five grease traps of 5.47 m^3 each and an approximate volume retention time of 0.5 h. The grease traps have a cylindrical shape with an internal radius of 1.2 m, 4.52 m width and 1.5 m length. Each fat trap has two prefabricated fiberglass covers, which allow their cleaning and the removal of accumulated grease and fats (AGUATUYA 2013).
- Ten UASB reactors of 30 m^3 each (one per train) that are 4 m high, built in masonry, with a design HRT of 9.1 h (AGUATUYA 2013). These reactors aren't integrated with a gas liquid-solid separator and do not have a biogas recovery system.
- Ten gravel filters of horizontal subsurface flow of 160 m^2 for a total area of 1,600 m^2, 0.8 m of depth and a porosity of 0.4 (AGUATUYA 2013).

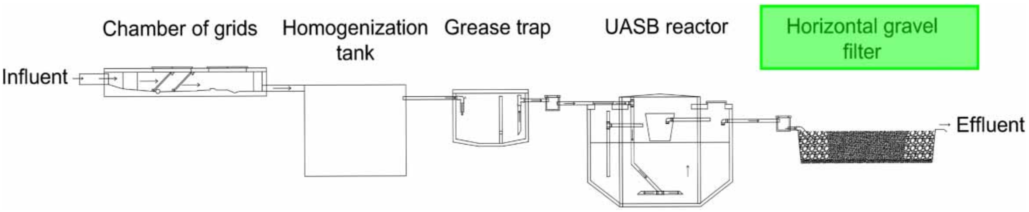

Figure 2 | Treatment train flow profile.

- Sludge drying area which consists of four sludge drying modules of 58.4 m^2 each, with a height of 0.15 m that guarantee the necessary volume for the reception of the generated sludge in each bioreactor, according to the drainage periods established in the design of the structures (AGUATUYA 2013).

Besides the treatment sequence described above, the plant is integrated with two water pumps in a lifting station before the inlet of the plant. The WWTP is also equipped with a flowmeter placed after the pumping station. The water entering the WWTP is accumulated in the pump station and then transported to the mechanized pre-treatment by the action of the pump. This feed to the treatment plant is discontinuous.

Sampling

To assess the performance of the system, grab and composite samples were collected within the WWTP. The samples were collected during seven monitoring campaigns carried out between March and December 2017. The location of sample points are shown in Figure 1, where D is the sampling point after the grease traps, R is the point after the UASB reactors and B corresponds to the sampling point after the HGFs. One sample at the influent (first stage), five samples after the grease traps (second stage), five samples after the UASB reactors (third stage) and five samples after the HGFs (fourth stage), were taken in each monitoring campaign. The first digit next to the letters indicates the module number and the second one makes reference to the train treatment number. The samples were collected within each treatment train alternately. This means that while in the first monitoring campaign samples were collected at trains labeled with odd numbers, during the second campaign samples were collected at trains labeled with even numbers and so on with successive campaigns. This approach was carried out in order to reduce the monitoring points and samples to be processed. A monitoring of physical-chemical characteristics and the volumetric flow at each stage of the treatment train was carried in seven campaigns. In addition, a hydraulic balance of the plant was formulated to have a better understanding of the plant retention times.

Measurement of parameters for water quality characterization

Nine parameters were determined: pH, temperature (T), electrical conductivity (EC), COD, TP, ammonia nitrogen ($N\text{-}NH_3$), total solids (TS), TSS and dissolved solids (DS).

Temperature, pH and electrical conductivity were measured *in situ* with portable instruments from HANNA and HACH. Additionally, COD, total phosphorus (TP), total nitrogen (TN), TS and TSS were determined at the AGUATUYA-UPB laboratory. The analyses were carried out using Standard Methods for Examination of Water and Wastewater as a reference (APHA/AWWA/WEF 1998).

Flow rate measurement

Flow rate measurement of 10 points (the effluent from each HGF) was performed through the volumetric method. This method was applied for the pipe effluent with a stopwatch and a vessel (a graded bucket of 10 liters). The measurement process was repeated three times at each sample point in order to obtain a significant measurement.

