

## Full Length Research Paper

## Post-treatment of municipal sewer in shallow polishing ponds

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Received 13 November, 2016; Accepted 15 February, 2017

This work aims to investigate the influence of polishing ponds (PP) depth on the post-treatment of sanitary sewers. Two treatment systems were designed and monitored. One system was an upflow anaerobic sludge blanket (UASB) reactor and intermittent flow sand filter; followed by a PP of 0.20 m depth with low superficial application rate ( $24.9 \text{ kgBOD}_5 \cdot \text{ha}^{-1} \cdot \text{day}^{-1}$ ), high sunlight incidence ( $597 \text{ Wm}^{-2}$ ) and enough biological carbon dioxide used to raise the average pH to 9.6, ensure an average removal of 81% orthophosphate and concentration of *Escherichia coli* lower than  $10^3 \text{ UFC}/100 \text{ ml}$ , which are the meeting requirements for unrestricted irrigation. The other system was a UASB followed by two PPs operated in parallel, at 0.20 and 0.60 m depths. The 0.20 m PP depth removed 80% of total Kjeldahl nitrogen, 53% of total phosphorus and 44% of orthophosphate. The 0.60 m pond depth showed low nutrient removal and a poor *E. coli* removal efficiency, 98.33% equivalent to 2 logs units. The ponds were fed by continuous systems.

**Key words:** Nutrient removal, polishing ponds, disinfection, sunlight.

### INTRODUCTION

The setup of a UASB reactor followed by a polishing pond is highly consolidated, mainly at a tropical climate region and in developing countries like Brazil. The polishing ponds are generally used as post-treatment of UASB reactors effluent, they are used to remove pathogens and nutrients, but do not stabilize the organic matter (Cavalcanti et al., 2002).

The main nitrogen removal mechanisms used for the

domestic sewage treatment in stabilization ponds are: Ammonia volatilization, biological nitrogen uptake, nitrification, denitrification, dead biomass sedimentation and sludge layer accumulation (Craggs, 2005). Despite all these nitrogen removal mechanisms in stabilization ponds, there are a general understanding among researchers that the predominant is ammonia volatilization due to high pH (Craggs, 2005; Park and

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Craggs, 2011; Assunção and Sperling, 2013). However, the operational and environmental conditions in which the removal occurs need more studies (Valero et al., 2010), because there are those who affirm that under favourable conditions for the algae growth, the main nitrogen removal occurs by algae absorption, despite the high pH values (Valero and Mara, 2007).

The residence time in stabilization pond permits various phosphorus removal mechanism, bio-assimilation, adsorption and chemical precipitation in pH values above 8 and high dissolved oxygen concentrations (Sperling and Chernicharo, 2005; Aslan and Kapdan, 2006; Cai et al., 2013; Wang et al., 2014). However, phosphates precipitation with earth alkali metals present in natural waters is considered as the main phosphorus removal (Cavalcanti et al., 2002), as a consequence of the rise in pH that favours phosphate precipitation (Sperling and Chernicharo, 2005). This results in a change in the balance of phosphate species, favoring the insoluble phosphate salts precipitation, e.g. calcium phosphate ( $\text{Ca}_3(\text{PO}_4)_2$ ), hydroxyapatite ( $\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$ ) and struvite ( $\text{Mg}(\text{NH}_4)(\text{PO}_4)$ ) (Haandel and Lettinga, 1994). Large phosphorus amounts may be stored as polyphosphate within bacteria and phytoplankton that can be released subsequently (Hupfer et al., 2007).

In this context, the polishing ponds suit a different reality. This is due to the possibility of exercising high photosynthetic rates, enabling high pH values providing a significant nutrients removal (Sperling and Chernicharo, 2005; Aslan and Kapdan, 2006; Cai et al., 2013; Wang et al., 2014; Gonçalves et al., 2016). When the pH reaches a value exceeding 9, the ammoniacal nitrogen removal is mainly attributed to ammonia volatilization and organic nitrogen decays due to sedimentation of algal materials (Mayo, 2013; Leite et al., 2011).

The solar irradiance greatly contributes to the algal biomass production, which also collaborates with bacterial decay, high hydraulic retention time ( $R_h$ ), low carbon dioxide levels and the bactericidal action of toxins originated from cyanobacteria and algae itself (Beran and Kargi, 2005; Moreira et al., 2009). When this solar energy goes directly into pond systems, it favours the decay of pathogens through the direct action of ultraviolet light-A (UVA) and ultraviolet light-B (UVB) in the destruction of DNA, RNA and other cell constituents of organisms, as well as joint activity of solar radiation, dissolved oxygen and high pH (Bolton et al., 2011). Algae and macrophyte organisms through photosynthesis make significant dissolved oxygen levels increase and ensure a diurnal pH changes, by consumption and remotion of  $\text{CO}_2$ .

The secondary objective of this research is to investigate the influence of the pond depth and the solar radiation, as primary energy source, on the polishing pond systems, using nutrients and *E. coli* removal indicators as base parameters. The main aim of this work is to complement previous ponds studies and their variables, e.g. depth, sunlight irradiance and nutrient

removal.

