

## A predictive model for ammonium removal in polishing ponds operated in sequential bath mode

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### ABSTRACT

The magnitude of pH changes in polishing ponds can be predicted by simple stoichiometric rules if the extent of processes affecting this parameter is known. Thus, the objective of this article was to develop a model that predicts pH variation and ammonia desorption in polishing ponds in sequential batches, depending on the rates of processes that affect pH in ponds and to evaluate the influence of temperature and depth on these processes. As the temperature conditions change during the year, for model validation, tests were carried out under two medium temperature conditions (hot period and cold period) and four lakes with depths between 0.2 and 1.0 m. The proposed model is validated by the good correspondence between the simulated and experimentally obtained values for the two temperature conditions and for both periods. For the hot period, the model excelled, presenting a high linear correlation, always with R<sup>2</sup> above 0.90 for all ponds. For the cold period, the lowest R<sup>2</sup> obtained was 0.74 for the four lakes. Thus, the proposed model is suitable to describe the pH variation and ammonia desorption in polishing ponds in sequential batches, at all analyzed depths and under both temperature conditions.

**Key words:** ammonia desorption, pH elevation, polishing ponds, predictive models, sequential batch

### HIGHLIGHTS

- A predictive model of pH variation and ammonia removal for sequential batch polishing ponds was developed.
- The model showed a high correlation between simulated and experimental values. Finding out how in SBPP the removal of ammonia takes place through volatilization.
- The predictive model can be used in SBPP for various conditions (temperature, depth, sewage characteristics) to obtain the retention time required for ammonia removal with good accuracy.
- The results indicate that SBPP requires a much smaller area than WSP, still showing ammonia removal.

## 1. INTRODUCTION

According to *Sbahi et al. (2021)*, the best criteria for choosing an effluent treatment system are high efficiency and low cost. UASB reactors (upflow anaerobic sludge blanket) have efficient organic material removal and a relatively low cost, and are widely used in many countries with hot climates as the first stage of effluent treatment (*van Haandel & Lettinga 1994; von Sperling 2015*). In Brazil, using a UASB reactor necessarily requires effluent post-treatment units to meet current release standards (*van Haandel et al. 2006*). This is because UASB reactors do not remove nutrients, pathogenic organisms, and surfactants sufficiently, therefore a post-treatment step is necessary not only for the additional polishing of the effluent in terms of organic matter concentrations (*van Haandel et al. 2006; Walia et al. 2020*).

*Khan et al. (2011)* report that there is a wide variety of post-treatment configurations that are based on combinations with UASB reactors, one of them being polishing ponds (PPs). PPs are shallow and designed specifically to improve UASB effluents. Due to the relatively low oxygen demand in PPs and the high photosynthesis rate in the transparent UASB, effluent dissolved oxygen tends to build up, so that PPs can be operated as flow through units or in sequential batch mode. PPs constitute one of the most attractive alternatives for disinfecting effluents from UASB reactors, because complete treatment can be achieved in a much shorter time than in conventional waste stabilization ponds (WSPs). In addition, PPs present adequate

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conditions for nutrient and pathogen removal (Cavalcanti 2003). PPs are systems with low operating costs, as they do not need energy input other than solar energy and do not require chemical product applications (Santos & van Haandel 2021).

According to van Haandel & Marais (1999), the release of large amounts of dissolved nutrients into water bodies tends to cause an exacerbated growth of aquatic life. Thus, to maintain the quality of water bodies within their legal classification, the quality of effluents released must be controlled. In most countries, nitrogen levels in effluent from wastewater treatment plants are regulated to mitigate the possible harmful effects of nitrogen discharge into water bodies (Park *et al.* 2015). Thus, nitrogen needs to be removed before releasing wastewater into receiving bodies.

In PP, ammonia volatilization is reported as the main mechanism of ammoniacal nitrogen removal (Alves *et al.* 2011; Leite *et al.* 2011; Santos & van Haandel 2021). Morais *et al.* (2021) showed that ammonia volatilization is a first order process regarding the dissolved  $\text{NH}_3$  concentration. The ammonia nitrogen fraction can be as gas ( $\text{NH}_3$ ) or in ionic form ( $\text{NH}_4^+$ ) depending heavily on pH and temperature. The ionization constant of ammonia is 9, so that at a neutral pH the undissociated form predominates and at a pH above 9. Since pH tends to increase with time, the  $\text{NH}_3$  concentration, and hence the desorption rate also increases.

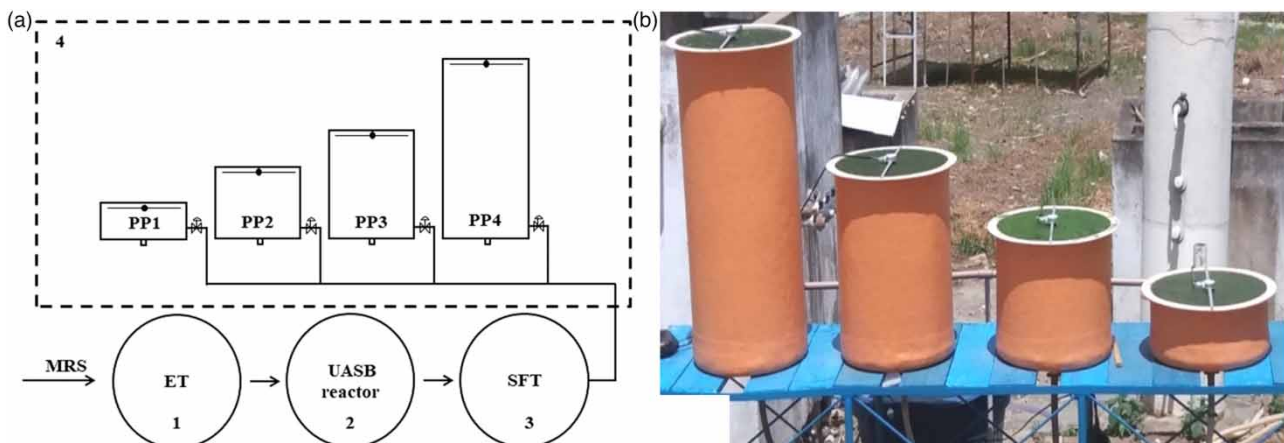
The pH is not only affected by the physical and biological removal of  $\text{CO}_2$ , but also by the desorption of ammonia that occurs when the pH is high. The desorption of  $\text{NH}_3$  is equivalent to the addition of a strong acid, reducing alkalinity and increasing acidity (Cavalcanti 2003).

Most studies with PPs for post treatment of UASB effluent use the flow-through regime. However, Albuquerque *et al.* (2021) showed that using sequential batch polishing ponds (SBPPs) is advantageous because it induces a more rapid elevation of the pH and, consequently, will accelerate the removal of nitrogen, as observed in the papers presented by Cavalcanti (2003) and Albuquerque *et al.* (2021). Moreover, Cavalcanti (2003) showed that bacterial decay (death) in ponds is a first-order process meaning that it is extremely advantageous to use the sequential batch rather than the flow-through regime.

