Post-treatment of UASB reactor effluent in waste stabilization ponds and in horizontal flow constructed wetlands: a comparative study in pilot scale in Southeast Brazil

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ABSTRACT

The results of a 20-month period study in Brazil were analyzed to compare horizontal-flow constructed wetlands (CW) and waste stabilization pond (WSP) systems in terms of land area requirements and performance to produce effluent qualities for surface water discharge, and for wastewater use in agriculture and/or aquaculture. Nitrogen, *E. coli* and helminth eggs were more effectively removed in WSP than in CW. It is indicated that CW and WSP require similar land areas to achieve a bacteriological effluent quality suitable for unrestricted irrigation (10^3 *E. coli* per 100 mL), but CW would require 2.6 times more land area than ponds to achieve quite relaxed ammonia effluent discharge standards (20 mg $NH_3\,L^{-1}$), and, by far, more land than WSP to produce an effluent complying with the WHO helminth guideline for agricultural use (≤1 egg per litre).

Key words | BOD, *E. coli*, helminths, land requirement, nutrients

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INTRODUCTION

Waste stabilization ponds (WSP) and Constructed wetlands (CW) have both been considered good choices for wastewater treatment, mainly in developing and/or warm climate countries. These natural treatment systems present several advantageous features, such as simplicity, low cost, low maintenance, robustness, and sustainability. On the other hand, as a disadvantage, both WSP and CW require large land areas.

Several studies conducted worldwide have shown that WSP can significantly remove pathogens and, if properly designed, also nutrients, particularly nitrogen. BOD and COD can also be effectively removed in ponds, but, as with suspended solids (SS), this may be impaired by algal growth; therefore, effluent discharge standards may not be met, particularly when they are set in terms of unfiltered BOD (Kadlec 2004; Mara 2004; von Sperling 2007). Several other studies indicate that CW can as well significantly reduce SS, BOD, pathogens, and nutrients, although there have been contradictory reports and/or less information regarding the last two parameters (Kadlec *et al.* 2000; Stott *et al.* 2003). However, information comparing CW and WSP land area requirements, performance and costs are yet either scarce or conflicting (Okurut & van Bruggen 2001; Senzia *et al.* 2003; Mara 2006).

In this paper, horizontal-flow (HF) CW and WSP (named here as polishing ponds), both as post-treatment systems of a UASB reactor, are compared in terms of land area requirements and performance to achieve effluent qualities suitable for surface water discharge and for wastewater use in agriculture and/or aquaculture.

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METHODS

Description and comparative evaluation of the wastewater treatment systems

The experiments were conducted in Viçosa, Minas Gerais State, Southeast Brazil (latitude: 20°45′14″S, longitude: 42°52′53″W, altitude: 650 m). The treatment plant consisted of an Upflow Anaerobic Sludge Blanket (UASB) reactor (field scale, 115 $m^3 d^{-1}$) followed by two parallel pilot scale post-treatment systems: (i) four polishing ponds in series; (ii) four HFCW in parallel, two of them with surface flow (SF) and the other two with subsurface flow (SSF); this system also included a fifth CW (SF), in series with one of the SSFCW. The CW consisted of inclined gravel channels planted with *Typha* sp. or *Brachiaria humidicola*. All ponds had area = 16.2 m^2 and length-to-breadth ratio = 2.0. The CW had the following dimensions (length × breadth): CW1 and CW2 (12 m × 2 m); CW3 and CW4 (8.6 m × 1.7 m); CW5 (7.8 m × 1.5 m).

Tables 1 and 2 present the different conditions under which these treatment systems were operated.

It is worth noticing that these two systems were not set for the specific comparative purposes of the present study. The WSP system was set in the first place, having been used in several previous studies. The experimental design of the CWs aimed primarily at the evaluation of different arrangements within this own system, and was based on Reed *et al.* (1995) model to attain effluents with 20 mg NH_3 L^{-1}. Hence, the wide range of different sizes of the WSPs and the CWs. Nonetheless, the final sizing (in terms of area) and the operation (in terms of flow rate) of the CWs were as much similar as possible to those of the WSPs in order to warrant sound comparisons between the performances of the two systems. Furthermore, the comparative analyses between the WSP and the CW were based on the hydraulic loading rates to achieve a given effluent quality, so that the corresponding land area requirements could be directly compared.

