Influence of temperature and pH on nitrogen removal in a series of maturation ponds treating anaerobic effluent

Fernando Augusto Lopes de Assunção and Marcos von Sperling

ABSTRACT

This paper presents an evaluation of the influence of pH and temperature on nitrogen removal in a series of three shallow maturation ponds serving as post-treatment of upflow anaerobic sludge blanket (UASB) reactor effluent (approximately 200 population equivalent). Monitoring was from January 2007 to May 2009. Throughout this period, the ponds maintained relatively stable operational conditions in terms of depth and hydraulic retention time, thus enabling the evaluation of the influence of variations in temperature and pH on the performance in terms of nitrogen removal. In general, as expected, the removal of nitrogen was more effective when the temperature and pH of the ponds were higher, implying that these variables are relevant in the removal of nitrogen. Due to the fact that these parameters are included in the prediction equations for effluent ammonia and total nitrogen found in traditional models from the literature, fitting of the models to the experimental data was investigated. The models gave acceptable fittings in the estimation of effluent concentrations of ammonia and total nitrogen from maturation ponds treating UASB reactor effluent.
Key words | ammonia, maturation ponds, nitrogen, pH, sewage, temperature

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INTRODUCTION

Maturation ponds are widely known for their high capacity in removing pathogens from sewage (Mara 2003), and this is usually the major reason for their inclusion in the last stage of treatment lines which are based on stabilization ponds. However, maturation ponds are also capable of achieving good removal efficiencies in terms of ammonia and total nitrogen, and this is the main focus of this paper. The main mechanisms for nitrogen removal in pond systems are reported to be: (i) ammonia volatilization, (ii) ammonia and nitrate assimilation by algae and consequent organic nitrogen sedimentation, followed by its retention in the pond bottom sludge and (iii) nitrification–denitrification. These mechanisms may act simultaneously and with variable degrees of importance, depending on the characteristics of the ponds and local weather conditions (Ferrara & Avci 1982; Pano & Middlebrooks 1982; Reed 1985; Senzia *et al*. 2002; Craggs 2005; Camargo-Valero & Mara 2006; Camargo-Valero 2008). Regardless of the prevailing mechanism, all of them are directly associated with the climatic and environmental factors affecting the ponds. Thus, parameters such as temperature and pH of the ponds can be directly related to higher or lower removal efficiencies.

Some models available in the literature associate the removal efficiencies of ammonia and nitrogen to these two parameters. Reed (1985) proposed a model which estimates the total nitrogen effluent concentration as a function of pH, temperature and hydraulic retention time in each pond, according to Equation (1).

$$C_e = \frac{C_0}{1 + t(0.000576T - 0.00028)e^{(1.08-0.042T)(\mathrm{pH}-6.6)}} \quad (1)$$

where: C_e = total nitrogen concentration in pond effluent (mgN/L), C_0 = total nitrogen concentration in pond influent (mgN/L), t = hydraulic retention time in the pond (d), pH = pH in the pond, T = temperature of the liquid in the pond (°C).

Temperature and pH are also included in the model developed by Pano & Middlebrooks (1982) for the prediction of effluent ammonia concentrations. However, instead of hydraulic retention time, the model uses the

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reciprocal of the surface hydraulic loading rate. There are two equations, one for temperatures below 20 °C (Equation (2)) and the other for temperatures ranging from 21 to 25 °C (Equation (3)).

$$C_e = \frac{C_0}{1 + (A/Q).(0.0038 + 0.000134T)e^{(1.04+0.044T)(\mathrm{pH}-6.6)}} \quad (2)$$

$$C_e = \frac{C_0}{1 + 5.035 \times 10^{-3}.(A/Q).e^{(1.540.(\mathrm{pH}-6.6))}} \quad (3)$$

where: C_e = ammonia concentration in pond effluent (mgN/L), C_0 = ammonia concentration in pond influent (mgN/L), Q = flow (m³/d), A = surface area of the pond (m^2).

The present study aims to evaluate the influence of these two parameters (pH and temperature) in the removal of ammonia and nitrogen in maturation ponds, as well as comparing the mean values observed during the 28 months of monitoring with the values estimated by well-known prediction models from the literature (Equations (1)–(3)). The main reason for the study is the fact that the two cited models have been derived for environmental conditions different from those of the present study (tropical region) and with different pond types (here, maturation ponds following upflow anaerobic sludge blanket (UASB) reactor). Therefore, there is a need for deepening the knowledge on factors affecting nitrogen removal in the variant ponds covered in this study.