According to Casagli *et al.* (2021), models are powerful tools for understanding, predicting and optimizing wastewater treatment systems. According to Cavalcanti *et al.* (2001), the magnitude of changes in pH in PPs can be predicted by simple stoichiometric rules, if the kinetics of the processes that affect this parameter are known. Thus, the objective of this article is to develop a model that predicts the variation of pH and ammonia desorption in SBPPs, depending on the rates of the processes that affect the pH in ponds and to evaluate the influence of operational conditions (notably the temperature and depth of the ponds).

## 2. MATERIAL AND METHODS

The experimental system for the development of this research consisted of a UASB reactor followed by four SBPPs of different depths, as shown in Figure 1. Municipal raw sewage (MRS) was pumped from the main sewer of the city of Campina Grande. The system comprised the following items:



**Figure 1** | Flowchart of the experimental system (a) and a photograph of the polishing ponds (b). Source: Authors (2022).

- (1) Equalization tank (ET): used for storage and homogenization, from which the sewage was continuously pumped to the UASB reactor.
- (2) UASB reactor: designed for a volume of 2.5 m<sup>3</sup> and a height of 1.7 m, and to treat a flow of up to 10 m<sup>3</sup>/d of sewage.
- (3) Storage and feeding tank (SFT): a fiber glass tank of 1 m<sup>3</sup> for storage the UASB effluent from which it was pumped in batches to fill the PPs.
- (4) Set of SBPPs: Consisting of four ponds made of fiberglass (PP1, PP2, PP3 and PP4), on an experimental scale, with a diameter of 0.5 m and depths of 0.2, 0.4, 0.6 and 1.0 m (volumes of 40, 80, 120 and 200 L) respectively, each pond has a register for filling and individual final effluent disposal. To keep the liquid phase homogeneous, simulating wind action, a slow mechanical stirrer with a thickness of 1 cm and a rotation speed of 6 rpm was installed in each pond. A sequential batch regime was applied, in which at each treatment cycle the treated effluent was discarded and after cleaning the ponds were fed again.

## 2.1. System evaluation and monitoring

The experiments were carried out in the municipality of Campina Grande-PB, located in the geographic area covered by the Brazilian semi-arid climate, where the summers are long, hot and with mostly clear skies. The winters are short, with rainfall and overcast skies. In general, the temperature varies from 20 °C to 32 °C (INMET 2020). Thus, the years can be divided into two periods: a hot period that occurs between September and May and a cold period that occurs between June and August. The experimental investigation was carried out between November 2018 and August 2019. Based on INMET data (2020), the average temperatures were calculated for both monitored periods. For the hot period, the average temperature was 25 °C and for the cold period 21 °C.

The system monitoring comprised these two temperature conditions, with sample collection time set at 9 h for both periods always carrying out daily analyses. Ammonia tests were performed, following procedures described in the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WWF, 2012), and total alkalinity, following the Kapp method described by Buchauer (1998). A multiparameter instrument Hanna HI 98,196 pH/ORP/DO was used to record the dissolved oxygen, pH and temperature values. Table 1 shows information on batches and TDH obtained during the monitoring periods.

## 2.2. Model for pH variation and ammonia desorption in SBPP

Van Haandel & van der Lubbe (2019) showed that the pH in biological reactors is mainly determined by the carbonic systems defined by the alkalinity and acidity. Loewenthal *et al.* (1986) defined alkalinity and acidity as follows:

$$\text{Alk} = 2[\text{CO}_3]^- = [\text{HCO}_3]^- + [\text{OH}]^- - [\text{H}]^+ \quad (1)$$

$$\text{Ac} = 2[\text{CO}_2] + [\text{HCO}_3]^- + [\text{H}]^+ - [\text{OH}]^- \quad (2)$$

Using the definitions of alkalinity and acidity, Deffeyes (1965) showed that for any pH, there is a linear relationship between these two parameters:

$$\text{Alc} = [\text{Ac} + 10^{(\text{pH}-\text{pK}1)} - 10^{-\text{pH}}] * [1 + 2.10^{(\text{pH}-\text{pK}2)}] / [1 + 2.10^{(\text{pK}1-\text{pH})}] \quad (3)$$

**Table 1** | Experimental data for each period of monitoring of the SBPPs

Pond	Hot Period		Cold Period	
	N° Batches	HRT (day)	N° Batches	HRT (day)
PP1	45	5	11	8
PP2	23	10	5	16
PP3	10	16	3	24
PP4	8	30	3	30

In fact, if the pH is in the neutral range ( $5 < \text{pH} < 9$ ), the influence of the carbonic system is predominant and the influence of the  $\text{H}^+$  and  $\text{OH}^-$  can be disregarded so that Equation (3) simplifies to:

$$\text{Alc} \approx \text{Ac} \left[ \frac{1 + 2.10^{(\text{pH} - \text{pK}_2)}}{1 + 2.10^{(\text{pK}_1 - \text{pH})}} \right] \quad (3a)$$

This is an implicit quadratic expression. This can be solved for  $\text{H}^+$ :

$$\text{H}^+ = \frac{\left\{ PK_1 \frac{\left( \frac{\text{Ac}}{\text{Alc}} - 1 \right)}{2} + PK_1 \left[ \frac{\left( \frac{\text{Ac}}{\text{Alc}} - 1 \right)}{2} \right]^2 - 4PK_1 * PK_2 \right\}^{0.5}}{2} \quad (4)$$

Knowing that the pH is the negative logarithm of the  $\text{H}^+$  concentration, one has:

$$\text{pH} = -\log \left\{ \frac{1}{2} * \left[ PK_1 \frac{\left( \frac{\text{Ac}}{\text{Alc}} - 1 \right)}{2} \right] + \left[ PK_1 \left( \frac{\left( \frac{\text{Ac}}{\text{Alc}} - 1 \right)}{2} \right)^2 - 4PK_1 * PK_2 \right]^{\frac{1}{2}} \right\} \quad (5)$$

The processes that develop in SBPPs that affect the pH are the physical and biological  $\text{CO}_2$  removals and  $\text{NH}_3$  removal by desorption. Removing  $\text{CO}_2$  reduces acidity and increases the pH value, while removing ammonia reduces alkalinity. From stoichiometry, the changes in alkalinity and acidity can be calculated as shown in Equations (6) and (7):

$$\Delta \text{Alc} = \Delta \text{N} / 14 \quad (6)$$

$$\Delta \text{Acd} = 2\Delta \text{CO}_2, \text{des} + 2\Delta \text{DO} / 32 + \Delta \text{N} / 14 \quad (7)$$

where:

$\Delta \text{Alc}$ : Alkalinity variation (meq/L);

$\Delta \text{Acd}$ : Acidity variation (meq/L);

$\Delta \text{N}$ : Observed variation of the concentration of ammonia in the pond (mg/L);

$\Delta \text{CO}_2, \text{des}$ : Variation of the  $\text{CO}_2$  concentration due to desorption;

$\Delta \text{DO}$ : Net DO production (photosynthesis - respiration) (mg/L).