## MATERIALS AND METHODS

### System description

The experiment was performed at the Experimental Station of Biological Sewage Sanitary Treatment (EXTRABES - Estação Experimental de Tratamentos Biológicos de Esgotos Sanitários), part of the Universidade Estadual da Paraíba (UEPB). At EXTRABES is located the east interceptor of the water and sewage company of the state (CAGEPA - Companhia de Água e Esgoto do Estado da Paraíba) in Campina Grande - PB, Brazil, whose altitude is 550 meters. All experiments with sewage in this laboratory are developed with the east interceptor, from where the sewage is collected by a motor-pump setup. It is routed to a vertical sand column followed by a 1000 liter tank, which operates as an equalization tank. However, before the systems are fed, the sewage is homogenized by an automated shaker pump.

Two experimental treatment systems were built to treat the raw sewage (RS) from the CAGEPA's interceptor: the first system was a compact station (UASB reactor coupled to a decanter followed by an intermittent flow sand filter); and the second system was the combination of UASB reactor and decanter. The effluents of these two systems were post-treated in polishing ponds.

### Operation condition

Each polishing pond area was  $10 \text{ m}^2$  (1 m wide and 10 m long). Ponds 1 and 2 (PP1 and PP2) were 0.20 m deep and operated with an hydraulic retention time ( $R_h$ ) of 6 days, while the polishing ponds 3 (PP3) with depth of 0.60 m were operated with  $R_h$  of 12 days. In Figure 1, a scheme of the system is presented.

PP1 was supplied by a compact station (CS) made up with fiberglass. The CS is composed of UASB in the center followed by a coupled decanter. Its effluent was pumped to feed the intermittent flow sand filter that fed the PP1 by gravity. To ensure intermittence in the sand filter of the CS, the pond was fed at intervals of 4 h (6 ciclos.day<sup>-1</sup>) with 55L pumped from the decanter to the filter, comprising 330 L.day<sup>-1</sup>. In Table 1 the physical and operating system configuration is presented for systems 1.

System 2 consists of a fibre UASB reactor with "Y" geometry coupled to a secondary sedimentation tank followed by two shallow polishing ponds operated in parallel. PP2 and PP3 were fed with 330 and 500 L.day<sup>-1</sup> continuous flow, respectively. The physical and operating system configurations for system 2, with ponds 2 and 3 (PP2 and PP3) are presented in Table 2.

### Analyses

The dissolved oxygen and oxygen production rate (OPR) analysis was performed using the semi-continuous method from Beluga S32c software. The whole procedure was carried out *in local*, seeking to maintain the actual conditions. The respirometer received signals provided by the dissolved oxygen (YSI 5718) and temperature electrodes, sending them to a computer running S32c software.

The alkalinity determinations were performed using Kapp method (Buchauer, 1998). The *Escherichia coli* determination and the analysis of the variables of interest were made regarding the recommendations of the Standard Methods for the Examination of Water and Wastewater (APHA, 2012). The variables are COD, BOD<sub>5</sub>, total phosphorus, total kjeldahl nitrogen, ammonia nitrogen, total solids, settleable solids, suspended solids, volatile solids and

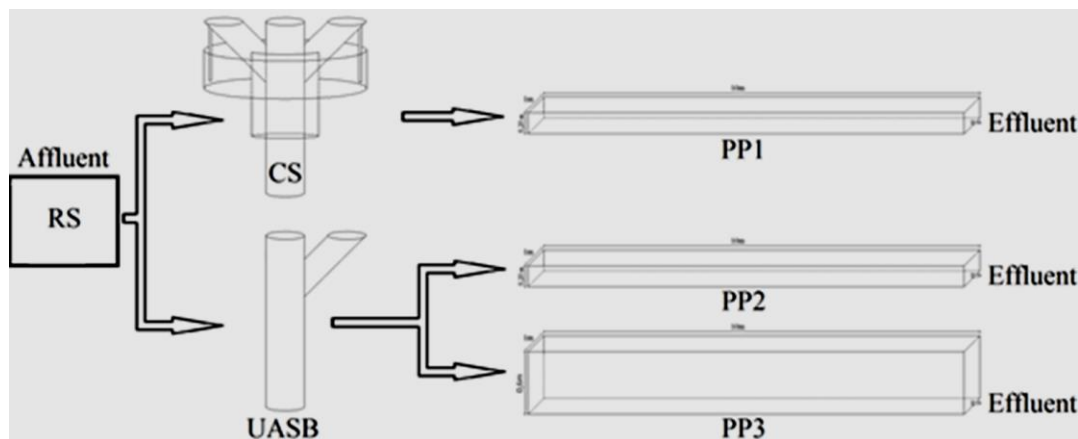


Figure 1. Scheme of the treatment systems used during for the research.

Table 1. System 1 operating parameters.

