Performance evaluation of a large sewage treatment plant in Brazil, consisting of an upflow anaerobic sludge blanket reactor followed by activated sludge

Pollyane Diniz Saliba and Marcos von Sperling

ABSTRACT

The objective of this study was to evaluate the behaviour of a system comprising an upflow anaerobic sludge blanket reactor followed by activated sludge to treat domestic sewage. The Betim Central sewage treatment plant, Brazil, was designed to treat a mean influent flow of 514 L/s. The study consisted of statistical treatment of monitoring data from the treatment plant covering a period of 4 years. This work presents the concentrations and removal efficiencies of the main constituents in each stage of the treatment process, and a mass balance of chemical oxygen demand (COD) and nitrogen. The results highlight the good overall performance of the system, with high mean removal efficiencies: BOD (biochemical oxygen demand) (94%), COD (91%), ammonia (72%) and total suspended solids (92%). As expected, this system was not effective for the removal of nutrients, since it was not designed for this purpose. The removal of *Escherichia coli* (99.83%) was higher than expected. There was no apparent influence of operational and design parameters on the effluent quality in terms of organic matter removal, with the exceptions of the BOD load upstream of the aeration tank and the sludge age in the unit. Results suggest that this system is well suited for the treatment of domestic sewage.

Key words | compliance, nitrogen, organic matter, performance, statistical analysis, wastewater treatment

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INTRODUCTION

Upflow anaerobic sludge blanket (UASB) reactors are widely used in domestic sewage treatment technology, mainly in warm-climate countries like Brazil, Colombia and India (Noyola *et al.* 2012; Chernicharo *et al.* 2015; von Sperling 2016) and are gaining ground in other countries, such as Indonesia and Angola (Khan *et al.* 2014). This is mainly due to the favourable climatic characteristics of these countries, and because these reactors are compact and more economical and simpler to operate, compared with most treatment systems. Furthermore, when compared to aerobic systems, such as activated sludge, anaerobic treatment is beneficial due to its lower production of excess sludge (von Sperling & Chernicharo 2005; Chong *et al.* 2012; Chernicharo *et al.* 2015).

However, limitations of a fully anaerobic system include the incomplete removal of organic matter, pathogenic organisms and nutrients (Chong *et al.* 2012). According to van Haandel & Lettinga (1994), a UASB reactor is able to remove organic matter by 65–80%, but has little effect on the removal of nitrogen and phosphorus and can generate an increase in ammonia concentrations in the effluent. Similar results were found by Khan *et al.* (2014), who reported that this technology has biochemical oxygen demand (BOD) and suspended solids removal efficiencies ranging from 55 to 75%. The effluent from UASB reactors may present BOD concentrations exceeding 60 mg/L and suspended solids ranging from 50 to 150 mg/L. Removal of thermotolerant coliforms is less than 90%. Chernicharo *et al.* (2015), in a review article on the applicability and challenges in terms of the implementation of UASB reactors, emphasized their great importance, but listed the following constraints that need to be addressed: (i) reactor: corrosion, feeding system, biogas (from tri-phase separator) and waste gas (from settling tank), odor emission, greenhouse gas emission, energy recovery; (ii) liquid effluent: residual carbon, nutrient, pathogen, surfactant, sludge inside the reactor and excess sludge, nutrient recovery, energy recovery, pathogen elimination, presence of sand and debris.

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Therefore, it is common to use UASB reactors followed by a post-treatment stage in order to adapt the effluent to the standards required by most environmental legislation and to protect the receiving water bodies (Chernicharo 2006). The main objective of an aerobic process as post-treatment of an anaerobic stage is to improve the final effluent quality, seeking to protect public health and the environment, and allow the reuse of water (Mungray & Murthy 2014). According to Kassab *et al.* (2010), the configuration of anaerobic treatment followed by aerobic treatment presents significant contributions to the overall performance of the systems, mainly with respect to the reduction in energy consumption and sludge production when compared with a conventional aerobic system. Von Sperling & Chernicharo (2005) reinforce this, by presenting the following ranges of values for both systems, expressed per population equivalent (p.e.): (a) for energy consumption, UASB + activated sludge uses 14–20 kWh/pe.year; conventional activated sludge uses 18–26 kWh/pe.year; (b) for sludge to be treated, UASB + activated sludge produces 20–32 g of dry solids/pe.d; conventional activated sludge produces 20–40 g of dry solids/pe.d. However, there is a need to evaluate the performance of these systems operating at full scale (Kassab *et al.* 2010), in order to produce design and operational parameters that can be used by practitioners.

The uniqueness of the UASB reactor configuration followed by activated sludge is that the former replaces the primary sedimentation tank from the conventional activated sludge system. Therefore, no separate thickening and digestion of primary sludge are required, since the excess sludge withdrawn from the anaerobic reactor is already thickened and digested. Typical values of treated effluents in a system composed of a UASB reactor and activated sludge are: BOD = 40 to 100 mg/L, chemical oxygen demand (COD) = 100 to 200 mg/L, total suspended solids (TSS) from 30 to 90 mg/L, and ammonia from 10 to 15 mg/L (von Sperling & Chernicharo 2002).

Regarding costs, von Sperling & Chernicharo (2005) present ranges of per capita values, expressed in US$ per p.e. Since costs vary over time and place, it can be said, based on the values presented by the cited reference, that UASB + activated sludge incurs around 70 to 75% of the construction costs and approximately 60 to 65% of the operation and maintenance costs of a conventional activated sludge system. But, of course, this can be variable, depending on the composition of costs in each situation.

Von Sperling *et al.* (2001) studied a pilot-scale plant composed of a UASB reactor followed by activated sludge to treat domestic sewage, and encountered good COD removal results (85–91%). A system composed of a UASB reactor and activated sludge, on a laboratory scale, was also studied by Cao & Ang (2009). In this study, the activated sludge system had an anoxic zone followed by the aeration tank and the effluent from that unit was recirculated internally. The results demonstrated that this system is suitable for the treatment of domestic sewage with regards to removal of COD and soluble COD, and that the nitrification process was satisfactory, while denitrification occurred only modestly.