In Equations (6) and (7), the magnitude of the pH variation can be determined as a result of alkalinity and acidity variations. In order to know the time required for the processes to develop, the kinetics of the relevant processes should be taken into account. [Morais et al. \(2021\)](#) showed that desorption/absorption processes in pond systems can be adequately described with Fick's Law, which states that the speed of the process is proportional to the inducing force of the process. For the volatile components ( $\text{CO}_2$  and  $\text{NH}_3$ ), the inducing force is the difference between the saturation concentration and the currently existing concentration, according to Equations (8a) and (8b).

$$\text{Ln} \left( \frac{[\text{CO}_2]_s - [\text{CO}_2]}{[\text{CO}_2]_s - [\text{CO}_2]_0} \right) = -k_{\text{dc}} t \quad (8a)$$

$$\text{Ln} \left( \frac{[\text{NH}_3]}{[\text{NH}_3]_0} \right) = -k_{\text{dn}} t \quad (8b)$$

Morais *et al.* (2021) determined the values of the transfer constants as functions of the depth and temperature

$$k_{dc} = (0.56/H)1.056^{(t-20)} \quad (9a)$$

$$k_{dn} = (0.20/H)1.095^{(t-20)} \quad (9b)$$

The CO<sub>2</sub> consumption rate can be conveniently determined from the oxygen production rate in the pond, considering that if 1 mol of oxygen is produced, 1 mol of CO<sub>2</sub> is consumed. The oxygen production rate can be expressed as shown in Equation (10):

$$\text{OPR} = -(d\text{CO}_2/dt)c = (d\text{O}_2/\Delta t)p \quad (10)$$

where:

OPR = (dO<sub>2</sub>/dt)<sub>p</sub> = oxygen production rate in the pond (molO<sub>2</sub>.L<sup>-1</sup>d<sup>-1</sup>)  
 = photosynthesis rate - oxygen consumption rate  
 := biological CO<sub>2</sub> consumption rate (molCO<sub>2</sub>.L<sup>-1</sup>d<sup>-1</sup>).

Equation (10) forms, with Equations (6) and (7), the basis for predicting pH variation and ammonia removal in SBPP. As these differential equations do not have an analytical solution, they must be solved numerically, as presented in van Haandel & van der Lubbe (2019). To do this, the differential equations must be written in terms of finite time elements that cause a finite change in the CO<sub>2</sub> and NH<sub>3</sub> concentrations, as shown in Equations (11) and (12):

$$\frac{\Delta[\text{CO}_2]}{\Delta t} = -Kdc[(\text{CO}_2) - (\text{CO}_2)_s] - \text{OPR} \quad (11)$$

$$\frac{\Delta[\text{NH}_3]}{\Delta t} = \text{NH}_3 - \text{Kdn}[(\text{NH}_3)_0] \quad (12)$$

These variations, in turn, result in alkalinity (Equation (13)) and acidity (Equation (14)) variations and also the change of the undissociated ammonium concentration (Equation (12)), as well as the total nitrogen concentration (Equation (15))

$$\frac{\Delta\text{Alc}}{\Delta t} = -\text{Kdn}[\text{NH}_3] \quad (13)$$

$$\frac{\Delta\text{Ac}}{\Delta t} = -2\{Kdc[(\text{CO}_2) - (\text{CO}_2)_s] - 2\text{TPO} + \text{Kdn}[\text{NH}_3]\} \quad (14)$$

$$\frac{\Delta\text{N}_{\text{tot}}}{\Delta t} = \text{N}_{\text{tot}} - \text{Kdn}[\text{NH}_3] \quad (15)$$

The pH variation can also be calculated from Equation (5) using changes in alkalinity and acidity. Considering that the H<sup>+</sup> and OH<sup>-</sup> concentrations are so low that they do not influence alkalinity and acidity:

Now the basis of a model is created that can describe pH variations, alkalinity, acidity and ammonium concentrations as a function of time in the SBPP. Table 2 summarizes the equations.

In addition to the values of the constant presented in Equations (9a) and (9b), the input data of the model are the characteristics of the UASB effluent used, which are obtained experimentally. The following input data are added to the model: Total ammonia, pH and alkalinity. Acidity can be calculated from pH and alkalinity and entered as input. These values depend on the temperature and depth which are also input data. TPO is not yet defined, but can be measured experimentally as the rate of change in DO concentration (Equation (8)). According to Santos & van Haandel (2021), there seems to be no expression that links the rate of this process to operating conditions, effluent characteristics and climate, and therefore it must be determined experimentally or estimated from previous experiments in similar ponds.

As the temperature conditions change during the year, tests were carried out under two conditions of average temperature and four lakes with different depths for the validation of the model.

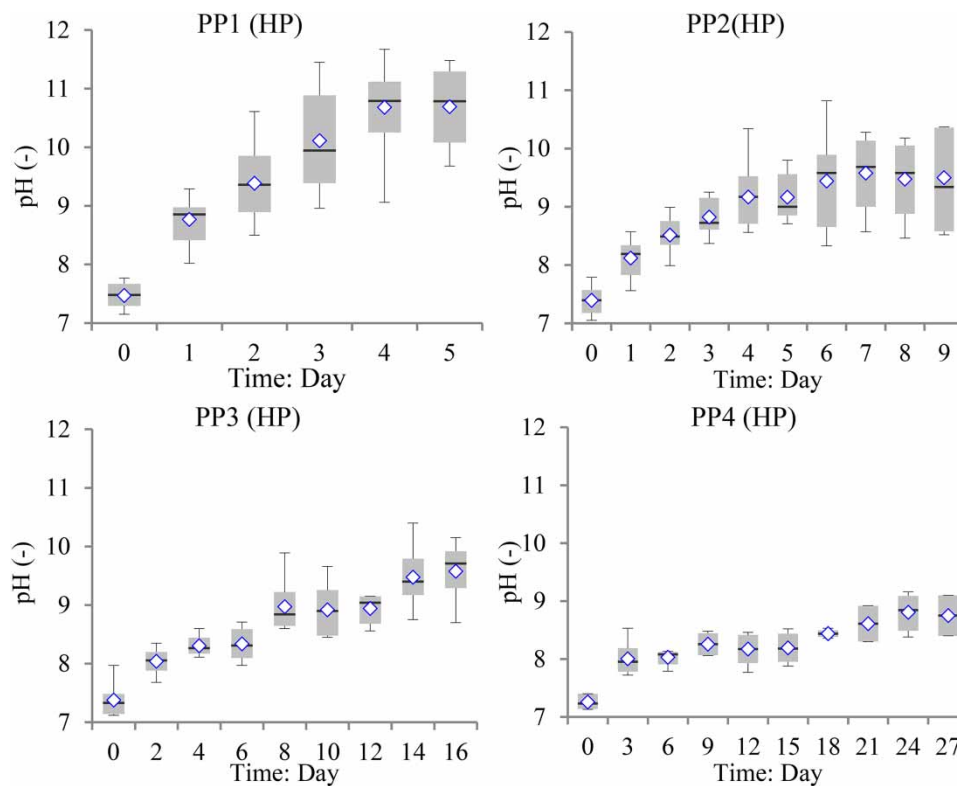
**Table 2** | Equations to calculate oxygen production and CO<sub>2</sub> and NH<sub>3</sub> desorption rates and the change of alkalinity, acidity, pH and ammonium as a function of time in the SBPP