Characteristics	UASB	Sand filter	PP1
Operation mode	Continuous	Batch	Continuous
Height (m)	1.8	0.9	0.20
Area (m <sup>2</sup> )	0.126	0.26	10
Volume (m <sup>3</sup> )	0.227	0.234	2.0
R <sub>n</sub> (days)	0.68	0.02	6.0
Flow (L.day <sup>-1</sup> )	330	330	330

R<sub>n</sub>, Hydraulic retention time; PP1, polishing pond post-treatment for sand filter effluent.

Table 2. System 2 operating parameters.

Characteristics	UASB	PP2	PP3
Operation mode	Continuous	Continuous	Continuous
Height (m)	1.9	0.20	0.60
Area (m <sup>2</sup> )	0.237	10	10
Volume (m <sup>3</sup> )	0.45	2.0	6.0
R <sub>n</sub> (days)	0.29	6.0	12
Flow (L.day <sup>-1</sup> )	1550	330	500

R<sub>n</sub>, Hydraulic retention time; PP2, polishing pond 0.20 m deep treating effluent from UASB; PP3, polishing pond 0.60 m deep treating effluent from UASB.

dissolved solids, and they were measured at the entry and exit points of the pond. Temperature measurements and alkalinity and pH analyses were performed daily.

To determine the mass balance of nitrogen matter at the ponds, Equation 1 was used. With it was possible to determine the total affluent nitrogen load daily applied (MN<sub>ti</sub>). The other fractions were determined using equations 1 to 4, according to Haandel and Van Der Lubbe (2012) and Mayo (2013).

$$MN_{ti} = MN_{te} + MN_x + MN_{lost} \quad (1)$$

$$MN_{ti} = Q_i (NTK_i + N_{oq}) \quad (2)$$

$$MN_{te} = Q_e (NTK_e + N_{oe}) \quad (3)$$

$$MN_p = MN_{ti} - (MN_{te} + MN_x) \quad (4)$$

MN<sub>lost</sub>: Nitrogenous matter lost (volatilization + denitrification); MN<sub>ti</sub>: flux of nitrogenous matter in the affluent (mgN.d<sup>-1</sup>); MN<sub>te</sub>: flux of nitrogenous matter in the effluent (mgN.d<sup>-1</sup>); MN<sub>x</sub>: nitrogenous matter in algae sludge (mgN.d<sup>-1</sup>); NTK<sub>a</sub>: total Kjeldahl nitrogen affluent (mg.L<sup>-1</sup>); NTK<sub>e</sub>: total Kjeldahl nitrogen effluent (mg.L<sup>-1</sup>); N<sub>oi</sub>: oxidized nitrogen affluent (mg.L<sup>-1</sup>); N<sub>oe</sub>: oxidized nitrogen effluent (mg.L<sup>-1</sup>).

Statistical inference methods with variance analysis (ANOVA) were applied to test the sample variable averages of the treatment systems at 5% significance level.

## RESULTS AND DISCUSSION

The average values of the parameters of interest for RS, effluents from CS, UASB reactor and the three ponds: PP1, PP2, and PP3 are presented in Table 3. Remember that RS was the affluent for both CS and UASB. The parameters of interest are: COD, BOD<sub>5</sub>, orthophosphate, total phosphorus, total Kjeldahl nitrogen, ammonia, nitrite, nitrate, solids and its fractions, and *E. coli* as pathogen indicators. These parameters were obtained during 9 months.

### Organic matter removal

It is observed in Table 3 that the CS and UASB reactor produced effluents with average COD 136 and 189 mgO<sub>2</sub>.L<sup>-1</sup>, BOD<sub>5</sub> 83 mgO<sub>2</sub>.L<sup>-1</sup> and 120 mg.L<sup>-1</sup> and volatile suspended solids of 59 and 74 mgTSS.L<sup>-1</sup>, respectively. An ANOVA statistical analyses results show that at a 5%

**Table 3.** Average values and standard deviation of the raw sewage and treated effluents during the experimental phase.