Since there was no measuring point for the exit of the grease trap and the exit of the reactors, those flow measurements were not taken.

Hydraulic balance of the plant

To describe the flow balance within the plant, a simple hydraulic balance was formulated. The data was collected through a 24-hour flow measurement, in which the effluent values were registered every hour. Those values were compared with the influent values recorded by the flowmeter. This measurement was performed in the month of December.

RESULTS AND DISCUSSION

Hydraulic balance of the plant

The hydraulic balance of the plant was formulated based on 24-hour flow monitoring. This balance has the influent data recorded by a flowmeter. In order to determine the HRT of the whole treatment plant, a graphic comparison between these two curves was made (Figure 3). The HRT calculated based on the average flow measured was 69.8 h. We can infer that the WWTP actually operates at approximately half of its design capacity.

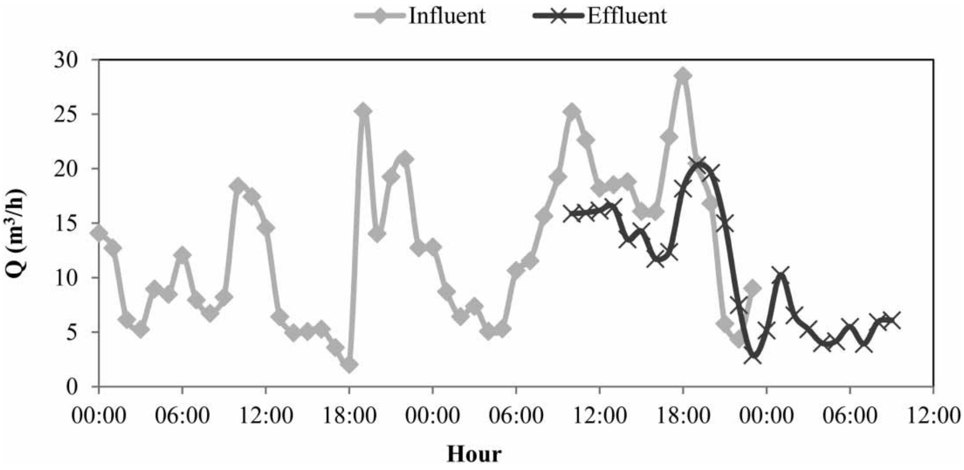

Figure 3 | Hydraulic balance of the treatment plant.

The HRT is distributed as follows: 24.5 h at the UASB, 42 h at the HGFs and the rest at the pre-treatment and the grease trap.

Up flow velocity (UFV)

Conditions inside UASB reactors must remain as constant as possible. In order to verify this, upflow velocity (UFV) was estimated. Increasing the UFV could have two side effects: it could increase the rate of collisions between suspended particles and thus enhance the removal efficiency or it could exceed the settling velocity of the particles, causing them to detach (Mahmoud *et al.* 2003). The mean UFV determined in the reactors was 0.16 m/h. GonCalves *et al.* (1994) found that with a UFV ranged between 0.75 and 0.9 m/h, low concentrations of TSS are obtained, even below 50 mg TSS/l. Other researchers like Moawad *et al.* (2009) described UASB reactors working under low velocities (0.39 ± 0.07 m/h), the COD removal efficiency was also low (57%). An inflow to the WWTP of discontinuous or intermittent type can have an effect on the UFV, making it not constant and having consequences for the efficiency of the reactor.