The Betim Central sewage treatment plant (STP) is located in the Metropolitan Region of Belo Horizonte, Brazil, and has a design capacity to treat 514 L/s (about 370,000 inhabitants). It is operated by the Water and Sanitation Company of Minas Gerais (COPASA) and monitored by physical and chemical analyses, which are carried out at laboratories of the company.

Considering the predominance of publications on this configuration (UASB reactor followed by activated sludge) depicting plants on a pilot scale, the scarcity of information from full-scale plants, and the importance of this treatment system, it is understood that the study of specific monitoring data for an STP is important for this process consolidation. Thus, the objectives of this work are to: (i) evaluate the influent and effluent concentrations and the removal efficiencies of several parameters, in each step of the liquid-phase treatment and in the system as a whole; (ii) perform a mass balance of organic matter and nitrogen; (iii) evaluate the influence of operational conditions in terms of design parameters and the relevant literature; and (iv) evaluate the influence of loading conditions on the performance of treatment units.

METHODS

Description of the Betim Central STP

The treatment process of the liquid phase at the Betim Central STP consists of preliminary treatment, UASB reactor, activated sludge aerobic reactor and secondary sedimentation tank. Excess sludge produced in the anaerobic reactors is dewatered in centrifuges and sent to thermal dryers, which are fed by energy from biogas generated in that unit. The centrate returns to the treatment process upstream of the UASB reactor unit. The material removed in the preliminary treatment and the dry sludge are sent to the landfill.

Raw sewage reaches the STP by gravity and passes through the preliminary treatment consisting of a coarse manual cleaning screen, fine mechanized screen, mechanical step screens and grit removal tanks. The sewage is then directed to the UASB reactors.

The Betim Central STP has six UASB reactors in rectangular format, where each unit is 12.8 m wide and 38.4 m long. The total liquid height is 4.7 m. Each reactor was sized to receive an average flow rate of 86 L/s and a maximum flow rate of 142 L/s.

The original design was to send the excess sludge from the activated sludge stage to the UASB reactors, where it would undergo digestion and thickening together with the anaerobic sludge inside. However, the operational staff decided to use two UASB reactor units exclusively as anaerobic sludge digesters (no incoming sewage) to promote the digestion of excess sludge from the activated sludge stage. The effluent from the four remaining UASB reactors, treating the influent sewage, was then sent to the aeration tanks. The monitoring data presented here reflects this operational condition.

The aerobic reactor (aeration tank) receives the effluent from the anaerobic reactors, the recirculated sludge from the secondary sedimentation tanks and part of the incoming sewage that passes only through preliminary treatment (15% of the inflow to the STP bypasses the UASB reactors and goes directly to the aeration tanks, to supply additional organic load for biomass growth in the aerobic stage). The STP consists of two rectangular aerobic reactors, measuring 50.0 m long and 12.5 m wide. The liquid height of the reactors is 6.16 m, resulting in a volume of 3,850 m^3 for each reactor. Each activated sludge reactor incorporates a selector unit comprised of three chambers in series in the inlet zone. These selector chambers are arranged upstream of the aeration zone, seeking to produce sludge with good settleability. They can be operated under aerobic or anoxic conditions, where in the latter case they also assist in achieving some denitrification. The Betim STP was not designed for high total nitrogen removal, as it does not have the internal recirculation line of the nitrified liquid and has an insufficient anoxic volume in the selector zone.

The effluent from the aeration tanks is directed to two circular secondary sedimentation tanks. Each unit measures 38.0 m in diameter and has an average liquid height of 4.5 m. The settlers were designed for a total average flow rate of 514 L/s.

When starting the operation of the treatment plant, the influent flow was low, because of lack of interconnections in the sewerage collection and conveyance system. In this situation, not all treatment units were used. As the flow and influent load to the STP increased, more units were put into operation.

Figure 1 presents an overview of the STP and its flowsheet, as well as the sampling and measurement points used in this work. Table 1 summarizes the design parameters adopted for the Betim Central STP, together with usual values recommended by literature.

Monitoring data

The material used for development of the work was made available by COPASA. It consists of historical data for the period from July 2010 (beginning of operation of the STP) until July 2014, making up 4 years. The parameters monitored and analysed in the work to evaluate the liquid phase are: BOD and COD (total and soluble), TSS, settleable solids, total nitrogen, ammoniacal nitrogen, organic nitrogen, nitrite, nitrate, phosphate and *Escherichia coli*. These parameters were sampled as follows: weekly sampling from July 2010 to December 2013 and sampling twice a week from January to June of 2014. Flow-proportional composite samples were collected in points A and E, according to Figure 1, and grab samples at the other points. The procedures for collecting and preserving the samples and the methods of analysis followed the recommendations of *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 1998).

Mass balance and evaluation of operational conditions

Performance evaluation of the units of the Betim Central STP was performed by comparing the operational parameters (such as food-to-microorganism ratio (F/M), sludge age and loading rates) with values indicated in literature and also with those used in the design of the plant (Table 1).

The COD mass balance was performed as described below. The average load of the liquid phase was obtained from the arithmetic mean of the product of the influent and effluent concentrations by the inflow and outflow of each treatment stage, respectively. For the solid phase of the system, i.e., calculation of the COD load removed both in the excess sludge from the UASB and in the excess sludge of the activated sludge stage, it was considered that the characteristics of the solids were similar to those of the UASB effluent and secondary sedimentation tank, respectively. For the mass balance calculations, treatment of the aerobic excess sludge in the two UASB units that had been reserved for digestion was not considered. Therefore, the UASB units mentioned here are the four units dedicated to treatment of the liquid, and not the sludge. Thus, the COD loads of the sludge from the UASB reactor

