Performance comparison between two equal stabilization ponds operating with and without sludge layer

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ABSTRACT

Stabilization ponds are a highly appropriate system for treating sewage in small to medium size communities. However, sludge accumulation at the pond bottom occurs with the passage of time, reducing the net pond volume, which, in principle, could affect its performance. The objective of this paper is to compare the behaviour of two equal ponds in parallel treating the same flow of municipal wastewater from an upflow anaerobic sludge blanket reactor in Brazil. Each pond treated a population equivalent of around 125 inhabitants. One pond had approximately 40% of its net volume occupied by sludge after 11 years of operation, while the other pond had previously undergone complete desludging. The study covers the removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), nitrogen fractions and coliforms. Owing to the presence of a sludge layer, the theoretical hydraulic retention time (HRT) was lower in the pond without sludge. For BOD, COD, SS and *Escherichia coli* there were no significant differences (Wilcoxon matched-pairs test) between both ponds. The pond without sludge had significantly better removal efficiencies in terms of total Kjeldahl nitrogen and ammonia-N. The sludge layer probably allowed the occurrence of removal mechanisms that compensated for the reduction caused in the HRT.

Key words | domestic sewage, maturation ponds, polishing ponds, sediments, treatment performance

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INTRODUCTION

In many countries in the world, the most widely adopted treatment systems are waste stabilization ponds (Kayombo *et al.* 2005; Noyola *et al.* 2012). These systems are considered simple and cheap to construct (needing no skilled labour) and to operate (no special equipment is needed), making them ideal for developing countries.

The upflow anaerobic sludge blanket (UASB) reactor followed by a polishing pond configuration is a very interesting alternative from technical, economic and environmental points of view, especially in warm climate regions (von Sperling & Chernicharo 2005). There are several studies available in the literature reporting performance data from this type of system (von Sperling *et al.* 2002; Cavalcanti *et al.* 2002; von Sperling *et al.* 2003; von Sperling & Mascarenhas 2005; von Sperling & Andrada 2006; Sato *et al.* 2006; El-Shafai *et al.* 2007; Oliveira & von Sperling 2009; Walia *et al.* 2011; Dias *et al.* 2014). The first polishing pond operating immediately after the UASB reactor exhibits mixed behaviour ranging between a facultative and a maturation pond. Its surface organic loading rate is comparable to those applied in low-loaded facultative ponds, whereas the hydraulic retention time (HRT) is short, similar to maturation ponds.

In treatment ponds, there are two distinct vertical compartments, a liquid layer and a sludge layer. These compartments are divided into three different layers (aerobic, anoxic and anaerobic) due to the vertical profiling of the oxygen gradient in the pond (Namèche *et al.* 1997; Keffala *et al.*, 2011). Besides the oxygen gradient, a variation in the sediment profile in terms of water content, organic matter, nitrogen and phosphorus can be observed. Namèche *et al.* (1997) detected this while studying aerated ponds in Belgium (Bertrix). In their study, they found that there was a variation along the profile due to bacterial activities and also a variation of the oxygen concentration in each layer.

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Ponds accumulate sludge at the bottom due to the sedimentation of suspended solids (SS) from the influent, as well as the sedimentation of dead algae and bacteria that grow in the pond (Bouza-Deaño & Salas-Rodríguez 2013). According to Namèche *et al.* (1997), Chabir *et al.* (2000), Picot *et al.* (2009) and Keffala *et al.* (2011), sludge accumulated at the bottom of stabilization ponds can exert substantial influence in the removal of pollutants due to the aerobic, anoxic and anaerobic layers. The bottom sludge contains anaerobic biomass that can potentially contribute to the conversion or removal of some constituents. On the other hand, sludge accumulation can affect the performance of the ponds by reducing their effective volume and shortening the HRT in the liquid column, which could lead to a decrease in the system's performance.

The aim of this paper is to evaluate the influence of sludge in the performance of two identical polishing ponds operating in parallel and treating UASB reactor effluent: one pond with sludge accumulated for more than 11 years of operation and the other without any sludge. Both ponds received the same influent flow and load.