MATERIAL AND METHODS

The research was carried out at the experimental sewage treatment plant UFMG/Copasa, which belongs to CePTS (Centre for Research and Training in Sanitation), located at Arrudas wastewater treatment plant in the city of Belo Horizonte, Brazil (coordinates 19°53′42″ S and 43°52′42″ W). The system receives typical sanitary sewage. The experimental apparatus consisted of a UASB reactor, followed by a series of three polishing ponds and a coarse rock filter installed at the final third of the last pond in the series (Figure 1).

The treatment system was designed to treat a population equivalent of 200 inhabitants. The UASB reactor has a net height of 4.5 m and a diameter of 2.0 m, and operates with an average influent flow of 29 m^3/d and hydraulic retention time of 11.7 hours. The three polishing ponds operated in

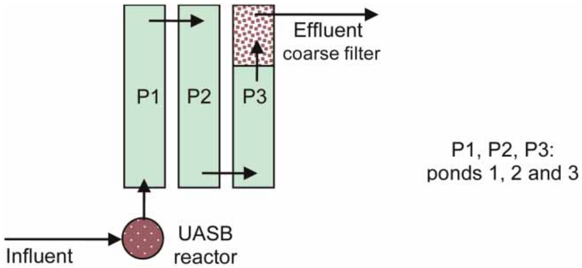

Figure 1 | Flowchart of the treatment system investigated.

series and their main characteristics are presented in Table 1.

Monitoring of the system was performed from January 2007 until May 2009, by physico-chemical analyses of samples of raw sewage and effluents from the UASB reactor, the three polishing ponds and the rock filter. The sampling of the raw sewage and the effluent from the UASB reactor was carried out through composite sampling, using automatic samplers that collected sewage hourly, amounting to around 5 L in 24 hours. For the pond effluent, sampling was performed at the outlet end by a column sampler along its depth, which is generally assumed as giving a good approximation to composite samples. The collection of samples and measurements took place weekly or fortnightly at 10 a.m. The number of samples (n) was around 50 for fortnightly samples and around 100 for weekly samples.

Physico-chemical analyses of biochemical oxygen demand (BOD) (total and filtered), chemical oxygen demand (COD) (total and filtered), suspended solids (total and fixed), total Kjeldahl nitrogen (TKN), ammonia, nitrite, nitrate, turbidity, total phosphorus and phosphate were

Table 1 | Physical and operational characteristics of the maturation ponds and rock filter

Characteristics	Unit	Pond 1	Pond 2	Pond 3	Filter
Length at bottom	m	25.0	25.0	16.5	8.5
Width at bottom	m	5.3	5.3	5.3	5.3
Liquid height	m	0.8	0.8	0.4	0.4
Embankment slope	°	45	45	45	45
Surface area (A)	m^2	184	184	138	56
Mean influent flow (Q)	m^3/d	29.0	29.0	29.0	29.0
Mean hydraulic retention time ($t = V/Q$)	d	4.3	4.3	1.5	0.6
Mean hydraulic loading rate (HLR = Q/A)	m^3/(m^2 d)	0.15	0.15	0.22	0.52

carried out from all sampling points. The samples were preserved in ice and transported for processing at the laboratory, according to recommendations by the *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA & WEF 1998). Measurements of pH and temperature were performed for the raw sewage and UASB reactor effluent. Measurements of pH, temperature and dissolved oxygen (DO) at a 20 cm depth were made for the ponds.

RESULTS AND DISCUSSION

General evaluation

The arithmetic means of the main parameters monitored in the 28-month period are presented in Table 2. The table shows that influent raw sewage can be considered diluted when compared to the concentrations of BOD, COD and total suspended solids (TSS) typically found in sanitary sewage – BOD ranging from 200 to 400 mg/L, COD between 400 and 800 mg/L and TSS between 250 and 400 mg/L (von Sperling & Chernicharo 2005). The concentrations of organic matter and suspended solids do not present a substantial decrease throughout the pond system, due to the production of organic solids (algae) in the ponds. Only the rock filter assists in further decreasing BOD, COD and TSS.

The fractions of nitrogen (organic, ammonia, nitrite and nitrate) throughout the treatment line indicate higher concentrations of ammonia followed by organic nitrogen, with the oxidized forms presenting low values (Figure 2). Ammonia concentration increased in the UASB reactor due to ammonification of organic nitrogen (see Table 2). A gradual reduction of ammonia throughout the polishing ponds was also observed (Figure 3). As expected, the rock filter played no important role in the N conversion processes. Organic N concentrations showed little variation along the system (Figure 4). Total nitrogen followed a similar behaviour to that observed for ammonia (Figure 5).