Parameter	Affluent			Effluents		
	RS ( $\bar{x}\pm\delta$ )	CS ( $\bar{x}\pm\delta$ )	UASB ( $\bar{x}\pm\delta$ )	PP1 ( $\bar{x}\pm\delta$ )	PP2 ( $\bar{x}\pm\delta$ )	PP3 ( $\bar{x}\pm\delta$ )
COD (mgO <sub>2</sub> .L <sup>-1</sup> )	489±26	136±34	189±26	140±57	185±50	147±37
BOD <sub>5</sub> (mgO <sub>2</sub> .L <sup>-1</sup> )	200±29	83±25	120±27	87±32	115±41	73±23
Phosphorus total (mgP.L <sup>-1</sup> )	8.06±1.15	4.73±0.88	7.22±1.14	1.46±0.74	3.38±1.20	7.14±0.68
Orthophosphate (mg P-PO <sub>4</sub> <sup>-</sup> .L <sup>-1</sup> )	5.38±1.52	3.49±0.75	4.83±1.01	0.65±0.62	2.69±0.71	3.75±0.64
T.K.N (mg N-TKN.L <sup>-1</sup> )	48.62±3.74	11.11±1.07	40.72±4.28	6.97±0.73	9.54±1.28	12.97±3.58
Ammonia nitrogen (mg N-NH <sub>4</sub> <sup>+</sup> .L <sup>-1</sup> )	39.03±3.81	8.36±0.61	38.27±5.47	2.02±0.33	3.78±1.34	7.63±3.88
Nitrite (mg N-NO <sub>2</sub> <sup>-</sup> .L <sup>-1</sup> )	-	0.47±0.42	-	0.84±0.23	0.06±0.18	0.05±0.10
Nitrate (mg N-NO <sub>3</sub> <sup>-</sup> .L <sup>-1</sup> )	-	29.63±4.27	0.30±0.02	0.47±0.32	1.30±0.83	2.90±0.50
Total solids (mg.L <sup>-1</sup> )	1112±154	1138±221	1068±155	1278±98	1217±110	1158±89
Volatile solids (mg.L <sup>-1</sup> )	436±120	216±113	283±150	232±89	301±139	303±102
Total suspended solids (mg.L <sup>-1</sup> )	248±44	59±17	74±14	27±10	48±28	44±10
Volatile suspended solids (mg.L <sup>-1</sup> )	196±40	49±6	57±29	19±10	47±22	42±14
pH	7.56±0.27	6.58±0.65	7.41±0.25	9.61±0.69	8.59±0.34	8.09±0.20
Alkalinity (mg CaCO <sub>3</sub> .L <sup>-1</sup> )	360±42	137±30	373±21	159±50	270±30	426±48
<i>Escherichia coli</i> (UFC/100 mL)	5.25x 10 <sup>6</sup>	7.13x 10 <sup>4</sup>	3.10 x 10 <sup>6</sup>	7.88x 10 <sup>2</sup>	9.40 x10 <sup>3</sup>	8.65x 10 <sup>4</sup>

RS, Raw sewage; UASB, effluent from UASB reactor; CS, compact station; PP1, effluent polishing pond coming from the compact station; PP2; PP3, effluent polishing pond coming from the UASB reactor.

significance level there was a significant difference ( $p < 0.05$ ) between the average COD values of the two produced effluents.

The low organic matter concentration provides a higher light penetration (Sperling, 2002), which results in a higher photosynthesis rate (Sigeo, 2004). Therefore, it is expected, for these effluents, a high pH and dissolved oxygen rates that will be discussed further below. Bastos et al. (2011), studying polishing ponds, obtained high pH for low depth, which is in line with this work.

### Nitrogen removal

PP1 is fed with an already nitrified affluent from the CS, as shown in Table 3, so that, the low concentrations of total Kjeldahl nitrogen (N-TKN 6.97 mg.L<sup>-1</sup>) and ammonia (2.02 mgN-NH<sub>4</sub><sup>+</sup>.L<sup>-1</sup>) were expected. The high organic nitrogen concentration (71%) is associated with the particulate matter present in the algae (Mayo, 2013).

PP2, with a depth of 0.20 m, was fed UASB reactor effluent and showed a considerable nitrogen removal. As can be seen in Table 3, the concentration of the final effluent from PP2 was 9.54 mg N-NTK. L<sup>-1</sup> and 3.78 mg N-NH<sub>4</sub><sup>+</sup>.L<sup>-1</sup>, so, about 60% of the N-NTK corresponds to N-organic, which was probably incorporated into the algal mass.

According to the mass balance of nitrogenous matter presented in Figure 2 and Table 4, the affluent of PP2 (effluent from UASB reactor) had an average flux of 13.54 gN.day<sup>-1</sup>, while the PP2 effluent had an average flux of 3.60 gN.day<sup>-1</sup> (3.15 gN-NTK.day<sup>-1</sup> + 0.02 gN-

NO<sub>2</sub>.day<sup>-1</sup> + 0,43 gN-NO<sub>3</sub>.day<sup>-1</sup>), resulting in a removal efficiency of 73.41%. The algal biomass consists of 52.4% carbon, 9.2% nitrogen and 1.3% phosphorus by weight (Park and Craggs, 2011). Also, there is a particulate nitrogenous matter that is settled at the sludge. It was not considered. Observing the values presented in Figure 2, it is noted that the organic nitrogen present at the effluent is 14% (1.90/13.54) gN.day<sup>-1</sup> of the affluent nitrogen. This percentage corresponds to the algal biomass produced at the polishing pond (Mayo, 2013). On the other hand, the fraction lost by ammonia gas desorption was 59.38% (8.04/13.54 gN.day<sup>-1</sup>), disregarding the denitrification at night. The desorption process can be considered as main mechanisms of nitrogen removal at PP2 (0.20 m deep and fed by UASB reactor effluent). The nitrified fraction was only 3%, even at good conditions such as: high dissolved oxygen concentration (Figure 4), considerable algal sludge layer settled at the pond with temperature higher than 30°C and average pH of 8.59 (Table 3). This finding is corroborated by Park and Carggs (2011) who ensure that in high rates ponds, major ammonia nitrogen transformation processes are nitrification and assimilation.