MATERIAL AND METHODS

Study location

The study was conducted at the Centre for Research and Training in Sanitation UFMG/COPASA (CePTS), in Belo Horizonte, Brazil (latitude 19 °53′ S). The system comprised a UASB reactor followed by two shallow maturation ponds in parallel (around 125 population equivalents for each pond) treating raw municipal sewage. Figure 1 presents the dimensions and operational characteristics of the ponds. The ponds were operational for more than 11 years, but Pond 2 had its sludge layer completely removed before the experiments. This was accomplished by draining the full volume of Pond 2, removing the sludge, and then refilling it with the effluent from Pond 1, which already contained the biomass (algae and heterotrophic microorganisms) necessary for its normal operation. Therefore, a new start-up period was not necessary. A bathymetric survey, together with a characterization of the solids in the sediments, was done in Pond 1 before the experiments.

Monitoring and data analysis

Weekly monitoring of influent and effluent from all units (inlet and outlet) was undertaken for 7 months, starting in May 2013. Monitoring in the ponds was not carried out in the effluent as such (ponds' take-off levels were around 10 cm below the surface), but close to the outlet zone, using a column sampler capable of collecting the sample over the full liquid column, thus leading to a more representative sample (see sampling points in Figure 1). The parameters evaluated were pH, temperature (T), redox potential (RPO), electrical conductivity (EC), dissolved oxygen (DO), chemical oxygen demand (COD – total and filtered), biochemical oxygen demand (BOD – total and filtered), total suspended solids (TSS), ammonia-N, nitrite-N, nitrate-N, total Kjeldahl nitrogen (TKN), total coliforms, *Escherichia coli*, total alkalinity and flow rate. All parameters were analysed according to the methodology described in *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 2009). Nitrite and nitrate were analysed using a Metrohm chromatograph, model 850 Professional IC (Metrohm, Herisau, Switzerland). Differences between ponds (in terms of both effluent concentration and conversion efficiency) were examined by means of the Wilcoxon matched-pairs test for dependent samples.

RESULTS AND DISCUSSION

Both ponds operated with the same mean surface organic loading rate of 119 kgBOD/ha·d, which is typical of

Item	P1 (with sludge)	P2 (without sludge)
Length at bottom (m)	25.00	25.00
Width at bottom (m)	5.25	5.25
Water level (m)	0.71	0.78
Embankment slope (°)	45	45
Surface area (m^2)	153	155
Flow (m^3/d)	18.9	18.9
Theoretical HRT* (d)	6.0	6.5

*Calculated without considering the reduction in volume due to sludge

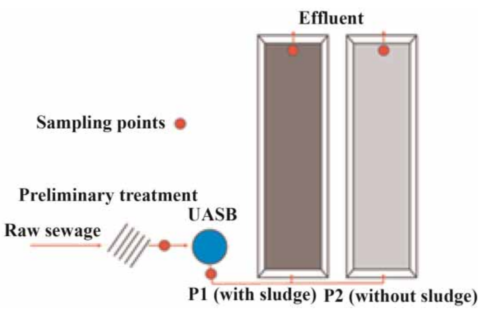

Figure 1 | Dimensions and mean values of operational characteristics of the ponds.

low-loaded facultative ponds. The average flow rate of the effluent from the UASB reactor was 37.8 $m^3 \cdot d^{-1}$, which, after splitting in half for both ponds, resulted in a mean flow rate of 18.9 $m^3 \cdot d^{-1}$ and a mean theoretical HRT of 6.0–6.5 d for the ponds with (P1) and without (P2) sludge, respectively. The ponds had a small difference in depth for topographical and hydraulic reasons. The average depth was 0.71 m in P1 (with sludge) and 0.76 m in P2 (without sludge), which led to the small differences in the HRT. It can be seen that both retention times are small for facultative ponds, but somewhat typical for maturation ponds. However, it should always be kept in mind that there was only one pond in the series, and that overall efficiencies cannot be compared with typical maturation pond systems that have three or four ponds in series.