Variable	Equation
DO production rate	$OPR = \Delta O_2 / \Delta t = -(\Delta CO_2 / \Delta t)$
CO <sub>2</sub> desorption rate	$(\Delta [CO_2] / \Delta t)_d = k_{dc}([CO_2] - [CO_2]_s)$
NH <sub>3</sub> desorption rate	$(\Delta [NH_3] / \Delta t)_d = k_{dn}[NH_3]$
Alkalinity variation	$\Delta Alk / \Delta t = -k_{dn}[NH_3]$
Acidity variation	$\Delta Ac / \Delta t = -2\{k_{dc}([CO_2] - [CO_2]_s) - 2TPO + k_{dn}[NH_3]\}$
pH variation	$pH_1 = -\log\{0,5(k_1(Ac_1/Alc_1 - 1)/2 + ((k_1(Ac_1/Alc_1/2)^2 - k_1K_2)^{1/2})\}$
CO <sub>2</sub> variation	$\Delta [CO_2] / \Delta t = -k_{dc}([CO_2] - [CO_2]_s) - TPO$
NH <sub>3</sub> variation	$\Delta [NH_3] / \Delta t = -k_{dn}[NH_3]$
Total N variation	$\Delta N_{tot} / \Delta t = N_{tot} - k_{dn}[NH_3]$

### 3. RESULTS AND DISCUSSION

Figure 2 shows the box-plot graphs of pH throughout the hot period for the four ponds studied. It can be observed that the data have a good homogeneity, since there are no outliers. In addition, the data did not show great discrepancy between the maximums and minimums. The averages and medians are also practically coincident, which indicates the symmetry of the data. This behavior was found for the two analyzed periods, as shown in Figure 3, where the pH data for the four lakes studied during the cold period are presented.

Comparing Figures 2 and 3, it can be seen that the pH tends to rise in both periods, but due to the higher incidence of solar radiation during the hot period, this elevation is faster. For example, for PP3, on day 12 for the hot period, the average pH was

**Figure 2** | pH change in the SBPP during the hot period of the year.

8.9, while for the cold period, the average was 8.5. However, under both conditions, the same behavior was observed for the four lakes, demonstrating that in SBPP, the pH tends to rise with the increase of retention time, which is a condition for nutrient removal. According to *Cavalcanti et al. (2002)*, under favorable conditions (low organic load, intense solar radiation, and high temperature) the consumption of carbon dioxide caused by photosynthetic activity is sufficient to raise the pH to values in the range of 9 to 10, mainly in shallow ponds. High pH values are responsible for ammonia removal (*Gonçalves et al. 2017*).

Figure 4 shows the box-plot graphs referring to the concentration of ammonia in the SBPPs during the hot period. Once more, there is a good homogeneity of the data, with outliers only in PP1. It is apparent that the data did not show great discrepancy between the maximums and minimums. It can also be observed that the means and medians are also practically coincident, which indicates the data symmetry. The same also occurred for the cold period, as seen in Figure 5, in which only PP1 presented outliers. Ammonia removal is attributed to volatilization. Several authors (*Cavalcanti et al. 2002*; *Alves et al. 2011*; *Albuquerque et al. 2021*; *Mahapatra et al. 2022*) claim that this is an effective method for removing nitrogen from ponds.

When analyzing Figures 4 and 5, it appears that the HRT for ammonia removal was lower in the hot period than in the cold period. This behavior was expected and was observed by other researchers such as (*Bastos et al. 2018*) and (*Sutherland et al. 2017*).

### 3.1. Validation of the model to predict the pH variation and ammonium in SBPP

The experimental pH values and ammonium concentration presented in Figures 2–5 can now be compared with simulated values generated by the model in Table 2. Figures 6 and 7 show the curves of simulated data and the experimental values as functions of the retention time for the four ponds and during the warm and cold periods, respectively.

It can be noted that in all cases, there is a close correspondence between the experimental and simulated data, so that it can be concluded that the model can adequately describe both the stoichiometric and kinetic aspects of the processes that affect/promote ammonia desorption in SBPP. It can be seen that as the pH increases in the ponds, there is a reduction in the