Zimmo et al. (2004) confirmed experimentally that 25% of nitrogen removal in shallow ponds (0.90 m) happens in biological processes of nitrification and denitrification. Leite et al. (2011), treating landfill leachate in a series of shallow ponds (0.50 m), was able to remove 99.5% of ammonia nitrogen and attributed this efficiency to the process of desorption of ammonia. Valero and Mara (2007) conducted experiments in a maturation pond on a pilot scale at United Kingdom and obtained low removal

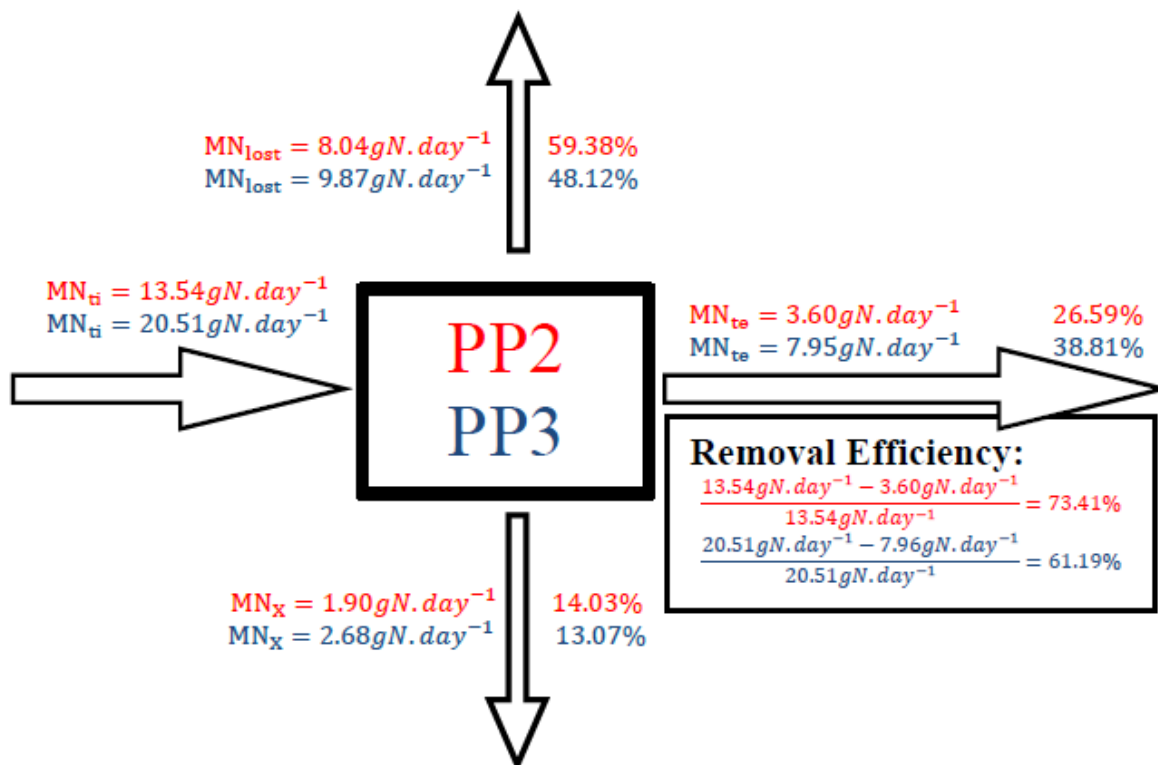


Figure 2. Nitrogenous mass balance for PP2 and PP3.

Table 4. Average values of nitrogenous affluent and effluent fractions.

PPP	Affluent					Effluent				
	N-NTK (g.day <sup>-1</sup> )	N-N <sub>Org</sub> (g.day <sup>-1</sup> )	N-NH <sub>4</sub> <sup>+</sup> (g.day <sup>-1</sup> )	N-NO <sub>x</sub> (g.day <sup>-1</sup> )	MN <sub>ii</sub> (g.day <sup>-1</sup> )	N-NTK (g.day <sup>-1</sup> )	N-N <sub>Org</sub> (g.day <sup>-1</sup> )	N-NH <sub>4</sub> <sup>+</sup> (g.day <sup>-1</sup> )	N-NO <sub>x</sub> (g.day <sup>-1</sup> )	MN <sub>te</sub> (g.day <sup>-1</sup> )
PP2	13.44	0.81	12.63	0.10	13.54	3.15	1.90	1.25	0.45	3.60
PP3	20.36	1.22	19.14	0.15	20.51	6.49	2.68	3.81	1.47	7.96

MN<sub>ii</sub>, Flux of nitrogenous matter in the affluent; MN<sub>te</sub>, flux of nitrogenous matter in effluent; N-NO<sub>x</sub>, oxidated forms of nitrogen.

of ammonia volatilization ( $15 \text{ gN-NH}_3 \cdot \text{ha}^{-1} \cdot \text{day}^{-1}$ ).