Figure 2 presents the results of the bathymetric survey undertaken in Pond 1 before the experiments and the characterization of the solids concentration in the sediments (dry matter). It can be seen that, in terms of volume, most of the solids accumulated near the inlet and outlet of the pond. A similar comment can be made about the total solids (TS) concentration (dry matter), which had values between 55 and 90 gTS/L (5.5–9.0% dry solids) in the first one-third of the pond length, concentrations between 35 and 10 gTS/L (3.5–1.0%) in the middle zone, and values between 30 and 75 gTS/L (3.0–7.5%) in the final one-third of the pond length. In terms of the composition of the sludge layer, the ratio of total volatile solids over TS (TVS/TS) had values between 40 and 45%, indicating a well-digested sludge, in which the larger fraction was inorganic. Full details of this part of the study can be found in Possmoser-Nascimento et al. (2014).

The volume of sludge accumulated in P1 during the 11 years of operation was 40% (43 m^3) of the pond volume. If the volume occupied by the sludge is considered and deducted from the total volume, the mean theoretical HRT (volume of the liquid layer/flow) in P1 reduces to 3.6 d, much smaller than the theoretical HRT of P2 (without sludge), which had a mean value of 6.5 d, taking into account all of its volume. Therefore, when comparing the performance of both ponds, it should be remembered that the pond with sludge (P1), although it had a similar total HRT to the pond without sludge, had short retention times in the liquid layer. Figure 3 presents the box-plot for the flow rate of the effluent from the UASB reactor and the resulting theoretical HRT in the two ponds (the HRT data in P1 are calculated taking into account only the liquid layer, that is, without considering the volume occupied by the sludge).

Table 1 presents the median values and standard deviation of the concentrations, together with the median removal efficiencies of the monitored parameters, indicating those that were significantly different between the two ponds.

When comparing the ponds with and without the sludge layer, it can be seen that the water quality constituents related to organic matter (BOD, COD), SS and coliforms

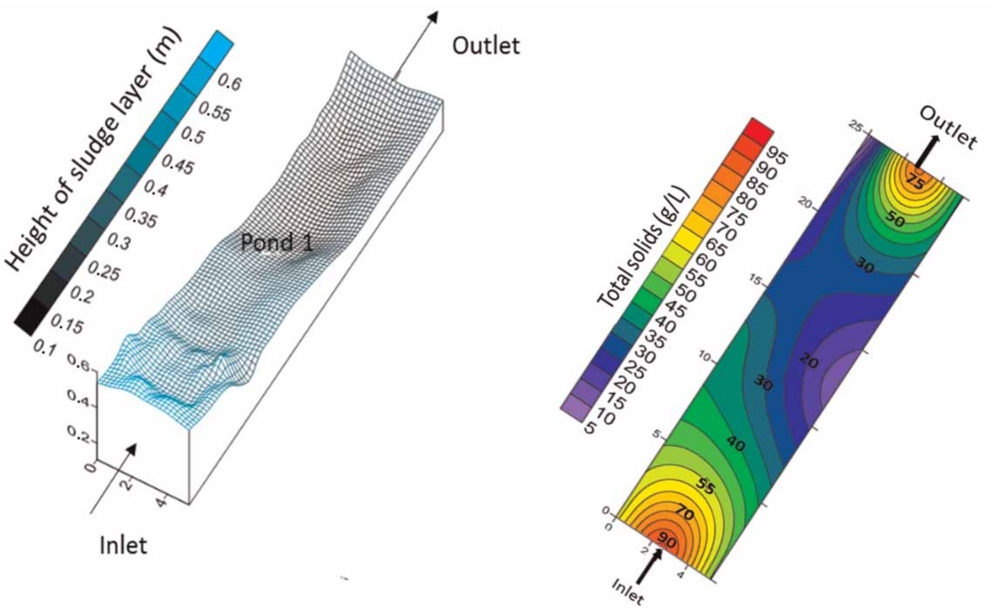

Figure 2 | Distribution of the height of the sludge layer (left) and TS concentration (dry matter) in the sludge (right) in Pond 1, after 11 years of operation.