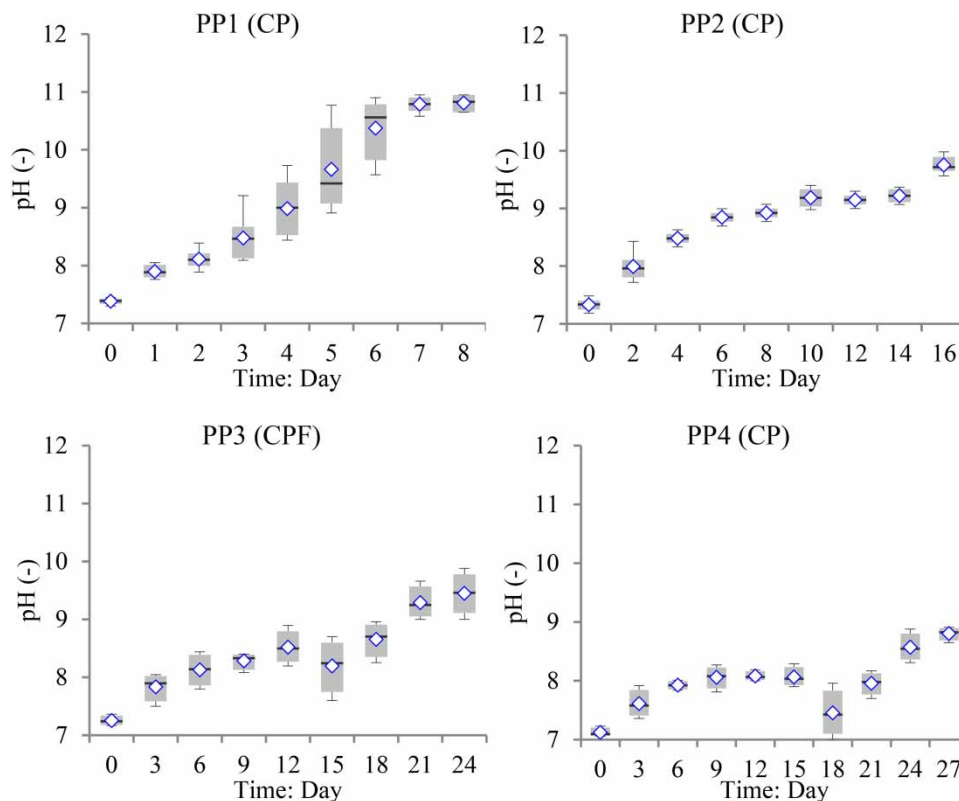
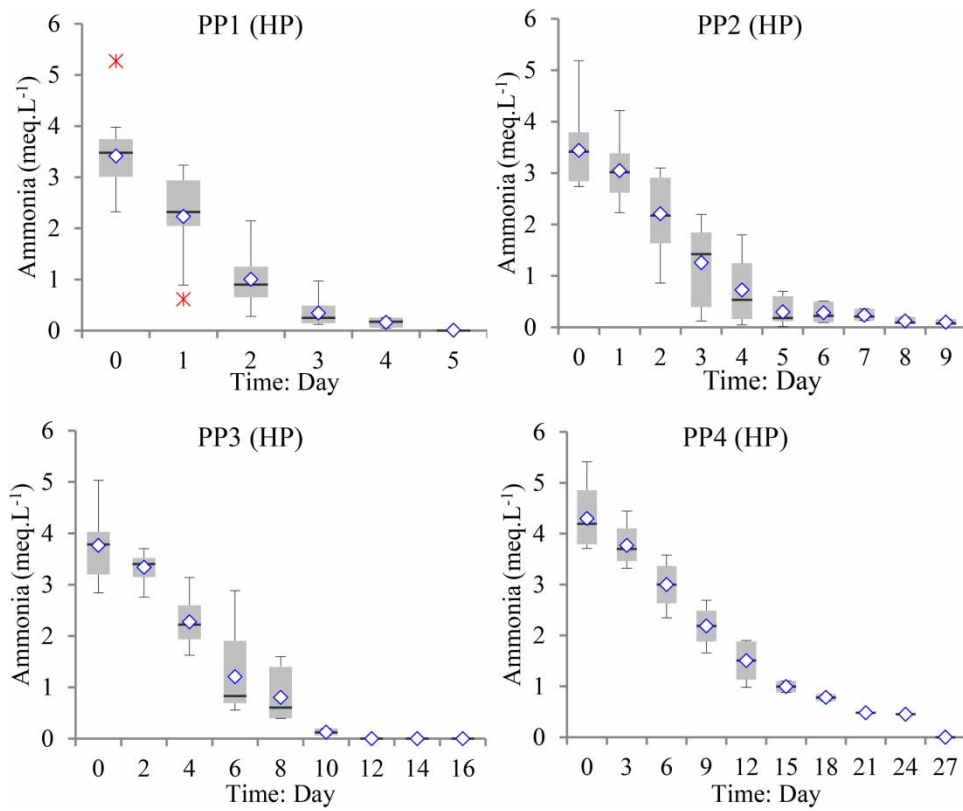
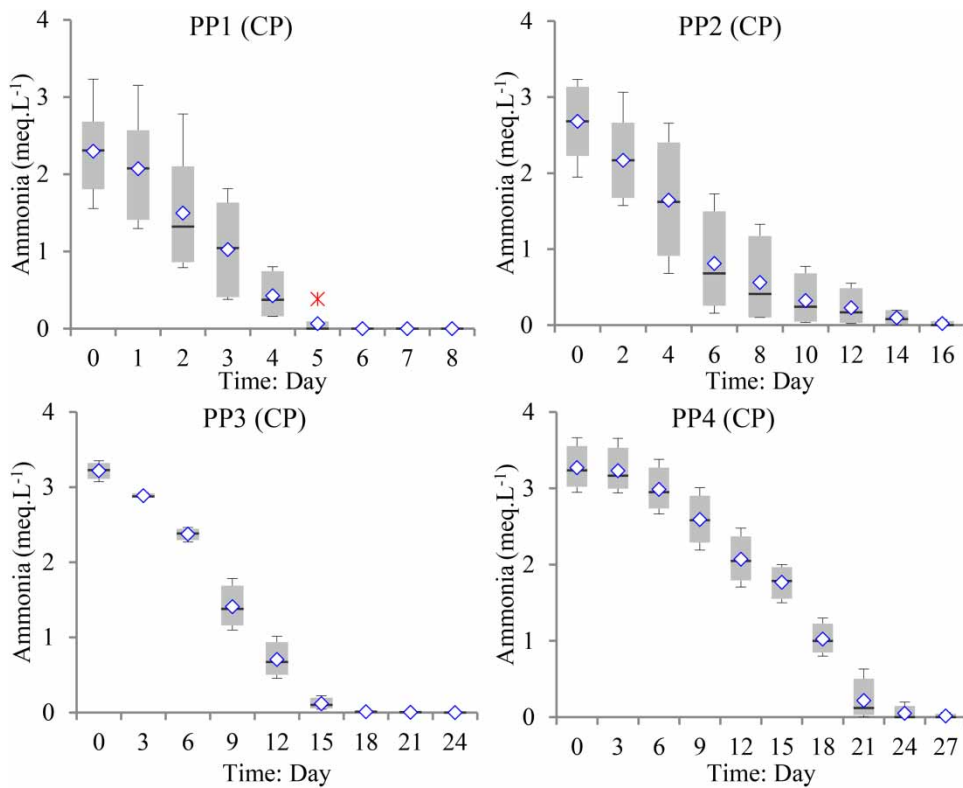


Figure 3 | pH change in the SBPPs during the cold period of the year.