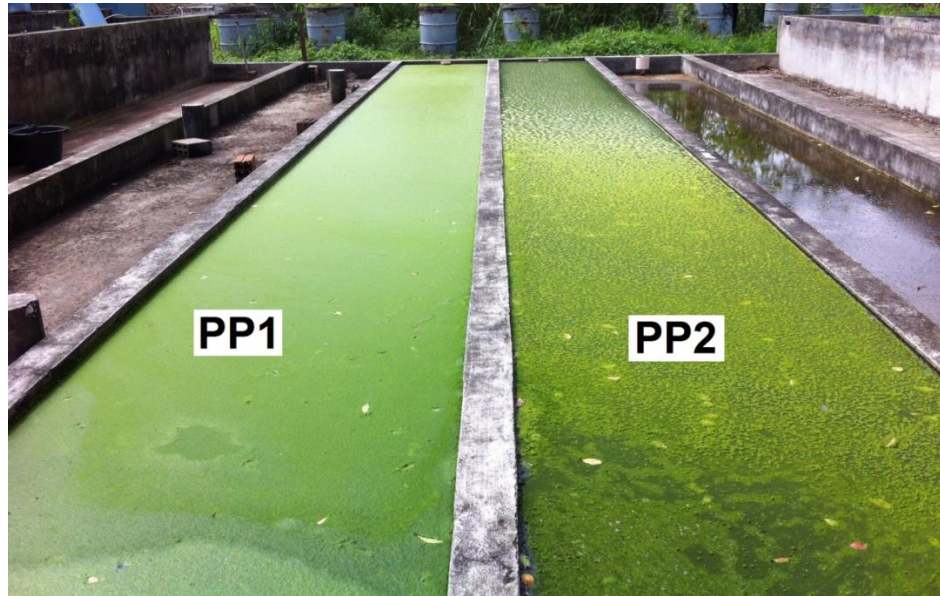
The average values of total nitrogen and its fractions for the RS and the effluents from CS, UASB reactor and the polishing ponds (PP1, PP2 and PP3) are shown in Table 4. In Figure 2, in the 0.6 m depth pond (PP3), the ammonia gas desorption was only 48.12 and 13% at the algal sludge.

The nitrogen mass balance (Figure 2) was used to calculate the average nitrogen removal variation from 61.19 to 73.41%. The associated mechanisms were ammonia volatilization, settle and biological absorption of nitrogen.

In Table 3, the pH was increased due to the biological use of CO<sub>2</sub> during intense algal metabolism (Shilton et al., 2008; Formagini et al., 2014). The rise of pH in the pond is a consequence of algal activity, which in the

specific case of this work, contributed little to the gas ammonia volatilization, a conclusion corroborated by Valero and Mara (2010).

It is important to note that the comparisons of organic nitrogen concentration between all ponds show that there are increases in its fraction among inflow and outflow. But while the PP3 and PP2 received a poor affluent concentration of 2.45 gN-Organic (25%) and produced effluent with 5.34 gN-Organic (41%) and 5.76 gN-Organic (60%), respectively, the PP1 with almost the same affluent concentration of 2.75 gN-Organic (25%) was responsible for major organic effluent concentration of 4.95 gN-Organic (71%). And these results make sense with the apparent behaviours (Figure 3). Algae production was high in PP1, which blocked the sunlight across the pond.



**Figure 3.** A picture of PP1 and PP2 from the operational period.

### Phosphorus removal

The average concentrations of orthophosphate and total phosphorus for raw sewage were 5.4 and 8.0 mg.L<sup>-1</sup>, respectively. These are typical values of an average sewage (Metcalf and Eddy, 2003). These same concentrations for PP1 affluent were 3.49 mg P-PO<sub>4</sub><sup>-3</sup>.L<sup>-1</sup> and 4.73 mg P.L<sup>-1</sup>, and for PP1 effluent they were 0.65 mg P-PO<sub>4</sub><sup>-3</sup>.L<sup>-1</sup> and 1.46 mg P.L<sup>-1</sup> (Table 3), providing an efficiency of 81 and 69 %, for orthophosphate and total phosphorus respectively.

The phosphate removal is primarily due to pH increase, which increases because the CO<sub>2</sub> consumption is greater than its production rate. The extent of the pH increase depends on the buffering capacity which in turn depends on the alkalinity. Low alkalinity leads to a greater pH increase as the results of Table 3 with PP1 (pH 9.6 for 159 mg CaCO<sub>3</sub>.L<sup>-1</sup>) and PP2 (8.6 for 270 mg CaCO<sub>3</sub>.L<sup>-1</sup>) show.