Influent and effluent wastewater characteristics

The main characteristics of the wastewater measured in seven monitoring campaigns at the influent and effluent of the WWTP are presented in Table 1. The values at the effluent (Out) represent the

Table 1 | Parameters measured at the inlet (in) and exit (out) of WWTP

	Measurement													
	1		**2**		**3**		**4**		**5**		**6**		**7**	
Parameter	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**	**In**	**Out**
TCOD (mg/l)	487	69	1,630	147	877	119	1,444	210	1,598	505	1,557	308		388
TSS (mg/l)	730	249	3,565	934	575	986	424	113	162	40	601	577		324
NH_3 (mg/l)	141.1	25.7	51.8	31.3	48.1	71.8	59.3	84.9	151.4	164.3	104.7	94.7		–
P (mg/)	8	3.6	17.6	14.1	13.2	13.6	22.2	10.5	23.2	34	82.7	21.7		–
pH	7.2	7.6	8.7	7.2	7.3	7.3	7.6	7.2	7.2	7.1	7.2	6.9	8.4	7.1
EC (mS/cm)	1.5	0.7	3.5	1.7	1.5	2.1	2	1.7	1.2	2.1	2	2.2	2.2	2.2
T (°C)	28.1	24.3	27.4	23.4	24.7	21.3	22.8	21.7	19	18.4	20.8	21.8	19.7	22.4

average of the values recorded at the exit of the HGFs in each monitoring campaign. The values of the influent (In) are single measurements at the inlet to the WWTP.

Table 2 shows a summary of the average values of the 10 treatment trains measured at the influent, the effluent from the grease traps, the effluent from the UASB reactors and the effluent from the HGFs.

Table 2 | Average concentrations ± standard deviations of monitored parameters ($n = 7$)

Parameter	**Unit**	**Influent**	**Grease trap effluent**	**UASB effluent**	**HGFs effluent**
TCOD	(mg/l)	1,266 ± 473	1,300 ± 666	752 ± 447	249 ± 158
TSS	(mg/l)	1,010 ± 1267	833 ± 600	569 ± 221	460 ± 382
NH_3	(mg/l)	93 ± 46	77 ± 25	77 ± 31	79 ± 50
P	(mg/l)	28 ± 27	15 ± 5	11 ± 4	16 ± 10
pH	–	7.7 ± 0.6	7.4 ± 0.1	7.1 ± 0.1	7.2 ± 0.1
EC	(mS/cm)	1.98 ± 0.76	1.78 ± 0.06	1.78 ± 0.05	1.78 ± 0.07
T	°C	24.01 ± 3.37	22.6 ± 0.6	22.7 ± 1.8	22.0 ± 0.85

One of the main objectives of this study was to determine the performance and efficiency of this system. Based on this characterization, other parameters were calculated, such as the volumetric organic load and the suspended solids load that allowed us to calculate the efficiency of the system.

Organic loading and suspended solids load

The main parameters that influence the substrate clogging process are the organic load and the suspended solids load (Álvarez *et al.* 2008); a deep analysis of SS and COD was performed.

Organic loading rate

Organic load is measured in the UASB reactors as organic loading rate (OLR) and expressed in kg-COD/m^3/day while at the HGFs it is measured as surface loading rate (SLR) and is expressed in g-COD/m^2/day. The OLR entering the reactors was calculated from the COD values measured at the output of the degreasers of each treatment module whose average values are shown in Table 2.

The values of the OLR versus the efficiency of the total COD removal are shown in Figure 4. The efficiency of the total COD removal was calculated from the percentage difference of the COD concentration measured at the output of the reactors, and the measured concentration at the input thereof

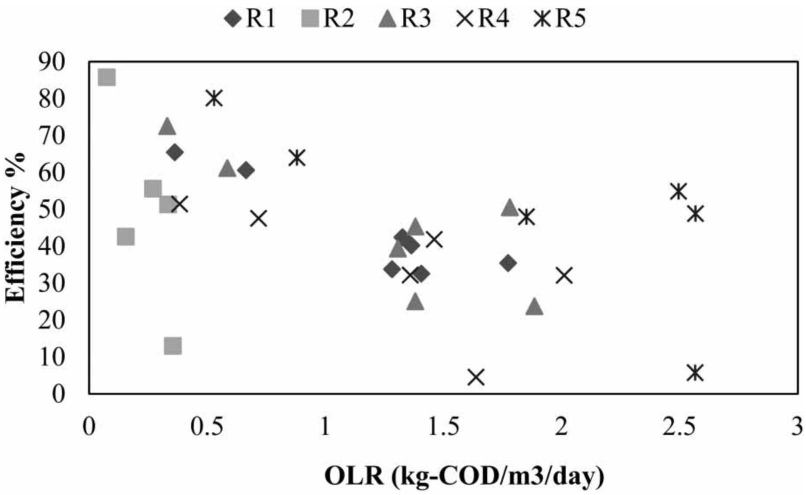

Figure 4 | Organic loading rate (OLR) vs. UASB reactor efficiency.