**Figure 4** | Ammonium removal as a function of the retention time in the SBPPs during the hot period.



**Figure 5** | Ammonium removal as a function of the retention time in the SBPPs during the cold period.



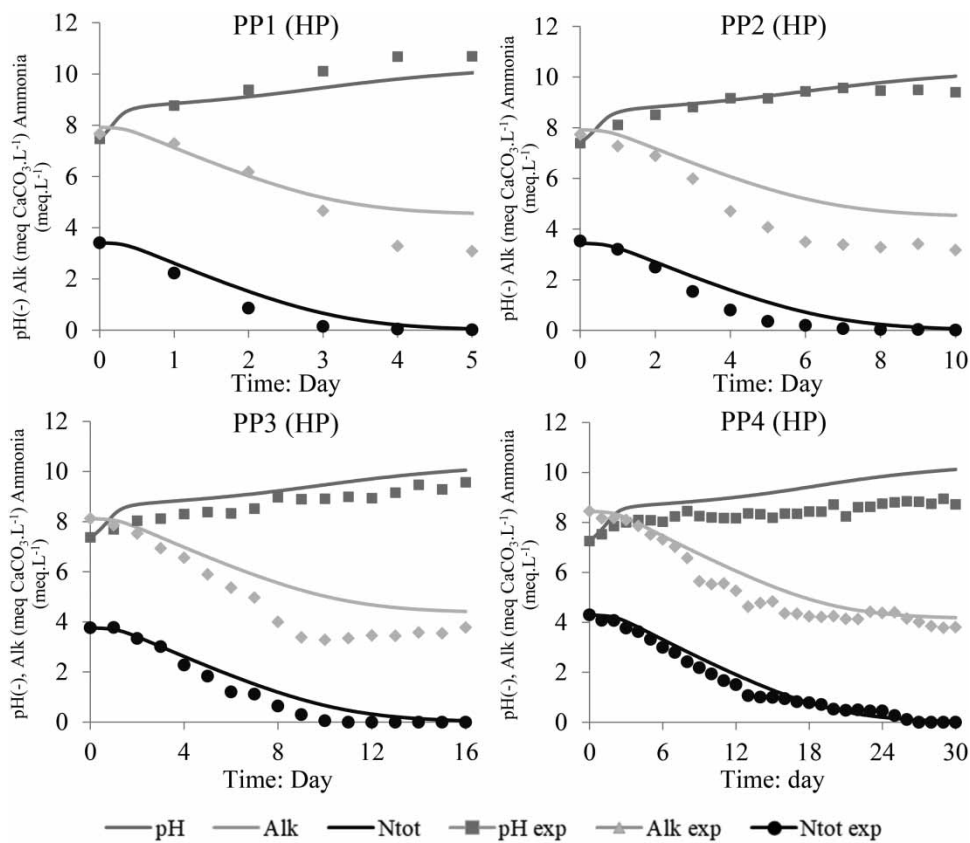
concentration of ammonia and, practically in the same proportion as the desorption of ammonia as the pH rises, the alkalinity is consumed (Bastos *et al.* 2010). In Figure 8, the graphs of the estimated values versus those observed experimentally for the pH in each of the PPs, during the hot period, are plotted.

It can be seen that the model provides a good fit, with an excellent  $R^2$  with no tendency to overestimate or underestimate the values. The model was able to explain 96, 90, 93 and 91% of the data variations observed in lakes PP1, PP2, PP3 and PP4, respectively. Thus, it is clear that there is a high correlation between the data predicted by the model and those obtained experimentally, revealing that the proposed model is feasible to predict the pH variation in SBPP, regardless of the pond's depth. Figure 9 shows the correlation between the estimated data versus those obtained experimentally for the cold period.

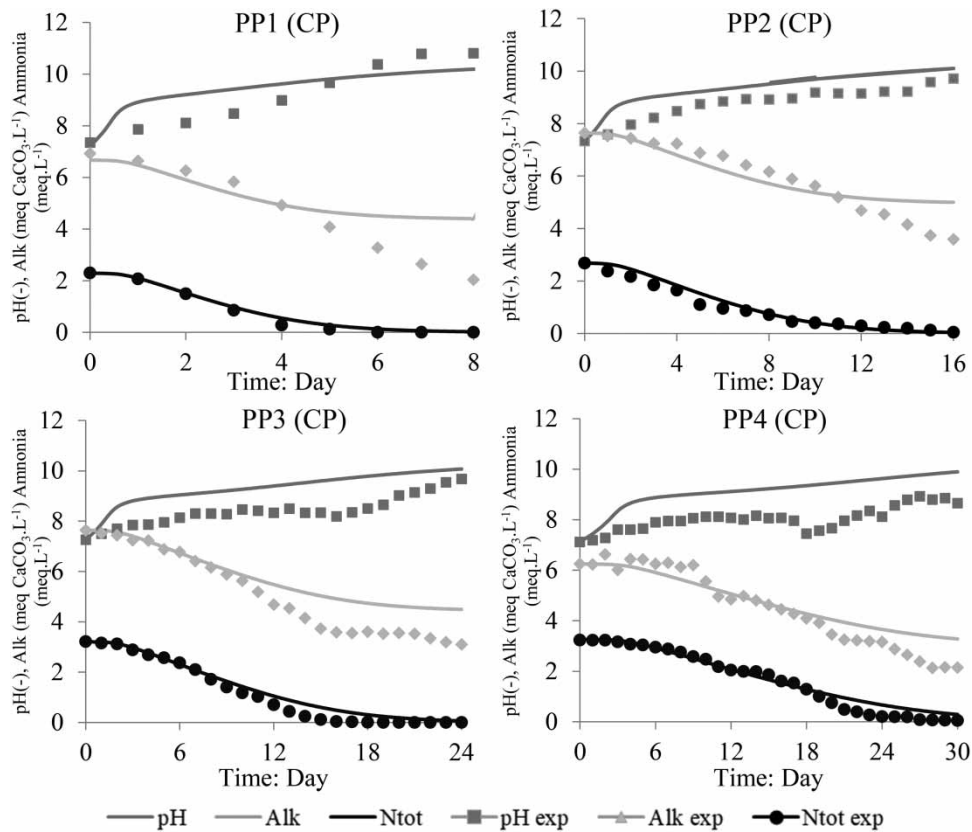
Compared with Figure 8, it appears that the model provided a little lower adjustment than that obtained for the hot period, however it presents a good  $R^2$  value for all lagoons. The model was able to explain 74, 91, 80 and 83% of the data variations observed in lakes PP1, PP2, PP3 and PP4, respectively. Figure 10 shows the graphs of estimated values versus those observed experimentally for ammonia in each of the polishing ponds during the hot period.

It can be noted that the model was able to explain 96, 95, 98 and 98% of the variations between observed and estimated data in lakes PP1, PP2, PP3 and PP4, respectively. Figure 11 shows the correlation between the data estimated based on the model versus those obtained experimentally from ammonia for the cold period. It appears that the model provided a good fit and a very representative  $R^2$  for all lakes, which was able to explain 99, 98, 98 and 98% of the data variations observed in lakes L1, L2, L3 and L4, respectively. This illustrates a strong relationship between estimated and experimental data.

Figures 6 and 7 show that for different depths and temperatures, the pH increase and retention time required to achieve ammonium removal can be predicted. This prediction is confirmed according to Figures 8–11, which show high correlations between the estimated and experimental values. According to Assunção & von Sperling (2012) the definition of parameters that influence volatilization in polishing ponds treating effluents from anaerobic reactors and the establishment of more



**Figure 6** | Experimental data and simulated curves for ammonia, alkalinity and pH as functions of the retention time during the warm period in the four SBPPs.



**Figure 7** | Experimental data and simulated curves for ammonia, alkalinity and pH as functions of the retention time during the cold period in the four SBPPs.

realistic models for this was a gap to be filled. With this work, it is verified that in SBPPs the predominant mechanism of ammonia removal is volatilization, also that this removal can be predicted for different temperatures and depths of polishing ponds.