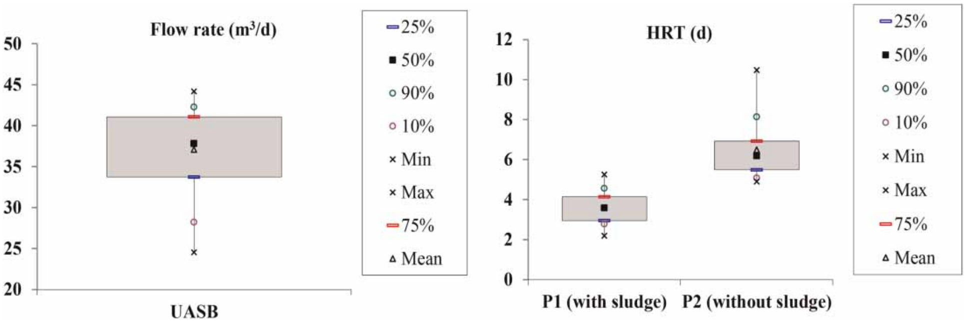

Figure 3 | Box-plot of the flow rate of the effluent from the UASB reactor and the theoretical HRT in the ponds with (P1) and without (P2) sludge.

showed no significant differences in terms of effluent concentration and removal efficiency. However, those related to the nitrogen cycle, either directly (TKN, ammonia, nitrate) or indirectly (total alkalinity, pH and RPO), indicated differences in the behaviour of both ponds, with a better removal of ammonia in the pond without sludge. The extent to which some of the environmental variables (pH, RPO, DO and temperature) fully influence or explain the ponds' behaviour is not entirely clear – even when they are significantly different, their dissimilarity may not be sufficient to lead to different performances. A full understanding would require, among other things, vertical profile measurements inside the ponds, microbial community characterization and hydrodynamic and kinetic experimental and modelling studies, all of which are beyond the scope of this research.

Figure 4 shows the total COD and BOD concentrations throughout the system. It can be seen from Figure 4 and Table 1 that the ponds did not contribute to further organic matter removal. Although only a few samples have been analysed for filtered COD and BOD, it is possible to see that the concentration of particulate organic matter was much higher than soluble organic matter in the ponds. These results are associated with algal growth in the ponds, contributing to the increase of particulate organic matter, and also SS (as seen from Table 1). There was no significant difference in effluent BOD, COD and SS from both ponds.

In terms of coliforms, both ponds presented high effluent concentrations, well above that allowed for unrestricted irrigation (10^3 MPN·100 mL^{-1}), as recommended by WHO (2006). This was entirely expected, since there were no cells in series or baffled ponds, which are typical arrangements for enhancing coliform decay. Dias *et al.* (2014) evaluated this same treatment plant, when it operated with three ponds in series for approximately 10 years, and observed *E. coli* concentrations below 10^3 MPN·100 ml^{-1} in the final effluent, even with total HRT in the system of around only 10 days.

The median removal efficiency for *E. coli* was 1.1 log units in the pond with sludge and 1.3 log units for the pond without sludge. Figure 5 shows the effluent *E. coli* concentrations and removal efficiencies throughout the system. The contribution of both ponds to the improvement of the effluent quality can be clearly seen, and it can also be observed that the performance of both ponds was similar (endorsed by the statistical analysis, which did not indicate significant difference between the ponds with and without sludge). This brings an important element to the analysis. Even though the HRT in the liquid layer in the pond with sludge (P1) was much shorter than in the pond with sludge (P2), both performances were similar. Assuming that coliform removal follows first-order kinetics, the removal efficiency depends on the product $K_b \times HRT$, where K_b is the coliform decay coefficient, expressed in d^{-1}. In the pond with sludge, it can suggested that the shorter retention time in the liquid is compensated for by a higher value of the decay coefficient K_b. This assumption is endorsed by von Sperling *et al.* (2005), who stated that shallow polishing ponds have higher K_b values, which compensate for their lower retention times, allowing them to achieve high efficiencies of coliform removal. Since the major mechanisms of coliform decay are associated with the top layer of the pond, in which UV radiation intensity, pH and DO are higher, it is reasonable to assume that a pond with a shallow liquid depth may present a comparable performance to that of a deeper pond.