Sample collection and analysis

Over 20 months (from November 2006 to June 2008) the treatment systems were monitored on a weekly-biweekly basis. Raw wastewater, UASB and CW effluents were sampled hourly from 6:00 am to 6:00 pm, and analysed as composite samples. Pond effluents were sampled using a column sampler, usually in the morning (grab samples). All these samples were analysed for the following parameters: *E. coli*, helminth eggs, BOD, COD, solids, nitrogen, and phosphorus. Pond profile measurements were obtained for DO, pH and temperature at 20-cm depth intervals from the ponds surface. In general, sample collection and analyses were carried out according to the *Standard Methods for the Examination of Water and Wastewater* (APHA 1998). *E coli* were enumerated using the chromogenic substrate method method (Colilert®). Helminth eggs were enumerated using the Bailenger modified technique (Ayres & Mara 1996).

RESULTS AND DISCUSSION

BOD, COD and TSS removal

Over the entire period of this study, the UASB reactor presented high removal efficiencies of total BOD_5, total COD and total suspended solids (TSS): average values

Table 1 | Pond characteristics

Parameter	Phase I November 2006–February 2007				Phase II March–August 2007				Phase III September 2007–June 2008			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Q	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.5	2.5	2.5	2.5
HRT	7.2	7.2	4.1	4.1	9.4	9.4	9.4	9.4	5.6	5.6	5.6	5.6
h	0.70	0.70	0.4	0.4	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
HLR	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.153	0.153	0.153	0.153

P: ponds; Q: flow rate ($m^3 d^{-1}$); HRT: hydraulic retention time (d); h: pond depth (m); HLR: hydraulic loading rate ($m^3 m^{-2} d^{-1}$).

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Table 2 | Constructed wetlands characteristics

Parameter	CW1 (SF)	CW2 (SF)	CW3 (SSF)	CW4 (SSF)	CW5 (SF)*
	Phase I (November 2006–February 2007)				
Plant	*Typha*	*Brachiaria*	*Brachiaria*	*Typha*	*Brachiaria*
A	24.0	24.0	14.6	14.6	11.3
Q	1.5	1.5	1.5	1.5	1.5
HRT	4.5	4.5	2.4	2.4	2.1
HLR	0.063	0.063	0.103	0.103	0.133
	Phase II (March–August 2007)				
	CW1 (SSF)	**CW2 (SSF)**	**CW3 (SSF)**	**CW4 (SSF)**	**CW5 (SF)†**
Plant	*Typha*	*Brachiaria*	*Brachiaria*	*Typha*	*Brachiaria*
A	24.0	24.0	14.6	14.6	11.3
Q	1.0	1.0	1.0	1.0	1.0
HRT	5.4	5.4	3.3	3.3	1.8
HLR	0.042	0.042	0.069	0.069	0.088
	Phase III (September 2007–June 2008)				
	CW1 (SSF)	**CW2 (SSF)**	**CW3 (SSF)**	**CW4 (SSF)**	**CW5‡**
Plant	*Typha*	*Brachiaria*	*Brachiaria*	*Typha*	–
A	24.0	24.0	14.6	14.6	–
Q	2.5	2.5	2.5	2.5	–
HRT	2.2	2.2	1.3	1.3	–
HLR	0.104	0.104	0.171	0.171	

*In series with CW3.
†In series with CW4.
‡Out of service due to operational problems.
CW: constructed wetlands; SF: surface flow; SSF: subsurface flow; A: area (m^2); Q: flow rate ($m^3\,d^{-1}$); HRT: hydraulic retention time (d); h: pond depth (m); HLR: hydraulic loading rate ($m^3\,m^{-2}\,d^{-1}$).

of 83%, 73% and 76%, respectively. The effluent quality requirements in Minas Gerais Sate are as follows: 60 mg BOD L^{-1} or 85% removal; 90 mg COD L^{-1} or 90% removal; 60 mg TSS L^{-1}, monthly average, and 100 mg TSS L^{-1}, daily maximum. These BOD standards were accomplished in 54% ($\leq$60 mg L^{-1}) and 40% ($\geq$85% removal) of the analyzed samples; TSS standards were achieved in 12 of the 20 months monitoring period ($\leq$60 mg L^{-1} average) and in 89% of the analyzed samples ($\leq$100 mg L^{-1} as daily maximum).