The removal efficiencies of ammonia, TKN and total nitrogen, calculated on the basis of the mean values presented in Table 2, are listed in Table 3. It can be observed that each pond makes its contribution to the removal of these nitrogen forms in the order of 20–30%. No data are presented for nitrites and nitrates, because, strictly speaking,

Table 2 | Mean values of the main parameters monitored throughout the treatment system

Parameter	Unit	Raw sewage	UASB	Pond 1	Pond 2	Pond 3	Rock filter
Total BOD	mg/L	161	64	57	68	78	58
Filtered BOD	mg/L	63	27	17	18	18	18
Total COD	mg/L	389	195	150	155	171	128
Filtered COD	mg/L	174	82	69	72	66	58
TSS	mg/L	191	85	56	59	95	49
Fixed suspended solids	mg/L	36	25	9	8	14	8
Volatile suspended solids	mg/L	155	60	47	52	67	41
Organic N	mgN/L	9	8	7	5	4	5
Ammonia N	mgN/L	26	30	23	16	12	13
Nitrite	mgN/L	0.13	0.07	0.20	0.81	0.98	0.81
Nitrate	mgN/L	0.11	0.14	0.15	0.34	0.31	0.17
TKN	mgN/L	34	37	30	21	15	18
Total N	mgN/L	34	39	30	22	16	19
Total phosphorus	mgP/L	1.69	1.73	1.97	1.95	1.96	1.96
Phosphate	mgP/L	0.80	0.89	0.90	0.84	0.78	0.88
Turbidity	NTU	129	79	31	39	48	42
pH	–	7.1	7.0	7.7	8.1	8.4	7.7
Temperature	°C	21.1	21.1	23.6	23.7	23.3	23.0
DO	(mg/L)	–	–	9.5	10.1	9.3	1.7

The number of samples (*n*) in each sampling point ranges from about 50 to 100 depending on the parameter

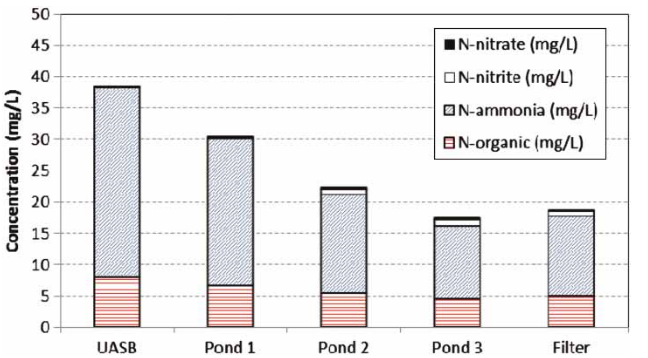

Figure 2 | Mean values of the different nitrogen fractions throughout the treatment units.

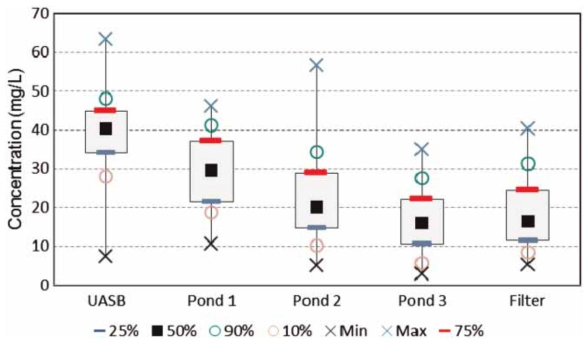

Figure 5 | Box-plot of total N concentration throughout the treatment units.

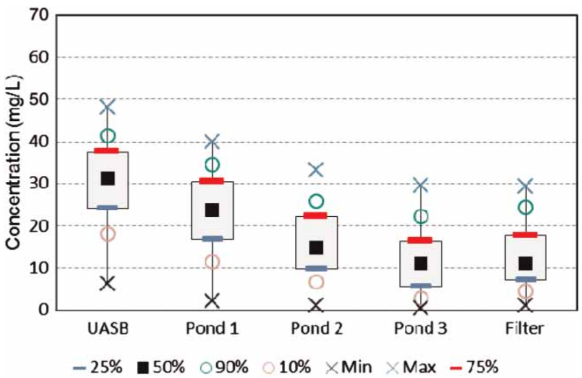

Figure 3 | Box-plot of ammonia N concentrations throughout the treatment units.

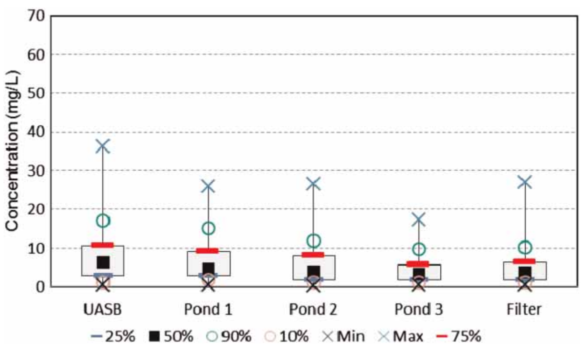

Figure 4 | Box-plot of organic N concentration throughout the treatment units.

there was no removal, but rather production (although very small).