whose average values are shown in Table 2. It seems the increment of OLR is highly related to the decrement of efficiency. This decreasing tendency confirms that the excess of organic load in the reactor reduces its contaminant removal. The values of OLR of the reactors analyzed in this research have a mean value of 1.24 ± 1.01 kg COD/m^3/d. The recommended OLR values for UASB reactors are in the range of 1.0–3.0 kg COD/m^3-d for wastewater with COD concentrations greater than 750 mg/l. The efficiency expected when reactors operate under these conditions is 70–75% (Álvarez *et al.* 2008). Even considering that the reactors of the Cliza WWTP are working under these conditions, average reactors' efficiencies were found to be between 35 and 50% during the monitoring period.

In addition, we determined the SLR of the HGFs. The estimated values are in the range of 32.1 ± 23.8 g-COD/m^2/d to 231.9 ± 171.4 g-COD/m^2/d. Álvarez *et al.* (2008) analyzed 16 WWTPs and determined an organic load rate for horizontal flow CWs of 5–20 g-COD/m^2/d with a COD removal efficiency of 68 ± 17%. Compared with these values, the organic load of the HGFs is higher, which may be due to a biomass washout from the anaerobic reactors because of the absence of a separator of three phases and the excessive load of solids received by the UASB reactors that passes to the HGFs. It has been found that decentralized water systems have higher concentrations of organic matter and suspended solids, as in this case. Cliza is an intermediate city where daily water consumption is much lower than in large cities, so less wastewater is produced, which means wastewater with higher concentrations entering the WWTP compared to typical wastewater characteristics (Singh *et al.* 2009).

Solids loading

During the study, the average values of TS for the influent and effluent were found to be 3,308 ± 2,743 mg/L and 1,112 ± 522 mg/L, respectively. It is evident that the concentrations of TS that entered the treatment plant were on average three times greater than the effluent, which could indicate an accumulation of solids in the sludge of each treatment.

Figure 5 indicates the variation of TSS for the influent and effluent of the plant. The peak at the second measurement could have been caused by the entry of industrial wastewater to the plant. The third measurement (performed on June 12) shows that the concentration of the effluent is higher than the concentration of the influent. This could be an indicator of a biomass washout.

The calculated suspended solids loading rate at the HGFs has a value of 196.8 ± 76.3 g-TSS/m^2/d, which is much larger than the values reported in literature. De la Varga *et al.* (2013) mentioned that the application of a wastewater pre-treatment is essential for the long-term operation of subsurface flow CW and anaerobic digesters could help preventing clogging. He also reported a solid loading

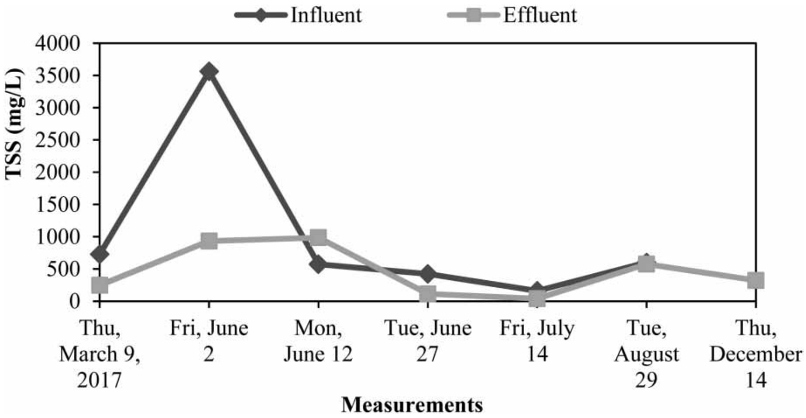

Figure 5 | Total suspended solids concentration for the influent and effluent.

rate of 5 ± 5.6 g-TSS/m^2/d at the WWTP based on UASBs followed by CWs, showing that an efficient anaerobic pretreatment can reduce the risk of clogging in the wetland. Álvarez *et al.* (2008) established a range of 1.4–3.3 g-TSS/m^2/day based on a literature review.