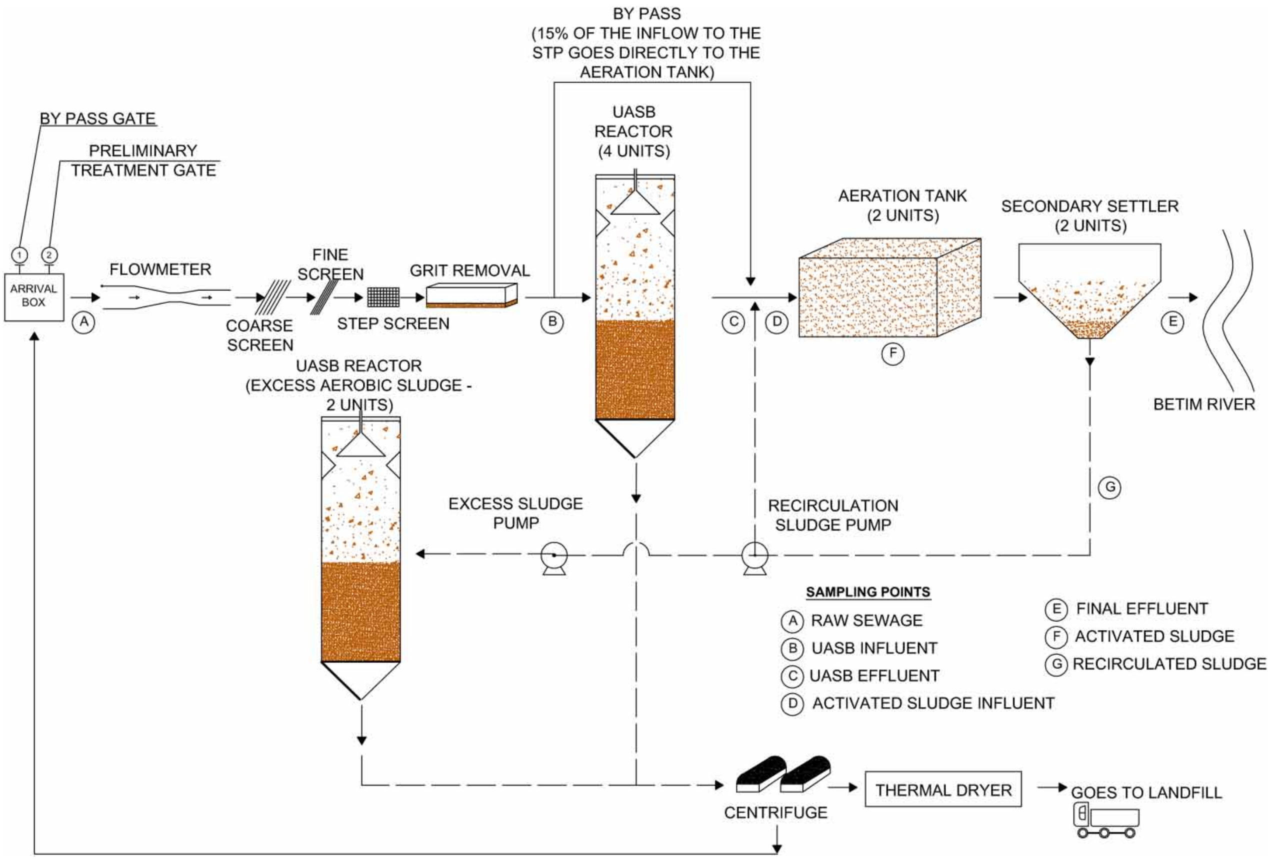

Figure 1 | Overview, flow sheet and sampling points of the Betim Central STP.

Table 1 | Typical literature values for the units of a UASB-activated sludge system and design values adopted for Betim Central STP

Unit	Parameter	Typical literature values	Betim Central STP design
UASB reactor	HRT (h)	4 to 12 h (Gavrilescu 2002) 7 h at 22–25 °C (von Sperling & Chernicharo 2005)	7 h and 24 min for the mean flow
	v (m/h)	0.5 to 0.7 m/h (von Sperling & Chernicharo 2005)	0.63 m/h
Conventional activated sludge – aeration tank	HRT (h)	6 to 8 h (von Sperling & Chernicharo 2005)	4 h and 10 min
	MLSS (mg/L)	1,500 to 4,500 mg/L (NBR 12209 2011)	2,862 mg/L
	MLVSS (mg/L)	1,500 to 3,500 mg/L (von Sperling & Chernicharo 2005)	2,100 mg/L
	VSS/TSS	0.70 to 0.85 (von Sperling & Chernicharo 2005) 0.75 (Wentzel *et al.* 2002)	0.73
	F/M (kg BOD/kg VSS·d)	0.30 to 0.80 kg BOD/kg VSS·d (von Sperling & Chernicharo 2005) 0.20 to 0.70 kg BOD/kg VSS·d (NBR 12209 2011)	0.35 kg BOD/kg VSS·d
	Sludge age (d)	4 to 10 days (von Sperling & Chernicharo 2005) 6 to 10 days (Alem Sobrinho 1983)	7 days
Conventional activated sludge – secondary settler	HLR (m^3/m^2·d)	16 to 32 m^3/m^2·d (Metcalf & Eddy 2014) ≤28 m^3/m^2·d for sludge age less than 18 days, or F/M greater than 0.15 kg BOD_5/kg VSS·d (NBR 12209 2011)	20 m^3/m^2·d
	SVI (mL/g)	0–50 (very good); 50–100 (good); 100–200 (average); 200–300 (poor); 300–400 (very poor) (von Sperling & Chernicharo 2005)	–
	SLR (kg/m^2·h)	4.0 to 6.0 kg/m^2·h (Metcalf & Eddy 2014) ≤6 kg/m^2·h, for sludge age less than 18 days, or F/M greater than 0.15 kg BOD_5/kg VSS·d (NBR 12209 2011)	–

Note: HRT = hydraulic retention time; v = upflow velocity; MLSS = mixed liquor suspended solids; MLVSS = mixed liquor volatile suspended solids; F/M = food-to-microorganism ratio; HLR = surface hydraulic loading rate; SVI = sludge volume index; SLR = surface solids loading rate.