In the ponds series, organic matter removal took place basically in the first pond, approximately 40 and 70% total BOD and filtered COD (data not included), respectively, producing effluents with median values around 20–30 mg BOD L^{-1} and 50–75 mg DQO_{fil} L^{-1}. After the first pond there was no clear further BOD removal. Nevertheless, the above mentioned Minas Gerais State BOD standard was consistently accomplished in the first pond. The CW presented even better COD (data not included) and BOD removal efficiencies (around 80% and 60%, respectively): all CW produced effluents with median values around 10–15 mg BOD L^{-1} (Figure 1).

Over the three operational phases an increase of total COD (data not included) and TSS along the pond series was recorded (Figure 2), certainly due to algae growth. As a result, the Minas Gerais State effluent requirements for both parameters were not consistently accomplished. In turn, the CW showed high TSS removal (around 70%), producing excellent effluent qualities, rarely above 20 mg TSS L^{-1} (Figure 2). It is worth noticing that CW5 (in series with CW3 or CW4) did not add noticeable further removal of BOD and TSS (Figures 1 and 2)

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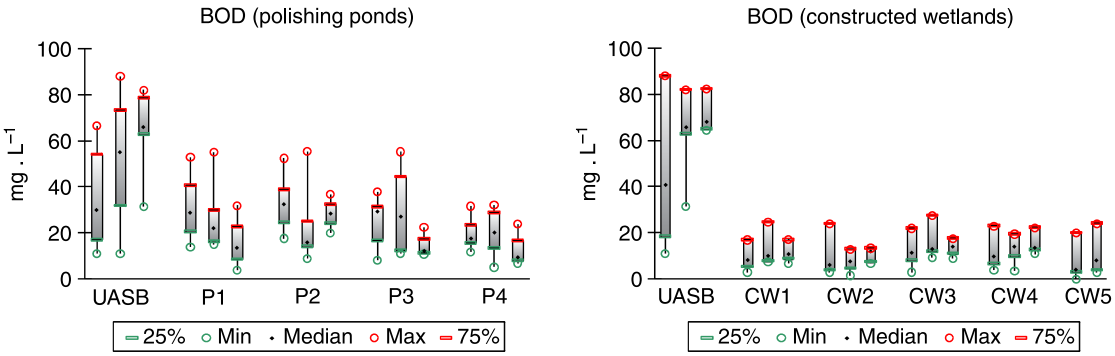

Figure 1 | BOD concentration in the anaerobic reactor effluent, along the pond series, and in the constructed wetlands effluents over the three operational phases. UASB: anaerobic reactor effluent; Pi: ponds effluents; CWi: constructed wetlands effluents.

In general, these results confirm the work of others, demon strating that CW are rather efficient in removing BOD, COD and TSS (Kadlec 2004; Sousa *et al.* 2004). In this work, they produced effluent qualities closely complying with very strict requirements, like those specified in the EU Urban Waste Water Treatment Directive (UWWTD) (mean values of 25 mg unfiltered BOD per litre for CW effluents), in the Environment Agency (the environmental regulator in England and Wales) (40 mg BOD L^{-1} and 60 mg TSS L^{-1} or 10 mg BOD L^{-1} and 15 mg TSS L^{-1} (95-percentile values), and in the USA (30 mg BOD L^{-1} and 30 mg TSS L^{-1} (Mara 2006).

Nutrients removal and biomass production

Ammonia concentration in the UASB reactor effluent was approximately 60% higher than in raw wastewater. TKN (NH_3 + Norg) and ammonia removal in the pond series were, approximate and respectively, 70% and 90% (Figure 3).