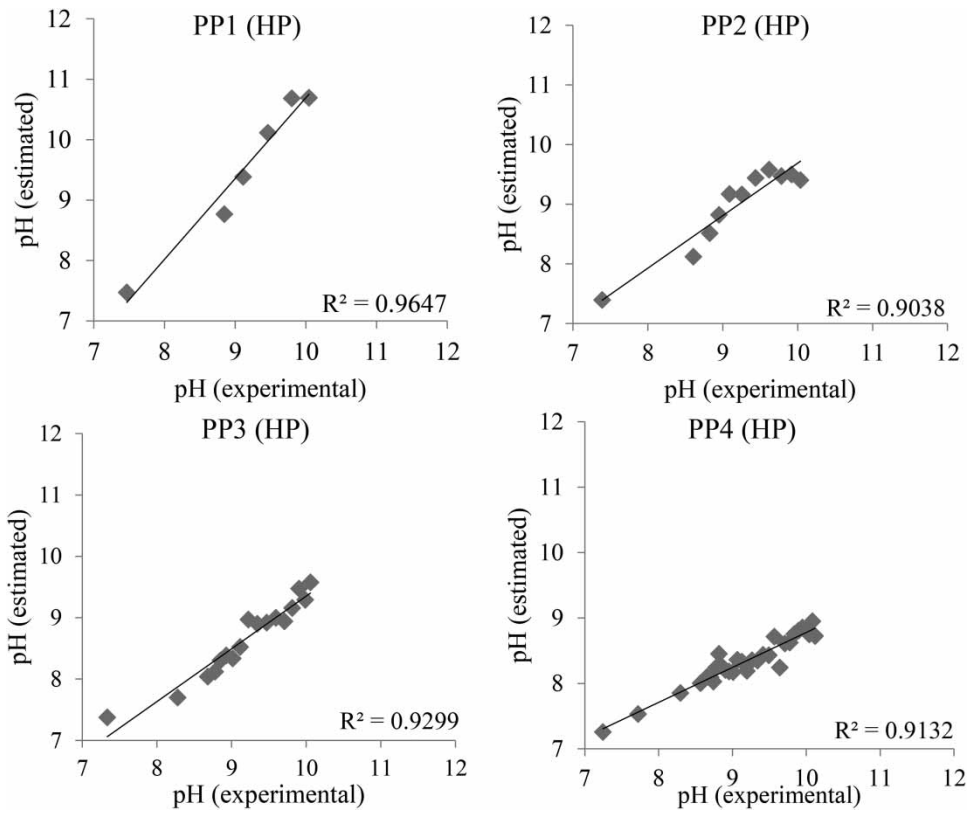
Thus, the proposed model can now be used to evaluate the behavior of this system under a variety of conditions. For different conditions, the retention time for complete or near-complete nitrogen removal can now be predicted using the model for simulating an SBPP under specified conditions of depth, temperature and sewage characteristics.

In practice, what really matters is not the retention time in a pond, but the area needed for treatment. These are related as shown in Equation (16).

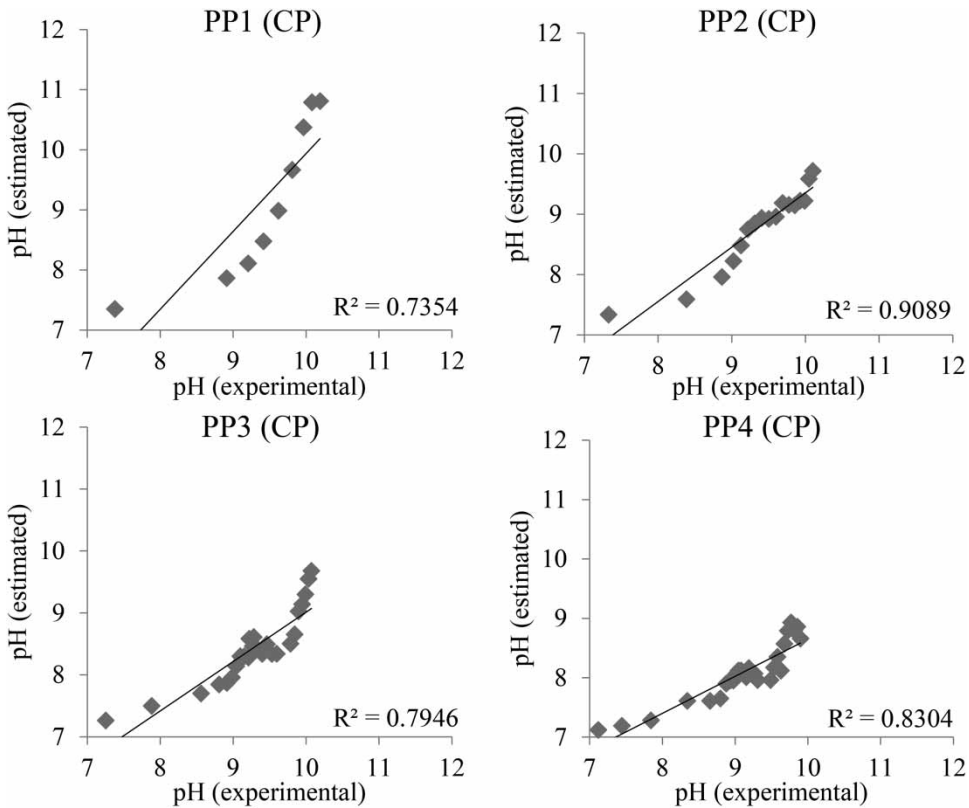
$$A = \left( \frac{\text{HTR} \cdot Q}{H} \right) \quad (16)$$

where: A = required per capita area (m<sup>2</sup> per inhabitant equivalent); HRT = retention time (d); Q = daily sewage production per capita (m<sup>3</sup>hab<sup>-1</sup>dia<sup>-1</sup>) and H = pond depth (m).