and from the excess aerobic sludge were obtained by proportionality between the particulate COD concentrations and TSS in the UASB effluent and in the final effluent and the sludge, assuming that both solids (solids in effluent and solids in sludge) had the same characteristics. For each data set, the particulate COD/TSS ratio was calculated, resulting in mean values of 1.83 for the UASB reactor effluent and 1.27 mg/L of particulate COD per mg/L TSS for the STP effluent. The particulate COD concentration in the excess sludge (anaerobic and aerobic) was obtained by means of the product of the particulate COD/TSS of the effluent by the TSS concentration of the sludge, and this concentration was multiplied by the sludge flow to obtain the COD load in the sludge. In the gas phase the COD load removed, i.e., converted into methane and carbon dioxide (in the UASB reactor) and carbon dioxide (in the aeration tank), was obtained by the difference between the load removed in the unit and the load removed in the sludge. The contribution referring to the centrate of the centrifuges, which is returned to the system in the box upstream of the UASB reactor and via the bypass, was not calculated due to lack of concentration measurements and because it was only a very small fraction in the mass balance.

The nitrogen mass balance of the Betim Central STP was estimated from the average loads of the various components of nitrogenous material throughout the treatment process. The average load for the liquid phase was calculated in a similar way to that for the COD. It is also important to note that there was no measurement of gaseous nitrogen and nitrogen removed with excess sludge from the UASB reactor and in excess sludge from the aerobic stage. Thus, the nitrogen load removed in the UASB reactor was obtained by means of the difference between the influent and effluent loads to this unit. In order to estimate the nitrogen load of the excess aerobic sludge, it was considered that the solids that comprise this sludge present similar characteristics to the solids in the secondary sedimentation tank effluent from the activated sludge stage. The organic N/TSS ratio resulted in a mean value of 0.23 mg/L of organic N per mg/L of TSS for the STP effluent. The concentration of organic nitrogen in the sludge was obtained by means of the organic N/TSS ratio of the effluent by the TSS concentration of the sludge, and this concentration was multiplied by the sludge flow to obtain the organic nitrogen load in the sludge. Furthermore, the loads of the various nitrogen forms in the excess sludge were estimated by adopting the flow rate of this sludge. The nitrogen gas load was obtained from the difference between the total nitrogen load in the influent for the activated sludge stage and the sum of the total nitrogen load in the effluent from the STP and the excess sludge.

RESULTS AND DISCUSSION

Evaluation of the concentrations and removal efficiencies

Table 2 presents the summary of the descriptive statistics of concentrations and removal efficiencies of each parameter studied.

The range of variation of these parameters in the influent to the Betim Central STP is within the range from low to medium strength (von Sperling & Chernicharo 2005; Metcalf & Eddy 2014). The low influent concentrations found are due to the fact that the infiltration component of the total flow was proportionally high, compared with the domestic sewage flow. The latter was low in the first years, as a result of missing connections of sewers to the main interceptor. This led to a more diluted wastewater, in comparison with wastewaters of medium to high strength.

The mean BOD concentration of the final effluent (12 mg/L) was well below the range indicated by von Sperling & Chernicharo (2002) (40–100 mg/L), but similar to that found by Mungray & Murthy (2014) (17 mg/L) and by Khan *et al.* (2014) (18 mg/L) in full-scale systems with a similar configuration. In addition, it was well below that required by the environmental legislation of the state of Minas Gerais (60 mg/L) (Minas Gerais 2008) and that stipulated in the design (30 mg/L).

In terms of each stage individually, it is observed that the preliminary treatment, as expected, presented a low BOD removal efficiency, since this is not its main objective. There is little data in the literature regarding the efficiency of the preliminary treatment, but attention should be given to the fact that the system under study included a sieving stage. The efficiency of the UASB reactor (58%) is within the typical literature range, although on the lower side, and smaller than the design value of 70%, while that of the activated sludge stage (83%) exceeded expectations, since it received an influent of lower biodegradability. The low efficiency of the UASB reactor is associated with the low influent concentrations (see explanation above), since the effluent concentrations from this stage are within the expected ranges reported in the literature (von Sperling & Chernicharo 2002).

The average effluent COD concentration (37 mg/L) was well below that required by state legislation (180 mg/L) and also below that found by von Sperling

Table 2 | Descriptive statistics on the concentrations and removal efficiency of the parameters monitored and studied in the Betim Central STP