The pond series provided substantial ammonia decrease, producing final effluents suitable for fish culture (≈3 mg NH_3 L^{-1}) (Mara *et al.* 1993), and in compliance with strict requirements, like the above mentioned England and Wales Environment Agency: 5 mg N-NH_3 L^{-1} (95-percentile values). The effluent quality specified in the Brazilian regulation (20 mg NH_3 L^{-1}) was consistently reached in the second pond effluent, and, most of the time, even in the first pond (excepted in Phase II, when the temperature was lower) (Figure 3).

This and previous works carried out on the same pond system (Bastos *et al.* 2007) have shown that ammonia removal was well explained by Pano and Middlebrooks model (Pano & Middlebrooks 1982), based on which (with pH = 7 as the minimum value recorded over the entire monitoring period) it is inferred that the Brazilian effluent quality standard (20 mg NH_3 L^{-1}) would be achievable with total HRT of 11 days; however, for an effluent quality suitable for fish culture (≈3 mg NH_3 L^{-1}) a total HRT

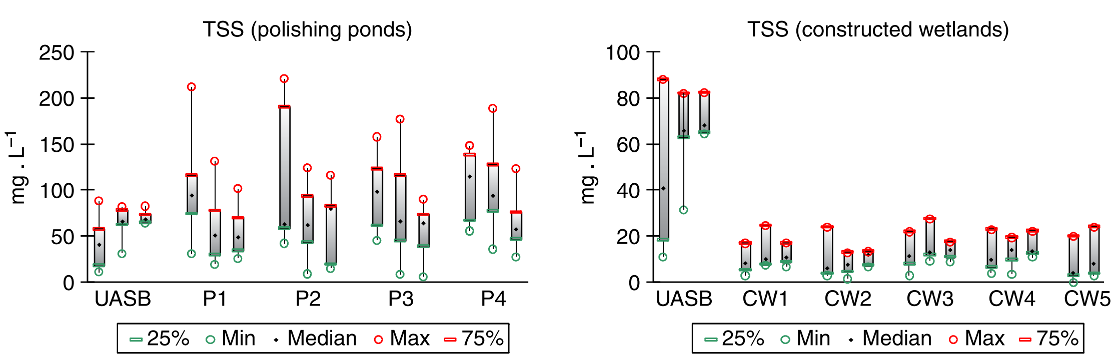

Figure 2 | TSS concentration in the anaerobic reactor effluent, along the pond series, and in the constructed wetlands effluents over the three operational phases. UASB: anaerobic reactor effluent; Pi: ponds effluents; CWi: constructed wetlands effluents.

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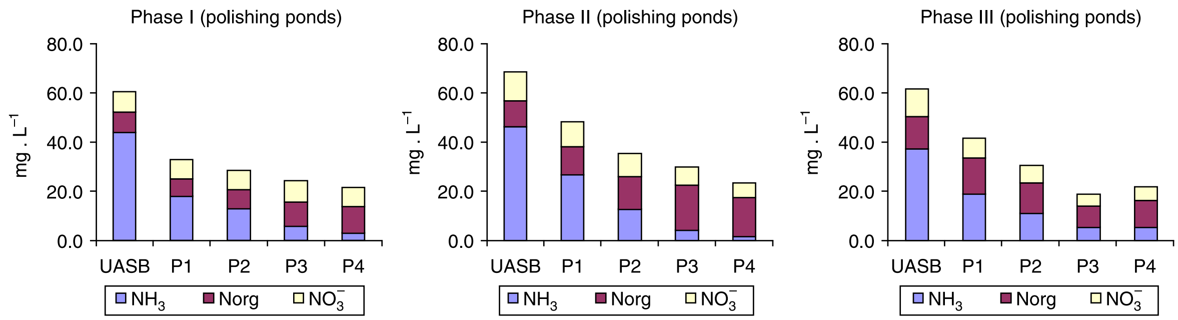

Figure 3 | Total Nitrogen (NH_3 + Norg + NO_3^-) average concentration in the anaerobic reactor and pond effluents over the three operational phases. UASB: anaerobic reactor effluent; Pi: ponds effluents.

around 30 days would be necessary. Thus, assuming pond depth = 0.9 m, and HRT = 11 days, the resulting HLR to achieve 20 mg $NH_3\,L^{-1}$ would be 0.082 $m^3\,m^{-2}\,d^{-1}$.