Relation between temperature and COD in UASB reactors

Even though mean temperature at the site is around 17 °C, there is a considerable variability of the diurnal cycle. Actually, high temperatures correspond to low viscosity, reducing hydraulic shearing force on particles, and low temperature is related to high viscosity, requiring more energy for mixing (Mahmoud *et al.* 2003).

As shown in Table 1, temperature remains in the range of 18.4 °C–28.1 °C. The lowest temperature registered after the UASB reactor was 18.5 °C in the fifth measurement (dry winter season). However, mean pH value is 7.2 ± 0.1, which is a clear indicator that reactors are not acidifying.

Figure 6 shows a comparison between mean values of the temperature and the COD removal efficiency of the UASB reactors.

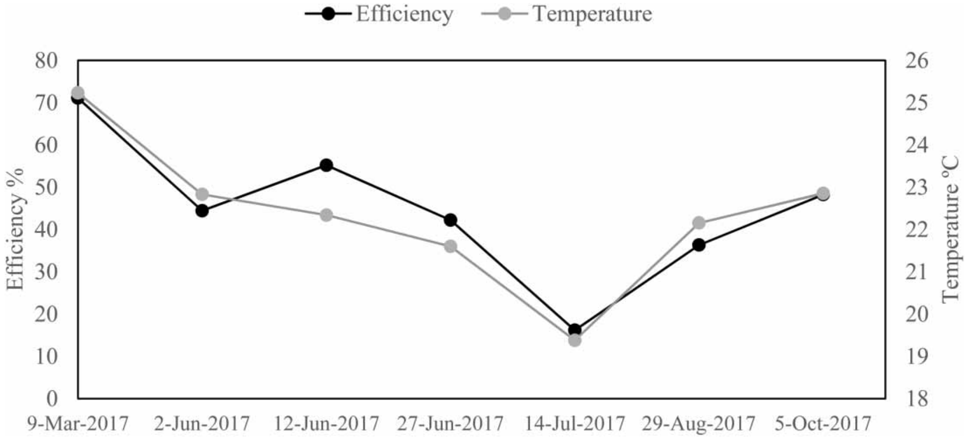

Figure 6 | Relation between the total COD efficiency and temperature values of the UASB reactor.

With these values a potential relation between temperature and the average efficiency in COD removal was determined, as is shown in Figure 7.

The tendency line has a quadratic correlation factor of 0.899, which could indicate that the efficiency is highly correlated to temperature and therefore it is crucial to monitor this parameter to guarantee an adequate performance of the UASB reactor.

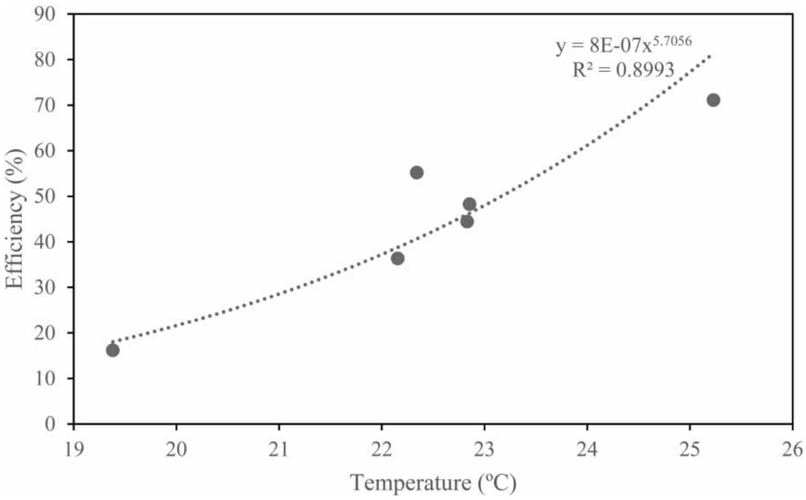

Figure 7 | Relation between the temperature and the average efficiency in COD removal for the measurements.