Parameter	Statistic	Raw sewage conc. (mg/L)	Preliminary treatment		UASB reactor		Activated sludge		Global effic. (%)
			Conc. (mg/L)	Effic. (%)	Conc. (mg/L)	Effic. (%)	Conc. (mg/L)	Effic. (%)	
BOD	Mean	195	171	5	64	58	12	83	94
	Median	196	160	16	57	64	10	86	95
	Standard deviation	69	79	46	33	20	9	13	4
Soluble BOD	Mean	82	66	64	38	71	5	92	97
	Median	83	53	67	36	73	5	93	97
	Standard deviation	31	35	17	10	11	2	4	1
COD	Mean	442	398	1	173	54	37	78	91
	Median	439	361	11	158	59	33	81	92
	Standard deviation	144	178	51	91	23	19	21	5
Soluble COD	Mean	189	153	65	92	71	26	86	94
	Median	178	142	65	84	77	25	87	94
	Standard deviation	68	65	10	34	13	8	6	2
Settleable solids (mL/L)	Mean	4.6	6.2	–	1.2	–	0.2	–	–
	Median	4.0	4.0	–	0.7	–	0.1	–	–
	Standard deviation	2.6	8.0	–	1.9	–	0.4	–	–
TSS	Mean	240	244	−21	71	64	19	79	92
	Median	224	209	6	59	69	14	82	93
	Standard deviation	121	178	106	48	30	15	14	7
Organic nitrogen	Mean	12.8	11.6	−22.5	5.0	34.8	2.0	55.3	75.3
	Median	13.0	11.0	0.0	4.0	60.0	1.8	74.4	85.6
	Standard deviation	7.5	7.3	101.1	4.7	109.0	1.5	57.5	30.7
Ammoniacal nitrogen	Mean	25.4	30.9	−30.9	31.6	−6.6	7.3	77.1	72.0
	Median	26.0	29.7	−30.8	32.0	0.0	4.0	90.0	83.6
	Standard deviation	7.8	10.5	31.6	8.9	29.6	8.9	29.5	33.0
Nitrite-N	Mean	–	–	–	–	–	0.8	–	–
	Median	–	–	–	–	–	0.2	–	–
	Standard deviation	–	–	–	–	–	1.4	–	–
Nitrate-N	Mean	–	–	–	–	–	10.3	–	–
	Median	–	–	–	–	–	8.5	–	–
	Standard deviation	–	–	–	–	–	8.6	–	–
Total nitrogen	Mean	38.3	42.5	−20.8	36.7	9.1	20.8	43.3	38.2
	Median	38.0	39.0	−20.0	37.0	15.9	20.2	40.7	39.3
	Standard deviation	12.5	15.2	27.6	10.4	25.9	9.2	21.9	24.8
Phosphate-P	Mean	5.4	6.3	−24.8	5.5	6.3	3.4	45.2	33.8
	Median	5.1	5.5	−17.7	5.2	14.7	3.1	43.7	37.7
	Standard deviation	1.7	2.2	41.5	2.1	38.8	1.4	22.5	34.3
E. coli (MPN/100 mL)	Geometric mean	1.05×10^8	–	–	–	–	2.27×10^4	–	99.83452
	Median	1.52×10^8	–	–	–	–	2.34×10^4	–	99.97952
	Standard deviation	4.3×10^8	–	–	–	–	3.07×10^6	–	0.73

Notes: 1. Removal efficiencies of soluble BOD and soluble COD were calculated based on (total influent concentration − filtered effluent concentration)/total influent concentration. 2. Statistical descriptors of removal efficiencies (mean, median and standard deviation) have been calculated based on the series of removal efficiencies calculated at each monitoring day. 3. Sampling points in Figure 1: raw sewage (A), preliminary treatment (B), UASB reactor (C), activated sludge (E). 4. Number of samples per parameter and sampling point (n): BOD (273), soluble BOD (63), COD (273), soluble COD (62), settleable solids (258), TSS (258), organic N (198), ammonia N (200), nitrite (118), nitrate (117), phosphate (163), *E. coli* (97).

et al. (2001), from 56 to 128 mg/L, and by Mungray & Murthy (2014) of 115 mg/L and 123 mg/L. The overall COD removal efficiency of the system presented an average value (91%) close to that found by von Sperling *et al.* (2001), and above the value obtained in the STPs studied by Mungray & Murthy (2014).

With respect to the biological removal efficiency [(total influent concentration – filtered effluent concentration)/ total influent concentration] of BOD and COD, it is found that the activated sludge, despite receiving an influent with lower biodegradability, was more efficient than the UASB reactor. In addition, the median of the overall biological efficiency of the system was 97% for BOD and 94% for COD, indicating the excellent performance of the entire process.

The mean value of the TSS concentration of the UASB reactor effluent (71 mg/L) was already below that required by the state environmental legislation (100 mg/L). However, the activated sludge unit contributed to a great improvement in the effluent quality (19 mg/L). This mean effluent concentration is lower than the mean value of 57 mg/L, obtained in a survey of 13 activated sludge plants in Brazil, without a UASB reactor (Oliveira & von Sperling 2011), but it could possibly still be improved further. Solids flux theory was used to compare applied with limiting load in the final clarifiers of Betim Central STP, but this analysis did not indicate problems of overloading and association with increases in effluent TSS concentration. One possibility, not proven, could be that some denitrification could be taking place in these sedimentation tanks, leading to N_2 bubbles release and carry-over of solids to the tank surface.

The removal of organic nitrogen occurred in both the UASB reactor (ammonification) and the activated sludge reactor. As was expected, the ammonia removal efficiency of the UASB reactor was practically nil or negative, since in this unit nitrification does not occur, but ammonification does take place. As expected, the removal of ammoniacal nitrogen through nitrification occurred only in the aerobic phase of the system. The effluent ammonia concentration was 7.3 mg/L (mean) and 4.0 mg/L (median), whereas the ammonia removal efficiency was 77% (mean) and 90% (median). These removal efficiencies are within the range found by Khan *et al.* (2014) (62% to 82%) and slightly lower than that obtained by Cao & Ang (2009) (92%). Given the warm temperature and the operating sludge age, full nitrification could be expected. Several factors may affect nitrification, but in the specific case of activated sludge systems treating anaerobic effluent, a concern is related to the inhibitory influence of hydrogen sulphide on nitrifiers. Because of this, the Brazilian norm for the design of STPs (Associação Brasileira de Normas Técnicas 2011) specifies that a higher sludge age should be adopted in the design of activated sludge systems acting as post-treatment of UASB reactor effluents.

As was expected, the ammonia removal efficiency by the UASB reactor was practically nil or negative, since in this unit nitrification does not occur, but ammonification does take place.

The nitrate concentration in the final effluent was quite variable, but it was below the estimated design value (35 mg/L) throughout the monitoring period. The nitrite concentration, in addition to presenting lower values than nitrate, as was expected, also had a smaller variation in this period.

The average total nitrogen removal efficiency was 38%, below the values found by Huang *et al.* (2007) (54 and 77%) and Garuti *et al.* (1992) (82%). This is explained by the fact that the Betim Central STP, different from the system studied by these two groups of researchers, does not operate with internal recirculation of the nitrified effluent to anoxic zones. Thus, if it was desired to increase the nitrogen removal efficiency of this STP, recirculation of the nitrified effluent in the aeration tank, to the anoxic zones, could be studied as an alternative.

The mean phosphate concentration of the final effluent was 3.4 mg/L, close to that found by Khan *et al.* (2014) and below the stipulated design value of 7.5 mg/L. As expected, the overall mean efficiency of phosphate removal (34%) was not high, despite exceeding the estimated design value (25%).