This total phosphorus removal efficiency (69%) was due to the low concentration of organic matter expressed as BOD<sub>5</sub> (83 mgO<sub>2</sub>.L<sup>-1</sup>) and 59 mgTSS.L<sup>-1</sup>, as shown in Table 3. There are sufficient conditions that make the photosynthesis average rate greater than the organic matter oxidation rate in the polishing pond (Figure 4); they ensure a 9.6 pH (Table 3), favouring the phosphate salts precipitation (Mara et al., 1992; Haandel and Lettinga, 1994; Mara and Pearson, 1998; Sperling et al., 2010). The low depth associated with a low organic matter concentration promotes greater light penetration (Sperling, 2002), which results in a higher photosynthesis rate (Sigee, 2004). Much lower results were obtained in South-Eastern Brazil in no similar experimental

conditions: Average removal of total phosphorus was of 23% in a pond with a depth of 0.3 m and HRT of 2.3 days (Bastos et al., 2007).

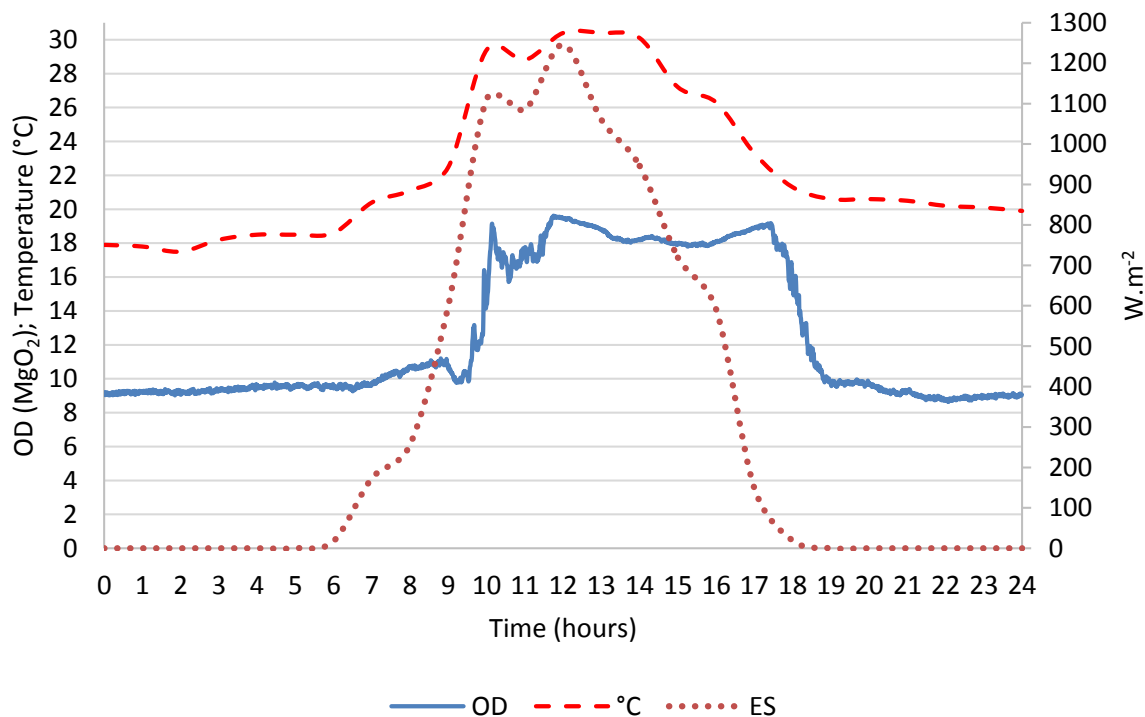
PP1 and PP2 produced effluents with average values of significant statistical differences ( $p < 0.05$ ). These ponds had the same dimensions and were operated in parallel, having similar temperature and solar radiance. Their only difference was the affluent. PP1 was fed by the CS and PP2 fed by UASB reactor. A quick analysis of UASB reactor effluent data from Table 3 revealed a high BOD<sub>5</sub> average concentration of 120 mgO<sub>2</sub>.L<sup>-1</sup> and total suspended solids concentration of 74 mgTSS.L<sup>-1</sup>. These are organic substances that hinder solar light penetration into the pond, limiting the pH to 8.6. This resulted in an overall phosphorus removal of 53%, producing effluent of 3.4 mg P.L<sup>-1</sup> (Table 3).

With respect to phosphorus removal in PP3 of 0.60 m depth, there was no significant total phosphorus removal (efficiency <2%), as shown in Table 3. It can be explained that 8.3 pH in this pond does not favour phosphate precipitation, and it is known that phosphorus removal in ponds is associated with insoluble phosphate salts precipitation and depends on a pH greater than nine.

Godos et al. (2009) confirm phosphorus removal efficiency less than 10% for stabilization ponds pH (~8.0). These authors ensure that pond effluent usually keeps high buffering capacity negatively interfering with the abiotic precipitation of phosphate ion.