The results of nitrogen removal indicate that ammonia-N and TKN concentrations were significantly higher and the removal efficiency significantly lower in the pond with sludge (Table 1 and Figure 6). The poorer performance of the pond with sludge could be related to the lower HRT in the liquid phase, but could also be due to the release of ammonia-N accumulated in the bottom sludge. However,

Table 1 | Median concentrations (standard deviation in parentheses) throughout the system and removal efficiencies of ponds P1 (with sludge) and P2 (without sludge)

		Concentrations throughout the system				Removal efficiencies (%)	
Parameter	N.	Influent	UASB	P1	P2	P1	P2
BOD (mg/L)	19	168(81)	70(15)	64(20)	55(25)	10	20
BOD filtered (mg/L)	9	–	–	21(9)	27(8)	–	–
COD (mg/L)	45	603(228)	213(56)	239(74)	220(67)	−13	−6
COD filtered (mg/L)	9	–	–	73(56)	70(53)	–	–
TSS (mg/L)	53	203(108)	49(21)	92(33)	91(31)	−79	−84
Total coliforms (MPN/100 mL)	19	2.5×10^{10} (7.3×10^{10})	3.0×10^{9} (1.2×10^{10})	1.9×10^{8} (1.5×10^{9})	1.1×10^{8} (5.9×10^{8})	1.0 log	1.3 log
E. coli (MPN/100 mL)	19	5.2×10^{9} (2.1×10^{10})	9.1×10^{8} (5.4×10^{9})	5.6×10^{7} (5.9×10^{8})	3.4×10^{7} (1.4×10^{8})	1.1 log	1.3 log
TKN (mg/L)	41	42(11.6)	39(6.1)	32(6.28)	31(6.27)	20	23
Ammonia-N (mg/L)	48	36(11.5)	37(4.8)	28(7.4)	23(6.3)	21	28
Nitrite-N (mg/L)	39	0.002 (0.58)	0.003(0.28)	0.005(0.29)	0.003(0.43)	–	–
Nitrate-N (mg/L)	34	0.49(0.53)	0.72(0.50)	0.71(0.63)	0.90(0.57)	−48	−116
DO (mg/L)	50	–	–	6.37(4.42)	6.06(3.13)	–	–
RPO (mV)	50	−130(94)	−103(62)	32(36)	43(41)	–	–
Total alkalinity (mg/L)	43	–	281(38)	246(23)	234(18)	14	19
pH	51	7.1(0.30)	6.9(0.24)	7.5(0.37)	7.6(0.35)	–	–
EC (μS/cm)	38	778(117)	760(39)	740(39)	714(35)	–	–
Temperature (°C)	50	23.6(1.2)	23.4(1.3)	21.5(2.0)	21.4(1.8)	–	–

E. coli and total coliforms are expressed as geometric means. Efficiency in %, except for *E. coli* and total coliforms, which are expressed as log units removed. Efficiencies are reported as medians of all the values of efficiencies. Underlined values indicate significant differences between P1 and P2 (p value $<.0.05$), according to the Wilcoxon matched-pairs test.

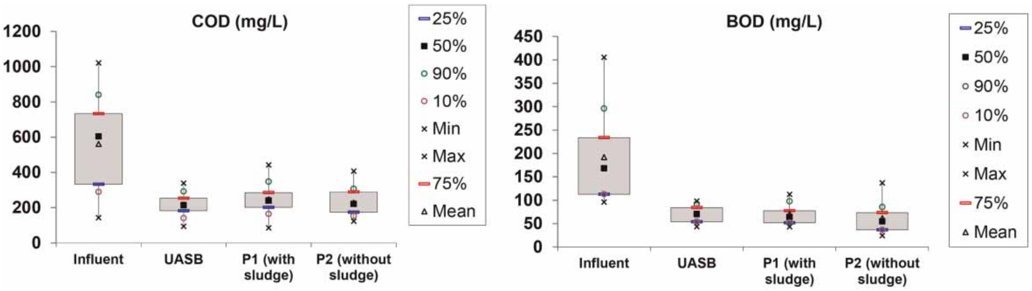

Figure 4 | Box-plot of total organic matter (COD and BOD concentrations) in the raw sewage and effluents from the UASB reactor and both ponds.