Regarding *Escherichia coli*, both the geometric mean concentration of the effluent (2.27×10^4 MPN/100 mL) and the mean removal efficiency (99.83% or 2.78 log units) were close to the values found by Khan *et al.* (2014). It should be noted that the Betim Central STP was not designed for removal of this parameter and yet it performs well, considering its treatment process.

The Mann–Whitney *U* non-parametric statistical test at 5% significance level was used to compare raw sewage and treated effluent in the dry (colder) (April to September) and rainy (warmer) (October to March) periods. For both the raw sewage and the treated effluent, most of the analysed parameters were influenced by seasonality, presenting lower concentrations in the rainy season, indicating a greater contribution of infiltration flow, besides the possible intrusion of rainwater in the sewerage system. However, the removal efficiency was not influenced by seasonality, except for ammonia, indicating that this is a robust treatment system capable of providing a consistent performance, regardless of the influent concentrations and period of the year.

In order to compare the performance of this system of UASB + activated sludge with other treatment plants operating exclusively with activated sludge systems treating raw sewage in Brazil, data from a survey undertaken by Oliveira & von Sperling (2011) with 13 full-scale activated sludge plants were used. The mean removal efficiencies obtained in this survey were: BOD 85%, COD 81%, TSS 76%, total N 50%, total P 46%, thermotolerant coliforms 99%. From the values presented in Table 2, it can be seen that the treatment plant under study (UASB + activated sludge) had a better performance than the group of activated sludge plants in terms of BOD, COD and TSS removal, and comparable results in terms of total nitrogen and total phosphorus removal.

Mass balance in the system

In order to facilitate visualization of the general performance of each unit regarding the removal of organic matter and nitrogen, mass balances in the system were elaborated (Figure 2), indicating the average estimated inlet and outlet loads in each unit of the STP.

In Figure 2(a), in the liquid phase loads are defined as follows: influent load = influent concentration × influent

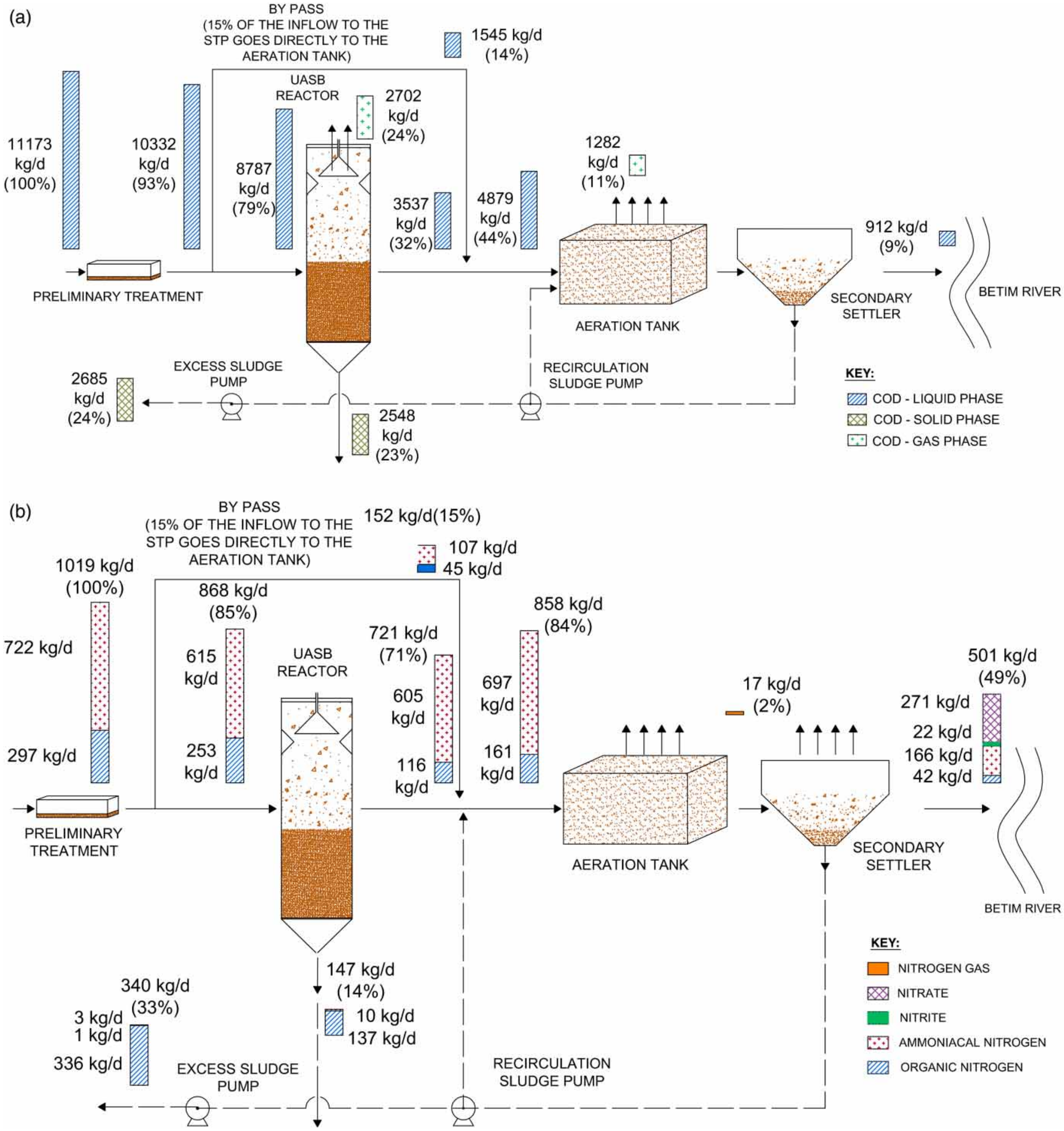

Figure 2 | (a) COD and (b) nitrogen mass balance (mean values) along the treatment system.

flow, and effluent load = effluent concentration × effluent flow; in the solid phase, the load removed in sludge = excess sludge flow × effluent concentration × (TSS concentration in excess sludge/TSS concentration in final effluent); and finally, in the gas phase, load = load in influent liquid phase − load in effluent liquid phase − load in solids phase.

