UASB-polishing ponds design parameters: contributions from a pilot scale study in southeast Brazil
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ABSTRACT
This paper presents the results of five years monitoring of an experimental wastewater treatment plant in southeast Brazil, comprised of a UASB reactor followed by a submerged aerated biofilter (BF) (field scale) and shallow polishing ponds (pilot scale). Three ponds in series achieved high quality effluent standards in terms of ammonia and E.coli, but a fourth pond did not result in further efficiency. Well established models to predict ammonia and E.coli removal in facultative and/or maturation ponds were, in a way, validated for polishing ponds too. The paper also includes results of input design parameters, such as pH and E.coli die-off rate constants, and their variation along the pond series.

Key words | ammonia, BOD, E.coli, pH

INTRODUCTION
Waste stabilization ponds (WSP) have long been considered a good choice for wastewater treatment, mainly in developing and/or warm climate countries. Their many advantages include: simplicity, low cost, low maintenance, robustness, and sustainability (Mara 2004). Shallow ponds following UASB (Upflow Anaerobic Sludge Blanket) reactors have been named polishing ponds to differentiate them from the classical concepts of facultative and maturation ponds. However, when the organic matter removal is ‘completed’, and the main, or the only, objective is the removal of pathogenic organisms, the most usual term is maturation ponds. In any case, polishing/maturation ponds can provide further removal of organic matter (BOD), achieve high ammonia removal and produce effluents of excellent bacterial quality, as long as they are properly designed (i.e. shallow ponds) (von Sperling 2007).

The removal of BOD, nitrogen and coliforms within WSP in warm climates is well documented (Silva et al. 1995; Soares et al. 1996; Mara 2004; von Sperling 2007), but not so much their specific modelling in polishing ponds. The Brazilian experience has shown that polishing ponds can absorb the UASB effluent’s organic load, so that they can be designed as maturation-like ponds, i.e. shallow ponds, aiming at pathogens removal (Cavalcanti 2003; von Sperling & Mascarenhas 2005).

Regarding coliforms removal, ponds are usually designed assuming that bacterial decay follows first order kinetics. Many researchers have found that the main mechanisms of bacterial die-off are associated with the pond depth (full penetration of the solar radiation in shallow ponds, leading to intense photosynthesis, significant production of oxygen and pH rising, thereby facilitating the photo-oxidation process that kills bacteria) (Curtis et al. 1992; Pearson et al. 1995; Pearson et al. 2005; von Sperling 2005). von Sperling (2007) proposed empirical equations for predicting coliforms die-off rate constants, based on field data from facultative and maturation ponds (pilot and field scale), and on a dispersed hydraulic flow regime (Equations(1) and (2)). With specific regards to polishing ponds, it is generally accepted that the die-off rates should be similar, or even higher than those usually assumed for facultative or maturation ponds (von Sperling 2007).

\[ K_b(\text{dispersed flow}) = 0.542 H^{-1.259} \]

(82 ponds in several countries) \((R^2 = 0.505)\) (1)
$K_0 (\text{dispersed flow}) = 0.917 (H)^{-0.877} (\text{HRT})^{-0.329}$

(33 ponds in Brazil) ($R^2 = 0.847$)  

(2)

where:

$K_0 =$ first-order rate constant for $E. coli$ removal (20 C)

(d$^{-1}$)

$H$: pond depth (m)

HRT: hydraulic retention time (days)

Pano and Middlebrooks (1982) proposed a model (Equations(3) and (4)) for ammonia removal, based on field data from facultative ponds in the USA receiving low surface organic loading (<40 kg BOD ha$^{-1}$d$^{-1}$). The model assumes that ammonia volatilization is the main mechanism of nitrogen removal. The model also assumes first order removal kinetics and complete mixing flow regime, and incorporates values for hydraulic loading, pH, temperature and coefficients derived from empirical data. However, it is required that pH values be assumed, which is something difficult to do with accuracy. Soares et al. (1996) found that Pano and Middlebrooks model were in good agreement with data from ponds in northeast Brazil. However, there still is little information about how well this model predicts ammonia removal in polishing