Removal efficiencies at the UASB reactors and the HGFs

Tables 3 and 4 present the removal efficiencies for each measured parameter and the comparison with the efficiencies found in literature.

Table 3 | Efficiencies of the UASB reactors

	Measurements								
Parameter	**[a]1**	**2**	**3**	**4**	**5**	**6**	**7**	**Range**	**References**
% COD	71.1	44.4	55.2	42.2	16.2	36.3	48.3	45–87.9	Chernicharo & Machado (1998), Gaur *et al.* (2017)
% TSS	48.2	38.9	−43.2	−26.8	−213.6	9.8	60.5	45–87.5	Chernicharo & Machado (1998), Gaur *et al.* (2017)
% NH_3	79.6	−55.8	−32.6	14.7	−29.2	8.4	–		
% P	46.8	9.3	−9.6	20.2	36.5	7.2	–		

[a]Measurement performed by CASA Laboratory.

Table 4 | Efficiencies for the HGFs

	Measurements								
Parameters	**[a]1**	**2**	**3**	**4**	**5**	**6**	**7**	**Range**	**References**
% COD	54.8	79.4	59.2	77.9	58.9	76.1	50.0	57.6–85.8	Álvarez *et al.* (2008), De la Varga *et al.* (2013)
% TSS	34.3	−6.7	−26.3	55.6	92.1	−14.3	52.4	67–96	Álvarez *et al.* (2008), De la Varga *et al.* (2013)
% NH_3	11.0	49.8	11.7	−4.4	−30.9	−16.5	–		
% P	11.7	−14.6	−6.4	−25.2	−122.8	−73.7	–		

[a]Measurement performed by CASA Laboratory.

Since UASB reactors aren't designed to remove phosphorus and nitrogen, we are focusing on the efficiency removal of COD and TSS. As shown in Table 3, the fourth, fifth and sixth measurements don't fit in the range found in the literature. This makes sense considering that in these three measurements the mean COD charge entering to the reactors was of 1,266 ± 473 mg-COD/L. This influent is considered to have a high concentration of COD for municipal wastewater with minor contributions of industrial wastewater (Henze *et al.* 2008). The increase at the influent concentration could be caused by new connections added recently to the sewerage system or a reduction in the flow presented at this season.

Although most of the COD removal efficiency values at the UASB were found to be within the range reported in the literature, TSS removal values in half of the monitoring campaigns were found to be below the values reported in the literature. The removal efficiency in TSS showed negative values, which can be evidence of biomass washout. This purge of solids is the main reason for the clogging at the HGFs.

The removal efficiency values of COD and TSS for the HGFs are shown in Table 4.

An acceptable average efficiency of 65% for COD removal was found at the HGFs stage, considering that there are no plants at these installations. The majority of the COD removal efficiency values are within the range reported in the literature; however, the values found for removal of TSS are below those reported. This may be due to the accumulation of solids at the HGFs, which had not received any type of maintenance since the WWTP began operation in March 2015.

Figure 8 presents the influence of every treatment to the global removal of total COD, where the UASB reactor has the higher participation in March, but it decreases at the fourth and fifth measurements. It is important to mention that when the reactor efficiency decreases, this might be compensated with the efficiency of the HGFs, which results in an acceptable global efficiency removal.