Nitrogen removal in the CW was much less effective than in the pond series, and varied widely: 20 to 70%, and 20% to 80% for TKN and ammonia, respectively. Based on the average results, the Brazilian effluent quality standard (20 mg $NH_3\,L^{-1}$) was attained in CW1 and CW2 (which had higher HRT), but not in CW3 and CW4. Also, as noticed for BOD and TSS, CW5 did not provide any remarkable additional TKN removal (Figure 4). Removal coefficients (K_{NT20}) were calculated (data not included) based on Reed *et al.* (1995) model for nitrogen removal in CW. Thus, assuming a design temperature (coldest months average value) of 17°C and a corresponding $K_{NT20} = 0.12\,d^{-1}$, the HLR necessary to achieve 20 mg $NH_3\,L^{-1}$ would be 0.032 $m^3\,m^{-2}\,d^{-1}$. In other words, it is suggested that HF CW require 2.6 times more land area than ponds to achieve the Brazilian standard of ammonia effluent quality. Senzia *et al.* (2003) found that ponds would require more land than SSHF CW to remove about 70–80% BOD, after a primary facultative pond. However, Mara (2006) demonstrated that SSHF CW requires 60 percent more land than a secondary facultative pond to produce the above mentioned UWWTD-quality effluent, 38 and ~ 1,000 percent more land than a secondary facultative pond and an unaerated rock filter to, respectively, produce 40 mg L^{-1}/60 mg L^{-1} (BOD/TSS) and 10 mg L^{-1}/15 mg L^{-1}/5 mg L^{-1} (BOD/TSS/N-NH_3) effluent qualities.

Phosphorus removal was only limited in both CW and ponds, around 30% in most treatment unities (only CW2 reached about 50%). Based on the *Brachiaria* productivity and nutrient contents (data not included), it was estimated that this plant accounted for up to 13% and 30% of total nitrogen and phosphorus removal, respectively. In general, the results of this work confirm some literature reports that nutrients removal in CW are limited to 40–60% and that plant uptake is responsible for about 20–30% of total removal (Brix 1997; Kadlec 2004; Sousa *et al.* 2004; Tunçsiper *et al.* 2006).

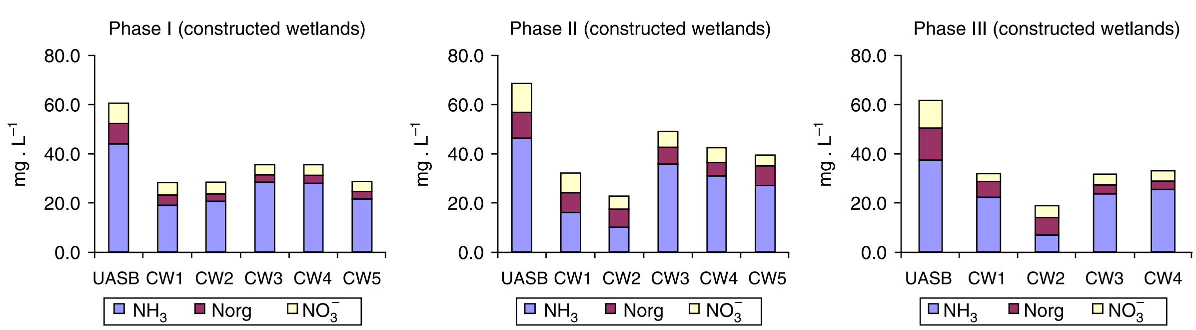

Figure 4 | Total Nitrogen (NH_3 + Norg + NO_3^-) average concentration in the anaerobic reactor constructed wetlands effluents over the three operational phases. UASB: anaerobic reactor effluent; CWi: constructed wetlands effluents.

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E. coli removal

E. coli removal in the pond series was quite similar during the three operational phases, reaching, up to the third pond, 4–4.5 log unit reduction. The fourth pond did not add further reduction. Pond 3 (systematically) and pond 2 (most of the time) presented effluent qualities in accordance with the WHO guidelines for restricted irrigation and aquaculture (assumed herein as 10^4 *E. coli* per 100 mL), as well as for unrestricted irrigation (assumed as 10^3 *E. coli* per 100 mL) (WHO 2006*a*,*b*) (Figure 5).