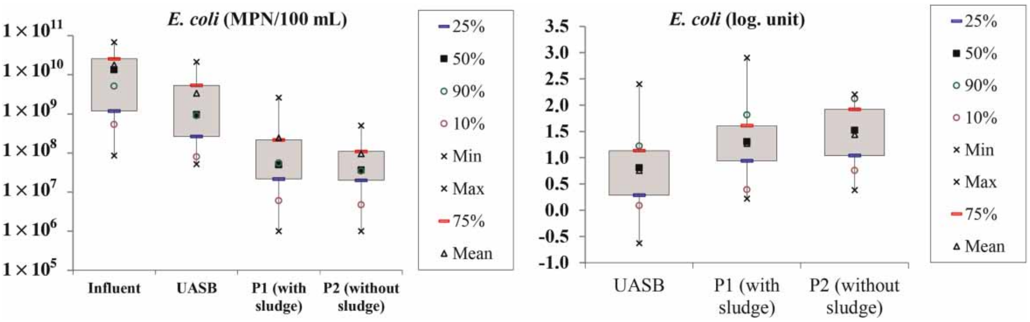

Figure 5 | Box-plot of the concentration and removal efficiencies of *E. coli* throughout the system.

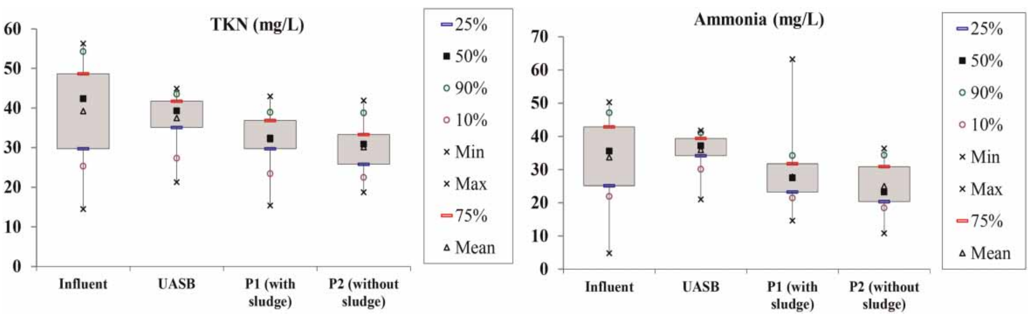

Figure 6 | Box-plot of TKN and ammonia-N concentrations throughout the system.

the shorter HRT in the liquid layer was possibly somewhat compensated for by other mechanisms associated with nitrification and denitrification in the sediments. Keffala *et al.* (2011) comment that, in the sludge layer, stratification occurs according to the oxygen gradient, forming three layers (aerobic, anoxic and anaerobic) with different thicknesses. The heterogeneity of the sediment due to the oxygen gradient (aerobic layer at the top few millimetres of the sediments and anoxic zone underneath it) may allow the two opposing processes (nitrification and denitrification) to occur. This gradient is maintained by the absorption of oxygen in the sediment–water interface via molecular diffusion. In the sludge, there is a variation of RPO, which makes an important site for bacterial activity processes in terms of nitrification and denitrification, as well as for decomposition processes (Namèche *et al.* 1997; Chabir *et al.* 2000).

Figure 7 shows the results of RPO and DO in the treatment system. As expected, RPO values were negative in the raw sewage and in the effluent from the UASB reactor. In the ponds, photosynthetic activity led to an increase of RPO, together with DO, which occasionally reached oversaturation values; RPO values in both ponds were significantly different.