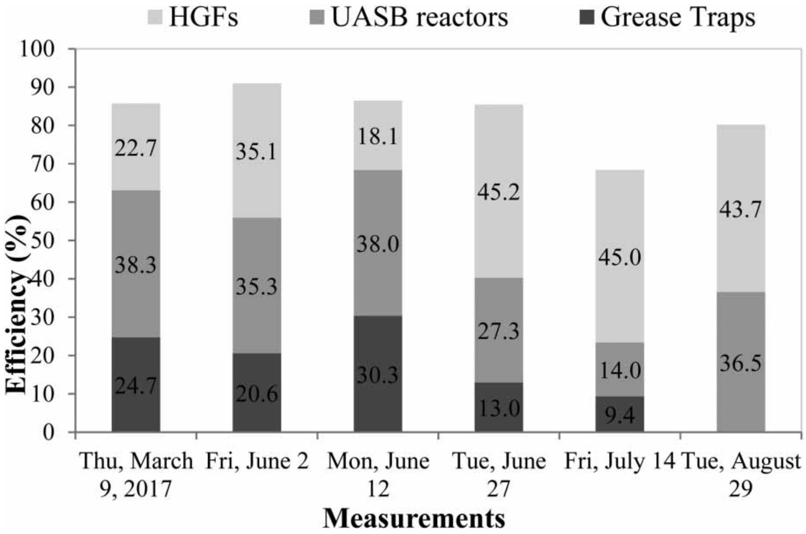

Figure 8 | Comparative efficiency in Chemical Oxygen Demand removal within the different processes.

Production of biogas

An anaerobic process of degradation of organic matter, such as UASB reactors, generates methane which can be used for energy purposes. The amount of methane produced will be influenced by the amount of organic matter degraded. According to IPCC (IPCC 2006) data, under optimal conditions (total absence of dissolved oxygen) an anaerobic reactor is capable of producing 0.25 kg of methane per kg of degraded COD.

Based on this approach, the amount of produced methane gas estimated from an average organic matter degradation rate of 0.59 kg COD/m^3 d is 0.15 kg of $CH_4/m^3 \cdot d$, which is currently released to the environment.

The IPCC assigns a global warming potential of 21 to methane, which means that it is a Green House Gas (GHG) with global warming potential 21 times higher than that of CO_2. Since methane is a flammable gas, produced amount can be captured and used to generate energy, or it can be burned to transform it into CO_2. This practice is recommended in order to reduce potential emissions to the environment.

CONCLUSIONS

The wastewater treatment system consisting of UASBs followed by HGFs has proven to be efficient to remove organic matter and TSS at an average temperature of 17 °C. The removal efficiencies of the WWTP were 83.9% and 36.8% for total COD and TSS respectively. The average effluents concentrations were 249 and 461 mg/L for total COD and TSS respectively. Even if the mean COD effluent remains under the limit established in the regulations, some of the measurements surpass this limit and the most of measured samples for TSS don't accomplish the limits established in Bolivian Regulation. The excess of TSS in the influent is a factor that can counteract the formation of granular sludge in the UASB reactors and cause substrate clogging in the HGFs.

The system was operated at temperatures ranging from 18.4 °C to 28.1 °C. The correlation found between temperature and total COD efficiency removal of the UASB reactors shows that when temperature increases so does the efficiency.

Despite the overload at the influent and the variability of the temperatures at which the system operates, efficiencies of the whole WWTP remain attractive for COD removal thanks to the combination of the UASB and HGFs system. The limited efficiency of the UASB, especially at low temperatures, is compensated for by the high efficiency of the HGFs.

In order to improve the efficiency of the UASB reactors, and consequently the efficiency of the whole plant, it is suggested to implement a primary sedimentation unit before the reactors, increasing the HRT of the whole plant and preventing an overload of solids entering the reactors. This unit could help to maintain a constant water flow to the reactors, which is critical to control linear velocities, thus providing uniform conditions to enhance the formation of anaerobic granules of good settling properties. It is also recommended to implement a biogas recovery system or the open flame burning of the same to reduce its potential contamination as a greenhouse gas.

Additionally, a consistent maintenance program for all processes must be carried out. And finally, the plant must implement a measuring device for the effluent in order to track the effluent flow in a more efficient way.

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