Based on these results and previous works carried out on the same pond system (Bastos *et al.* 2006*a*), it is inferred that the WHO guidelines are achievable with a pond system with total HRT of: 10 days for restricted irrigation and aquaculture, and 17 days for unrestricted irrigation. *E. coli* die-off rate constants (K_{b20}) were calculated for each pond (pond 1 = $0.98\,d^{-1}$, pond 2 = $1.11\,d^{-1}$, pond 3 = $1.35\,d^{-1}$). Based on the dispersed flow regime model (von Sperling 2007), assuming a design temperature = 17°C, pond depth = 0.9 m, and HRT = 17 days, the HLR necessary to achieve 10^3 *E. coli* per 100 mL would be $0.053\,m^3\,m^{-2}\,d^{-1}$.

In general, the CW showed 2–4 log unit of *E. coli* reduction, producing effluents with 10^2–10^4 *E. coli* per 100 mL (geometric means), however in a much less stable rate than the ponds (Figure 5). Excepted for Phase III, CW1 and CW2 (which had higher HRT) presented higher efficiency removal than CW3 and CW4. CW5 (SF) added about 1 log unit reduction. The removal efficiency recorded in this study is higher than those reported in some other works conducted in temperate climates, under similar conditions of HRT and HLR, but comparable to others carried out in Brazil (Kadlec *et al.* 2000; Thurston *et al.* 2001; Sousa *et al.* 2004). Since there are no generally accepted design equations for *E. coli* removal in CW (Kadlec *et al.* 2000; Mara 2006), the HLR range of the best performance period of the CW (0.042–$0.069\,m^3\,m^{-2}\,d^{-1}$) was taken for comparative analysis. Therefore, it is assumed that the ponds and the HF CW land area requirements to achieve the WHO guidelines for unrestricted irrigation are rather similar.

Helminth eggs removal

Helminth eggs were detected in pond 1 effluent in 50%, 20% and 43% of the analyzed samples during, respectively, Phase I (arithmetic means = 2.6 eggs per litre; HRT = 7.2 days), Phase II (arithmetic means = 0.96 egg per litre; HRT = 9.4 days) and Phase III (arithmetic means = 1.57 eggs per litre; HRT = 5.6 days). Pond 2 (accumulated HRT = 11.3 days) effluent was sampled only in Phase III, showing 47% positive samples (arithmetic means = 1.5 eggs per litre). Considering the average number of eggs in the ponds series influent (30.5 eggs per litre), and according to Ayres *et al.* (1992) model, a HRT as low as 3.6 days would suffice for the WHO guideline accomplishment (≤1 human intestinal nematode egg per litre (WHO 2006*a*). However, based on an adjusted equation derived from experimental data obtained exclusively in this pond system (Bastos *et al.* 2006*b*), a HRT of around 6 days would be necessary.