### Pathogenic organisms' removal

The polishing ponds are designed shallow to facilitate sunlight penetration through the whole water body,



**Figure 4.** Dissolved oxygen behaviour ( $\text{mg}\cdot\text{L}^{-1}$ ), temperature and irradiance held *in loco* in the pond of 0.20 m deep.

optimizing the performance of the mechanisms of pathogen inactivation by sunlight (Shilton and Walmsley 2005; Verbyla and Mihelcic, 2015). *E. coli* bacteria are organisms that have a higher survival in treatment systems, so that these *E. coli* are obvious indicators of hygienic quality, regarding the removal of pathogens.

According to the data presented in Table 3, the geometric average of *E. coli* present at raw sewage was  $4.65 \times 10^6$  CFU/100 mL. These values are within the range of  $10^6$  to  $10^9$  CFU/100 mL established by Metcalf and Eddy (2003) as typical for wastewater.

The effluent from PP1, with a 6 days hydraulic detention time ( $R_h$ ), had an *E. coli* concentration under  $10^3$  CFU/100mL, which fits microbiological values suggested by the World Health Organization WHO (2006) in treated sewage for unrestricted irrigation. Note that PP1 was fed with CS effluent, an *E. coli* concentration of  $7.13 \times 10^4$  CFU/100 mL only. PP1 results are close to those of other studies (Sousa et al., 2005; Leite et al., 2009), wherein they suggest the application for agriculture reuse, favorable in semi-arid agriculture in Northeast Brazil.

Furthermore, PP2, whose affluent had an *E. coli* average concentration of  $3.10 \times 10^6$  CFU/100 mL, produced an average concentration effluent above  $10^3$  CFU/100 mL; therefore it did not suit the requirements for sanitary quality suggested by the World Health Organization, WHO (2006).

As can be shown in Figure 4, the solar irradiance

remained on the average value of  $591 \text{ W}\cdot\text{m}^{-2}$ , assuring intense photosynthetic process by algae. It resulted in an oxygen average concentration of  $18.0 \text{ mgO}_2\cdot\text{L}^{-1}$ , that ensures an average rate of oxygen production of  $2.00 \text{ mgO}_2\cdot\text{L}^{-1}\cdot\text{h}^{-1}$  over 9 h per day, as shown in respirogram in Figure 4. In previous study, Sweeney et al. (2007) reported for the summer a dissolved oxygen level over than  $30 \text{ mgO}_2\cdot\text{L}^{-1}$  in the upper area of the stabilization pond. Nevertheless, *E. coli* removal efficiency was only 3 log units.

According to the authors (Ouali et al., 2014; Beutel and Larson, 2015), *E. coli* decay increases in direct proportion with the dissolved oxygen and increased pH. The high dissolved oxygen concentrations imply a reactive oxygen formation, such as singlet and superoxide that contribute to the pathogenic organisms decay (El Hamouri et al., 1994; Bolton et al., 2010; Bolton et al., 2011). These cases were observed during the experiment. Figure 4 and Table 3 showed that PP2 with a dissolved oxygen close to  $18 \text{ mgO}_2\cdot\text{L}^{-1}$  at midday and average 8.6 pH had the highest nutrient and pathogens removal efficiency among all the ponds treated effluent from UASB reactor. Beutel and Larson (2015) obtained similar behaviour for dissolved oxygen and temperature relation.

The polishing pond PP2 (0.20 m), operated with full  $R_h$  of 6 days, produced an effluent with *E. coli* average concentration of  $9.1 \times 10^3$  CFU/100 mL. This concentration is of the same magnitude order with this parameter measured for the effluent from PP3 (0.60 m;  $8.6 \times 10^4$

CFU/100 mL). This pond was operated at  $R_h$  of 12 days. Both ponds had an *E. coli* removal, not achieving the requirements recommended by the World Health Organization WHO (2006). Therefore, these effluents are fit for cereals and other fertigation application. Sperling et al. (2010) obtained similar results in operating polishing pond depth of 0.60 m and TDH for 12 days.

## Conclusion

The compact station effluent favored PP1 performance ( $R_h$ : 6 days, high sunlight incidence:  $597W.m^{-2}$  and temperature ranging from 20 to  $32^{\circ}C$ ), achieving a  $CO_2$  biological consumption sufficient to raise the pH to 9.6, ensuring an phosphorus average removal of 69 and 81% of orthophosphate and *E. coli* concentration less than  $10^3$ CFU/100mL. This effluent can be used for unrestricted reuse. On the other hand, PP2 with similar conditions (0.20 m deep and same  $R_h$ ) but different affluent removed only 73.42% of N-TKN, 53% of phosphorus and 44% of orthophosphate. The difference was due to the better affluent of PP1 ( $10^4$ - $10^5$  CFU/100mL,  $BOD_5$  83  $mgO_2.L^{-1}$  and 59  $mg.TSS.L^{-1}$ ).

The present study provided relevant contributions to pond research. The short hydraulic retention time for shallow pond ensured a higher algae production at PP1, allowing a new perspective for the next studies on algae production for power generation and an efficient combination of anaerobic and aerobic treatment with potential effluent for reuse.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

## ACKNOWLEDGEMENT

The authors would like to thank CAPES and CNPq.

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