$C_e = \frac{C_o}{1 + [(A/Q)/(0.0038 + 0.000134 \times T) \times e^{(1.041 + 0.044T) \times (pH - 6.6)}]}$  

$T < 20 \text{ C}$

(3)

$C_e = \frac{C_o}{1 + [5.035 \times 10^{-7} \times (A/Q) \times e^{(1.340 \times (pH - 6.6))}]}$  

$T \geq 20 \text{ C}$

(4)

where:

$C_o =$ ammoniacal nitrogen concentration in pond effluent (mg L$^{-1}$)

$C_e =$ ammoniacal nitrogen concentration in pond effluent (mg L$^{-1}$)

$Q =$ wastewater flow rate (m$^3$ d$^{-1}$);

$A =$ pond area (m$^2$);

$T =$ water temperature (°C);

pH = pond water pH

RESULTS AND DISCUSSION

Water temperature

Base on local climate data and field measurements, an equation relating air and water temperature was derived (Equation (5))

$T_w = 8.7 + 0.73 \times T_a$  

$R^2 = 0.79$  

(5)

where:

$T_w =$ water temperature (°C)

$T_a =$ air temperature (°C)

The local mean temperature of the coldest month is around 17°C. Based on Equation (5), the correspondent mean water temperature would be 20.6°C, which could be taken as a local input design parameter, for instance in Pano and Middlebrooks equations or in the dispersed flow model for coliforms removal.
BOD surface loading rates and BOD removal

Over the entire period of the study the UASB + BF presented high removal efficiency of total BOD$_5$ (70% - 80%, mainly in the UASB). Consequently, the surface organic loading rates on the first pond were relatively low. In the ponds series, BOD removal took place basically in the first unity, which added up to 30% of total BOD removal, and produced effluents with average values around 20–80 mg BOD L$^{-1}$. After the first pond there was no clear further BOD removal (Figure 1). Similar results were found by von Sperling & Mascarenhas (2005).

DO and pH

The surface organic (and ammonia) loading rates variations did not seem to impair algal photosynthesis and the maintenance of aerobic conditions in the ponds. Even in the first pond, and at the deepest measuring points, DO were at the worst in the range of 2–3 mg L$^{-1}$, usually at dawn (Figure 2). As a result, pH was also kept at high values in all ponds, always above 7.5 at mid-depth and never below 7 at any depth (Figure 3).

Overall, pH increased along the pond series, reflecting the prevailing conditions in each unity: more intense algal...
activity in the last ponds and, consequently, higher uptake of carbon dioxide, along with lesser carbon dioxide production due to lower bacterial activity. Negative correlations were found between pH values and pond depths, although neither strong nor statistically significant; Spearman correlation coefficients were: all ponds = −0.4906; pond 1 = −0.4325; pond 2 = −0.2478; pond 3 = −0.1382; pond 4 = −0.6475.

Considering the entire period of study, mean pH values at the surface level (0.15 m) and at mid depth were: 7.7 and 7.6 (pond 1), 8.1 and 7.8 (pond 2), 8.7 and 8.2 (pond 3), 8.7 and...
8.4 (pond 4). Therefore, as an input design parameter, a minimum pH value of 7.5 could be assumed for the first pond and, subsequently, pH rise of around 3–5\% in the second pond and 5–7\% in the third pond. Apparently, no marked further increase is to be expected in a fourth pond.

**Nitrogen removal**

Ammonia concentration in the UASB effluent was approximately 60\% higher than in raw wastewater. Nevertheless, the pond series provided substantial TKN (NH₃ + N_(org)) (≈ 70\%) and ammonia (≈ 90\%) removal, producing effluents in compliance with strict surface water discharge standards, as well as suitable for fish culture (3–5 mg NH₃ L⁻¹). Pano and Middlebrooks model (Equation (4)) found good agreement with the experimental data (Figure 4): Willmott coefficient (d) = 0.88. In the Willmott test, the ‘coefficient of agreement’ (d) ranges from zero (complete dispersion) to 1 (perfect agreement between two models) (Willmott et al. 1985).