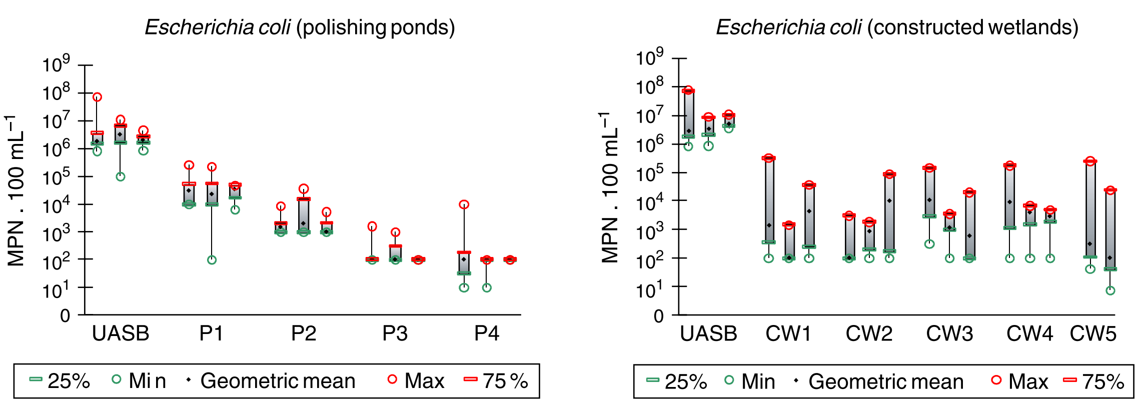

Figure 5 | *E. coli* concentration in the anaerobic reactor effluent, along the pond series, and in the constructed wetlands effluents over the three operational phases. UASB: anaerobic reactor effluent; Pi: ponds effluents; CWi: constructed wetlands effluents.

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Helminth eggs removal rates and detection in the CW effluents varied widely. Overall, more than 1 egg per litre were detected in approximately 40% of the analysed samples in CW1, 50% in CW2, 20% in CW3, 60% in CW4, and 30% in CW5. In principle, it could be inferred that the HRT values tested in this work (1.3–5.4 days) were not sufficient for an effective and consistent eggs removal in these gravel beds CW (8.6–12 m long and eggs loading rates of 7.8×10^2–2.8×10^3 eggs $m^{-2} d^{-1}$). However, it has been shown elsewhere that bed length, rather than HRT, may be more an important factor for egg removal in CW. Stott *et al.* (2003) reported 90% and 100% eggs removal, respectively in 50 m beds loaded at 4.4×10^2 eggs $m^{-2} d^{-1}$, and 100 m beds at 2.2×10^2 eggs $m^{-2} d^{-1}$, with HRT as low as 0.5 days. Stott *et al.* (1999) reported that 100 m beds challenged with a mean daily load rate of $1–7 \times 10^6$ eggs d^{-1} ($0.5–3.6 \times 10^4$ eggs $m^{-2} d^{-1}$) completely removed all eggs, with the majority of eggs removed within the first 10 to 25 m of the bed. The results of both these works suggest that removal is improved with increasing bed length, but the authors recognize that eggs removal mechanisms in CW need to be further evaluated, as well as the removal performance for systems operating under continual high parasite loading rates. Thus, it seems that the bed lengths tested in the present work may have been too short, and/or the eggs loading rates too high.

Based on the general understanding that HRT = 8–10 days is sufficient to achieve the WHO guideline for irrigation (Ayres *et al.* 1992; Bastos *et al.* 2006*b*), which was somehow confirmed in this work, and assuming pond depth = 0.9 m, and HRT = 10 days, the HLR necessary to achieve ≤ 1 human intestinal nematode egg per litre would be 0.090 $m^3 m^{-2} d^{-1}$. According to the above mentioned works of Stott *et al.* (1999, 2003), it is herein assumed, in a conservative approach, that 50 m HF gravel bed CW would effectively remove helminth eggs. Considering such a length and the length-to-breadth ratio tested in this work (≈1:5), this would result in 1,000 m^2 gravel channels; finally, assuming an influent flow of 2.5 $m^3 d^{-1}$ (the highest flow rate tested in this study), the resulting HLR would be 0.0025 $m^3 m^{-2} d^{-1}$, i.e. a far higher land area requirement than that estimated for the pond series.

CONCLUSIONS

Nitrogen was more effectively removed in WSP than in CW. Moreover, CW required more land to achieve surface water discharge standards, in terms of ammonia. On the other hand, the CW were more effective in removing BOD, COD and TSS, producing effluents of excellent quality. The ponds produced effluents complying with the Brazilian BOD standards for effluent discharge, but would need polishing treatment for COD and TSS removal. CW and WSP have shown to require similar land areas to achieve a bacteriological effluent quality suitable for unrestricted irrigation, but *E. coli* was removed in a more consistent rate in the WSP. Helminth eggs were effectively removed in the WSP, but not so reliably in the CW, which seems to require much more land than WSP to comply with the WHO guidelines for irrigation. Taking into further consideration that CW usually require more maintenance labour than WSP, it is concluded that polishing ponds treating UASB reactors effluents is more an advantageous choice than horizontal-flow CW.

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