As expected, it can be seen that COD removal by the preliminary treatment was very small (7%), and both the anaerobic phase and the aerobic phase played an important contribution in the removal of organic matter, resulting in a mean effluent load corresponding to 8% of the influent load to the STP, i.e., an overall efficiency of 92%. The high organic matter removal by the anaerobic phase motivated the operation to use the raw sewage bypass in order to guarantee adequate availability of organic carbon to the microorganisms of the aerobic stage.

The COD fraction that is removed with the sludge in the anaerobic and aerobic stages represented about 29% and 55%, respectively, of the total COD influent to each stage. In the gas phase, the removal of this parameter represented about 31% in the anaerobic process and 26% in the aerobic process. These values were slightly different from those suggested by von Sperling & Chernicharo (2005): 5 to 15% removal via sludge and 50 to 70% methane gas conversion for anaerobic systems, and 30 to 40% removal via sludge and 40 to 50% conversion into carbon dioxide for aerobic systems. Thus, the results suggest that COD removal by sludge was higher than expected, while lower production of methane and carbon dioxide gas was obtained.

A UASB effluent ammonia load higher than the influent load was expected by the ammonification process. Nevertheless, these values were very close (influent and effluent ammoniacal nitrogen loads equal to 615 kg/day and 605 kg/day, respectively), indicating that there was also nitrogen assimilation by bacteria present in this unit.

The final effluent of the STP, as expected, presented a higher load of nitrate and only small fractions of nitrite, ammoniacal nitrogen and organic nitrogen.

One of the forms of nitrogen removal in the Betim Central STP is through the withdrawal of excess sludge from the UASB reactor and from the aerobic phase. Thus, the difference found between the influent and effluent loads to these units (UASB and activated sludge) represents the amount of nitrogen used for growth of microorganisms, which, when discarded from the system, carry with it the nitrogen consumed. Ammonia present in this sludge refers to the liquid concentration that is discarded along with the solid portion.

The removal of total nitrogen in the Betim Central STP occurs via the wastage of sludge, as well as the nitrate fraction which, through processes such as denitrification, is reduced to nitrogen gas, separating itself from the liquid medium. In Figure 2, the gaseous nitrogen was represented in both the secondary settler and the aeration tank, with an estimated load considered not excessively high. This is because the Betim Central STP was not designed with the purpose of biologically removing nitrogen. Thus, the denitrification process probably occurred either in the aeration tanks (in the anoxic zone chambers of the biological selector and inside the flocs) and/or in the secondary settlers, since in these environments anoxic conditions can be formed (presence of the nitrate formed in the aeration tank and absence of oxygen).

Compliance with design parameters and influence of the operational conditions on the quality of the treated effluent

In this section the STP and each stage (UASB, aeration tank and secondary settler) were evaluated throughout the monitoring period with regards to meeting the estimated and adopted design values. The operating conditions were also compared with values indicated in the literature. In addition, the influence of operating and loading conditions on the performance of the STP, as measured by the BOD removal efficiency at each stage, was evaluated, considering that the overall treatment objective of Betim Central STP is the removal of organic matter. Table 3 shows the descriptive statistics of the main operational variables. Graphics of operational conditions and BOD removal efficiency changing over time are provided in the Supplementary Material (available with the online version of this paper).

Both the influent flow and BOD load to the STP were below the estimated design values during the entire monitoring period. The values increased over the years, indicating that adhesion to the sewage collection network and interconnections of the conveyance system took place gradually.

During most of the monitoring period, the UASB reactor operated under adequate conditions with respect to the hydraulic retention time (HRT) and the upflow velocity. Therefore, it was not possible to observe a clear relationship between these parameters and the BOD removal. Even with velocities slightly above the design value, the UASB reactor presented high efficiencies, indicating that there is no loss of organic matter by drag in the upward flow or by reduction of the filtration capacity of the expanded bed, as mentioned by Leitão *et al.* (2006). According to these authors, high upflow

Table 3 | Descriptive statistics referring to the operational parameters of the Betim Central STP units

Unit	Parameter	STP design	Mean	Median	Minimum	Maximum	Percentile 10%	Percentile 90%	Standard deviation	Coefficient of variation
STP	Flow (L/s)	514	302	323	90	464	215	382	71	0.24
	BOD influent load (kg BOD/d)	16,724	5,184	4,954	407	13,915	2,259	8,099	2,456	0.47
UASB reactor	HRT (h)	7.4	8.8	8.3	5.17	25.04	6.4	10.4	2.9	0.33
	v (m/h)	0.63	0.57	0.56	0.19	0.90	0.45	0.73	0.13	0.23
Aeration tank	BOD influent load (kg BOD/d)	5,760	2	2	306	10	922	3	1	0.62
	HRT (h)	4.2	6.1	6.1	3.0	16.3	4.6	7.2	1.6	0.26
	MLSS (mg/L)	2,862	5,405	5,017	1,586	14,575	3,320	7,761	1,988	0.37
	MLVSS (mg/L)	2,100	3,433	3,271	1,018	8,695	2,131	4,827	1,173	0.34
	MLVSS/MLSS	0.73	0.64	0.65	0.25	0.85	0.55	0.73	0.07	0.12
	Sludge age (d)	7	16.4	13.4	2.4	75.3	6.9	30.7	11.8	0.72
	F/M (kg BOD/kg VSS·d)	0.35	0.09	0.09	0.02	0.34	0.04	0.15	0.05	0.56
Secondary settler	HLR (m^3/m^2·d)	19.6	25.0	24.3	6.8	55.0	18.9	31.4	6.1	0.25
	SLR (kg SS/m^2·h)	–	5.8	5.4	2.0	12.7	4.7	12.5	2.3	0.39
	SVI (ml/g)	–	65	59	20	286	41	91	31	0.47

Notes: 1. STP = sewage treatment plant; HRT = hydraulic retention time; MLSS = mixed liquor suspended solids; MLVSS = mixed liquor volatile suspended solids; HLR = hydraulic loading rate; SLR = solids loading rate; SVI = sludge volume index. 2. Statistical descriptors of removal efficiencies (mean, median and standard deviation) have been calculated based on the series of removal efficiencies calculated at each monitoring day.

velocities may cause expansion of the sludge bed, leading to a reduction in the solids retention capacity and possible solids losses in the final effluent. At Betim Central STP high upflow velocities were not found to be associated with a deterioration of the effluent quality.