**E.coli removal**

The treatment system reached high E. coli removal efficiency: ≈ 0.7 log unit reduction in the UASB + BF followed by ≈ 4 log units reduction up to the third pond. The fourth pond did no add further removal. Pond 3 consistently produced effluent qualities complying with the WHO guidelines for unrestricted irrigation (assumed herein as 10³ E.coli per 100 mL); pond 3 (systematically) and pond 2 (most of the time) achieved the WHO guidelines for restricted irrigation and aquaculture (assumed as 10⁴ E.coli per 100 mL) (WHO 2006a, b) (Figure 5).

E. coli die-off rate constants (K_b) (dispersed flow, 20°C) were calculated for each pond, considering the whole period of this study. The dispersion number was estimated assuming d = 1/(L/B) (L = length, B = breadth) (von Sperling 1999). The average calculated K_b values were: 0.98 (pond 1), 1.11 (pond 2), 1.35 (pond 3), and 0.99 (pond 4). In other words, an increase of approximately 13\% of K_b values was recorded from pond 1 to pond 2, and 22\% from pond 2 to pond 3. No further removal was recorded in the fourth pond.

K_b estimated values using von Sperling equations (Equations (1) and (2)) were not in fine agreement with the calculated K_b values, in general underestimating them (d = 0.64 for Equation (1); d = 0.67 for Equation (2)). Similar results were found when comparing the observed and estimated (using Equations (1) and (2)) values of effluent E. coli

**Figure 4** Ammonical nitrogen concentration in pond effluents: estimated values according to Pano and Middlebrooks model (NH₃ est) and measured values (NH₃ obs).

**Figure 5** E. coli concentrations in raw wastewater (RW), and in the effluents of the UASB, the biofilter (BF), and the pond series.

**Figure 6** Observed and estimated values of effluent E.coli concentrations using von Sperling models, Equation (1) (left) and Equation (2) (right).
concentrations: \( d = 0.45 \) for Equation (1); \( d = 0.55 \) for Equation (2) (Figure 6).

It is worth noticing that von Sperling models were obtained from databases which included much wider values of pond depths and hydraulic retention times than those tested in this work. von Sperling et al. (2005) and von Sperling (2007) had already noticed that \( K_b \) values obtained from polishing ponds in Brazil (including the ones of this study) were higher than those predicted by Equation (1), and that shallow ponds (\( h<1.0 \) m) tend to present very high \( K_b \) values.

CONCLUSIONS

In general, these results confirm a well established understanding that shallow polishing ponds designed for the removal of ammonia and coliforms provide additional BOD removal and face no problems of organic overloading.

Within the experimental conditions of this study (a series of four pilot scale ponds, pond depth = 0.4–0.9 m, \( L/B = 2 \), \( HRT = 4.1–9.4 \) d), the following points related to design criteria of polishing ponds are highlighted: (i) it seems that Pano and Middlebrooks model can be confidently used to predict ammonia removal in polishing ponds; (ii) von Sperling equations tend to underestimate \( E.coli \) \( K_b \) values, hence \( E.coli \) removal; therefore, designing polishing ponds based on them incorporates a factor of safety; (iii) a series of three ponds showed to achieve high quality ammonia and \( E.coli \) effluent standards, whereas adding a fourth pond seems to be worthless.

These results also provided the following sound information about input design parameters: (i) a pH value of 7.0 can be confidently assumed in the first pond and, subsequently, a pH rise of 3–5% in the second pond and 5–7% in the third pond; (ii) an \( E.coli \) \( K_b \) value of 1.0 could be assumed in the first pond and, subsequently, an increase of 10% in the second pond and 20% in the third pond.

Finally, it is recognized that since these results derive from pilot scale ponds, adopting safety factors (like using von Sperling equations) may be a realistic design approach.

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REFERENCES