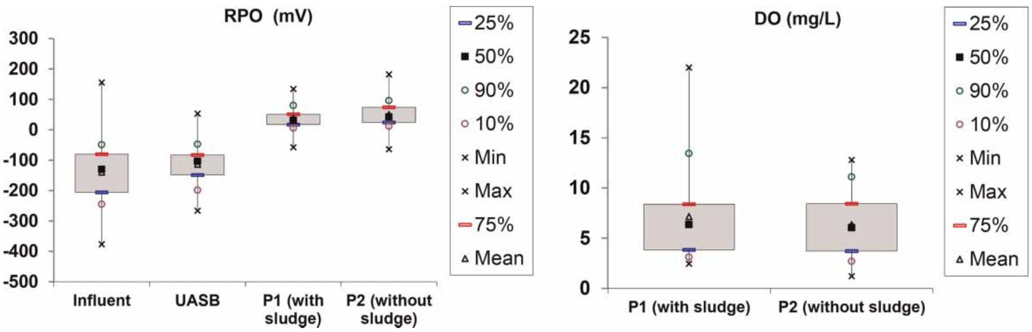

Figure 7 | Box-plot of the RPO throughout the system and DO concentration in the ponds.

Another factor in the performance of the pond with sludge in terms of nitrogen transformations may be associated with the anaerobic layer, which may favour the degradation of organic nitrogen and ammonia release. Algae absorb ammonia, and the fraction of algal biomass, which settles and is incorporated in the sludge layer, may lead to subsequent ammonia release (Camargo Valero *et al*. 2010). Senzia *et al*. (2002) reported that algae and bacteria have a higher preference for ammonia compared to nitrate and that the latter is usually consumed only when the former is not available.

Total alkalinity in the pond without sludge was significantly lower than that in the pond with sludge, suggesting more intense nitrification (Figure 8). Apparently, this could be endorsed by the lower ammonia concentration in the pond without sludge. Although nitrate concentrations in the pond without sludge were higher (which could also support the hypothesis of nitrification), it should be stressed that they were consistently low in both ponds, as shown in Figure 8. If nitrification took place, denitrification also happened in the two ponds, as suggested by the low nitrate values.

Volatilization of free ammonia is also likely to be a minor mechanism in terms of nitrogen removal, as shown by Assunção & von Sperling (2012) in the same pond system (in a prior period, when the operation was with three ponds in series).

CONCLUSIONS

The ponds with sludge (Pond 1) and without sludge (Pond 2) presented similar performances in terms of organic matter, SS and coliforms, despite the fact that the sludge occupied about 40% of the volume of Pond 1, resulting in the reduction of the HRT in the liquid layer. Although significantly better in the removal of nitrogen, the pond without sludge was still not able to lead to low effluent TKN and ammonia-N concentrations. Nitrite and nitrate concentrations were low in both ponds. For some parameters (EC, RPO, pH and alkalinity), even though the concentrations were significantly different in both ponds, this difference was small and not likely to have major implications in the ponds' performance.

Overall, it can be said that both ponds had a similar performance in terms of the major wastewater constituents, with the sludge layer probably allowing the occurrence of removal mechanisms that compensated for the reduction it caused in the HRT in the supernatant liquid layer. As a practical output of the study, even if there could be a prior

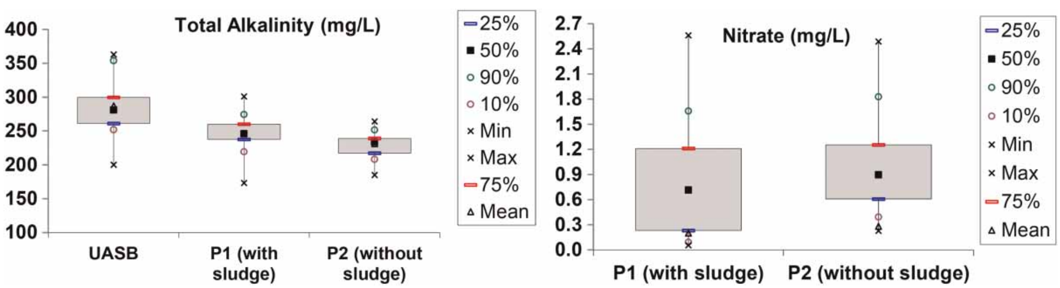

Figure 8 | Box-plot of total alkalinity throughout the system and nitrate concentration in the ponds.

indication of the need to remove the sludge in Pond 1 after the 11 years of operation, due to the fact that it was occupying 40% of the total volume, in terms of overall performance this recommendation does not seem to be sustained.

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