As with the influent organic load to the STP, the influent BOD load to the aeration tank oscillated and increased throughout the monitoring period. As expected, this parameter was associated with the performance of the unit, with higher loads related to high biological efficiencies. This can be explained when considering that the organic matter removal can be facilitated at high influent concentrations, given the robustness of the activated sludge process and provided the influent concentrations are within the acceptable limits of the applied load.

Both the mixed liquor volatile suspended solids and the mixed liquor suspended solids in the aeration tank exceeded the design values most of the time. In the case of mixed liquor suspended solids (MLSS), during about half of the monitoring period the values were above those of literature and the Brazilian norm NBR12209 (maximum value of 4,500 mg/L), indicating that the aeration tank operated with a large mass of solids. The mixed liquor volatile suspended solids (MLVSS) were in the range of both conventional activated sludge (1,500 to 3,500 mg/L) and activated sludge with prolonged aeration (2,500 to 4,000 mg/L).

During most of the time, values of the MLVSS/MLSS ratio were below those estimated in the design and outside the range of typical activated sludge reactors. As mentioned by Fan *et al.* (2015), the low MLVSS/MLSS values can be explained by the low organic load in the influent to the SPT and by the high sludge age in the system. Although higher biological efficiency and better effluent quality were expected for lower MLVSS/MLSS ratios, the influence of this parameter on system performance could not be clearly observed.

Although the Betim Central STP was designed as a conventional activated sludge system, the values of the sludge age were, for most of the monitoring period, above the usual range for this process, resulting in a more stabilized sludge. This is explained by the influent loads being lower than those adopted for design and by the high concentration of volatile solids in the aeration tank.

Higher sludge ages resulted in greater biological efficiency. This can be explained by the fact that the growth time of heterotrophic bacteria was satisfied, allowing for proper degradation of the influent organic matter. Because the sludge age influences both settleability of the sludge (Çakici & Bayramoğlu 1995) and the quality of the effluent, proper monitoring of this parameter is very important for good performance of the treatment plant.

The F/M was below the design value for conventional activated sludge (0.35 kg BOD/kg VSS·d) throughout the study period. The low values of the F/M can be explained by the high concentration of VSS in the aeration tank, as well as the low BOD load in the influent to the STP. It could be expected that lower F/M values would result in greater biological efficiency. However, it was not possible to observe a relationship between these two parameters.

The surface hydraulic loading rates (HLRs) on the secondary settler, during the majority of the monitoring period, were within the typical range for a conventional activated sludge system (16 to 32 $m^3/m^2 \cdot d$). However, higher values were observed. But even when operating under overloading conditions, the HLR in the secondary clarifiers did not seem to have affected the system performance. This probably occurred because of the low values of the sludge volume index (SVI) and the good settling properties of the sludge.

Using the limiting solids flux theory, according to the methodology proposed by von Sperling & Fróes (1999), it was found that the secondary sedimentation tanks operated under both underloaded and overloaded conditions. It could be expected that the solids flux in the secondary settler had an influence on the performance of this unit, especially with respect to loss of solids in the effluent. However, in the Betim Central STP, the applied solids flux generally did not appear to influence the removal efficiency of particulate BOD.

The SVI was in the range considered good (50 to 100 mL/g) during almost the entire study period, indicating that the sludge presented a good settleability, contributing to a good quality of the final effluent. Considering the indications of Hreiz *et al.* (2015) and that the Betim Central STP presented high sludge ages, it could be expected that the sludge would present poor settleability. However, the presence of the selector compartments probably contributed to the production of a healthy biomass, reducing the quantity of filamentous bacteria and leading to a high quality sludge with regards to sedimentation. Thus, the SVI did not appear to influence the efficiency of BOD removal or affect the effluent quality due to loss of solids.

All the results presented here indicate that the BOD removal efficiencies depended not only on one variable or loading factor, but on several factors combined.

CONCLUSIONS

Based on the full-scale performance evaluation of a large STP composed of a UASB reactor followed by activated sludge operating in a warm-climate country, the study of the Betim Central STP allowed the following conclusions to be drawn.

The system composed of the UASB reactor followed by activated sludge showed to be very effective for the treatment of domestic wastewater, with respect to removal of organic matter (BOD: 94% and COD: 91%) and solids (TSS: 94%). The system was not designed for nitrogen, phosphorus and coliform removal, but even so its performance exceeded expectations in these areas.

The COD mass balance showed the removal at each stage (aerobic and anaerobic), and when compared to the literature, indicated a lower production of biogas at the plant. However, the nitrogen mass balance showed the behaviour of the nitrogenous matter throughout the treatment system, in addition to indicating the anticipated low removal of this parameter, with still high concentrations in the final effluent.

The low influent load to the STP resulted in small values of MLVSS/MLSS and F/M, and also a high sludge age. Because of this, even though the activated sludge stage had been designed for a conventional sludge age, it operated for long periods with typical extended aeration ranges, leading to aerobic sludge digestion.

Although some high values of MLSS resulted in a higher solids flux to the secondary settler, they did not lead to deterioration in effluent quality related to solids loss in the final effluent.

Despite the occurrence of high values of sludge age, the Betim Central STP presented a sludge of adequate settleability, possibly due to the selector chambers at the entrance of the aeration tank.

Based on this overall evaluation, it can be concluded that the configuration of UASB reactors followed by activated sludge process is more than adequate for the treatment of domestic wastewater in warm-climate regions.

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