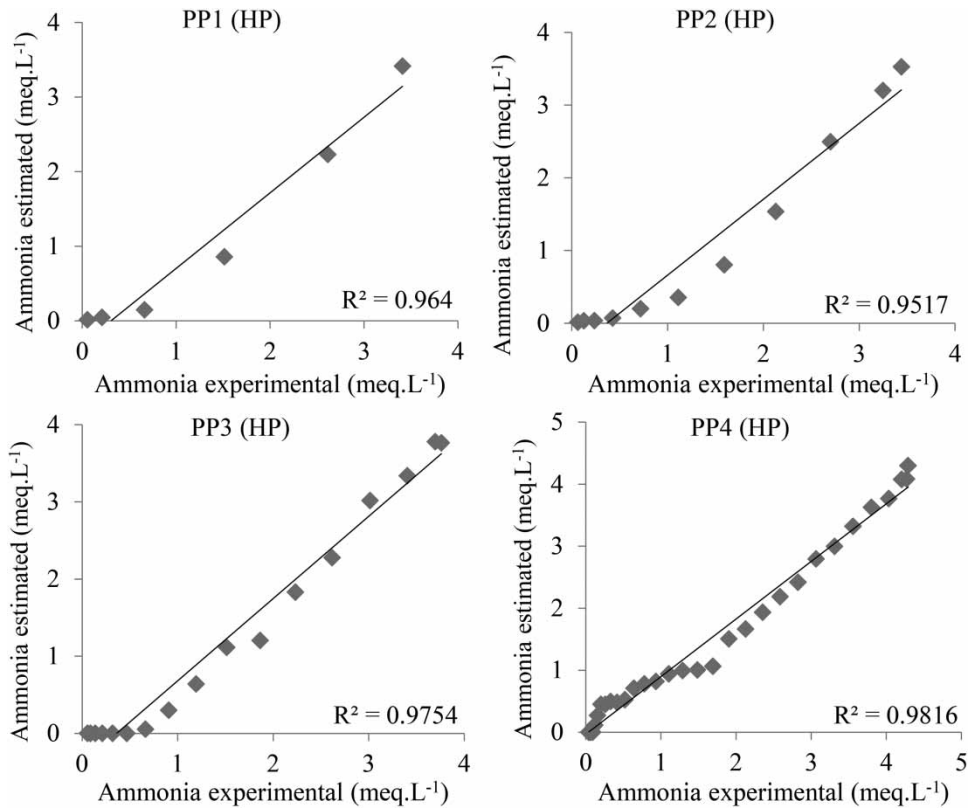
Figure 12 shows the per capita area required for essentially complete ammonia removal as a function of SBPP depth in hot and cold periods. The estimate was assumed for a small or medium city, in which the contribution of domestic effluent per inhab/day is around 100 L (von Sperling 2017) but it can easily be extended for any value by Equation (16). The area normally adopted in WSPs of (3 m<sup>2</sup>/inhabitant equivalent) and retention time (30 d) are also indicated, although in conventional WSPs, nitrogen removal is very poor, even for the large area and long retention time. It can be observed that there is a very large reduction of the SBPPs compared to conventional ponds.



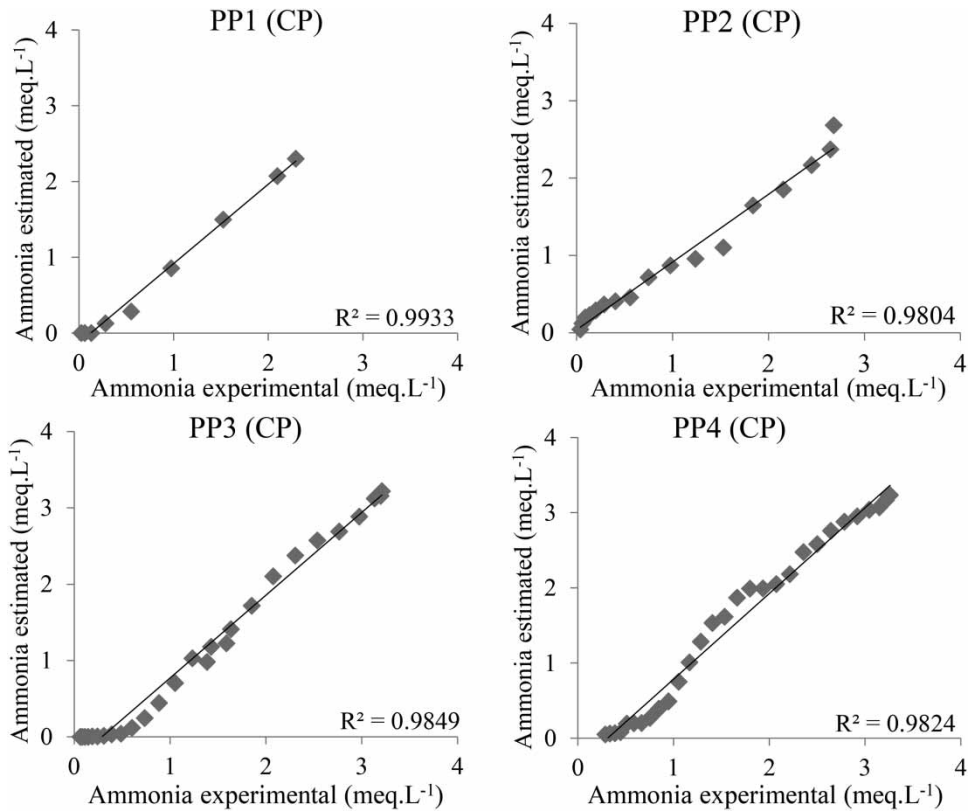
**Figure 8** | Dispersion of estimated versus experimental pH values for the hot period.



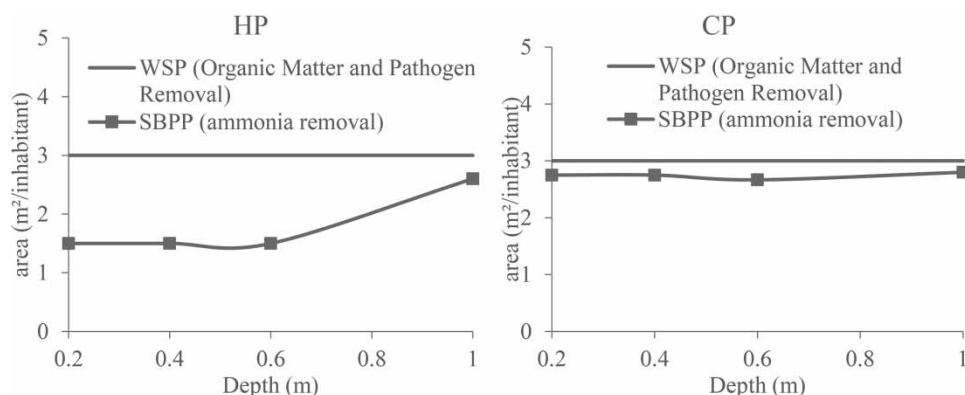
**Figure 9** | Dispersion of estimated versus experimental pH values for the cold period.



**Figure 10** | Dispersion of estimated versus experimental ammonia values for the hot period.



**Figure 11** | Dispersion of estimated versus experimental ammonia values for the cold period.



**Figure 12** | Per capita area of SBPP as a function of depth for ammonia removal in hot and cold periods.

#### 4. CONCLUSIONS

Assuming that the variation of the ammonium concentration in sequencing batch polishing ponds is a first-order process that can be described by Fick's law and that the pH in these ponds can be calculated from stoichiometric calculations, a model was developed for the variation of these parameters as functions of time.

The proposed model was validated by the good correspondence of simulated values and experimentally obtained values as functions of time for a variety of operating conditions. For temperatures in the warm and cold period, it was observed that the model could predict well the pH variation and ammonia concentration for different depths. The definition of a model that could predict the removal of ammonia in PPs in the post-treatment of UASB reactor effluent was a gap to be filled.

Thus, it becomes feasible to use the predictive model to estimate the pH variation and the ammonia removal in SBPPs for different depths, temperatures, and sewage characteristics, obtaining the necessary HRT with good precision.

The experimental results also show that the required area for SBPPs is much smaller than for conventional WSPs.

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#### DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

#### CONFLICT OF INTEREST

The authors declare there is no conflict.

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