The temperatures observed during monitoring varied depending mainly on the seasons of the year, with the months from April to September being marked by mild temperatures (average temperature of raw sewage of 18.6 °C), while in the months of October to March higher temperatures were observed (average temperature of raw sewage of 23.7 °C). The temperature variation monitored at a depth of 20 cm at 10 a.m. along the pond series is

Table 3 | Mean removal efficiencies (%) of nitrogen fractions throughout the pond system

Parameter	Pond 1	Pond 2	Pond 3	Global ponds
Ammonia	23	30	25	60
TKN	19	30	29	59
Total N	23	27	27	59

presented in Figure 6, with almost no variation throughout the system.

The pH exerts direct influence on the ammoniacal nitrogen equilibrium. When pH increases, the equilibrium between the ammonium ion (NH_4^+) and free ammonia (NH_3) tends to shift towards the formation of free ammonia, i.e., its gaseous form can escape into the atmosphere. The pH variation observed throughout the polishing ponds is presented in Figure 7. It is observed that the pH tends to increase over the series of ponds, probably due to the predominance of photosynthesis over respiration, especially in Pond 3, which operated at lower depth (0.6 m). Algal photosynthesis removes CO_2 from the liquid, therefore reducing carbonic acidity and increasing pH.

It is known that temperature and pH vary during the day, as influenced by day/night time conditions. This

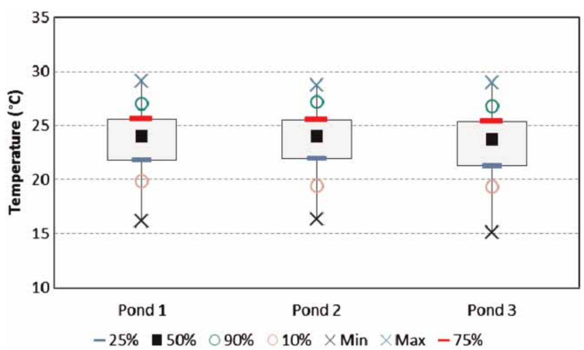

Figure 6 | Box-plot of temperature throughout the ponds.

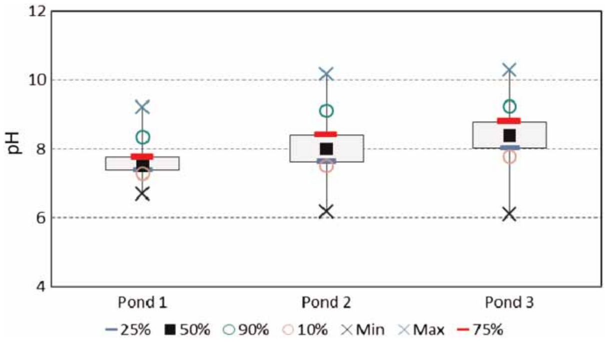

Figure 7 | Box-plot of pH throughout the ponds.

hourly variation cannot be assessed at this study, since measurements were done around 10:00 a.m. The conditions in this hour reflect the influence of the preceding night, but also the onset of important photosynthetic activity. Influence of day and night conditions on the removal of ammonia can be found at another study in this same pond system (Chiatti & von Sperling 2012).

The surface loading rates in the ponds (BOD and ammonia) are presented in Figures 8 and 9. The average organic loading rates were 70, 58 and 76 kgBOD/(ha d) for Ponds 1, 2 and 3, respectively. Taking into consideration the tropical conditions of the study area, it is observed that the maturation ponds operated with typically low surface organic loads. This enables the predominance of photosynthesis over respiration, leading to an increase in pH and dissolved oxygen. The surface organic load of Pond 3 was slightly higher because it had a smaller surface area.

Influence of temperature and pH in the removal of ammonia

In order to verify the influence of temperature in the removal of ammonia in the ponds, average effluent concentrations from each pond were separated by temperature range measured during the period (<20 °C; 20–22 °C; 22–24 °C; 24–26 °C; >26 °C). One can see from Figure 10 that there are lower average effluent concentrations of ammonia when the temperatures are higher. The non-parametric Kruskal–Wallis test was applied in order to see whether there are significant differences between the median values of effluent ammonia concentration among the five different temperature ranges. The *p*-values obtained were all well below 0.05 (0.0001 for Pond 1; 0.0000 for Pond 2; 0.0000 for Pond 3), indicating that, for all the ponds, the median effluent ammonia concentrations were significantly different in the five temperature ranges.

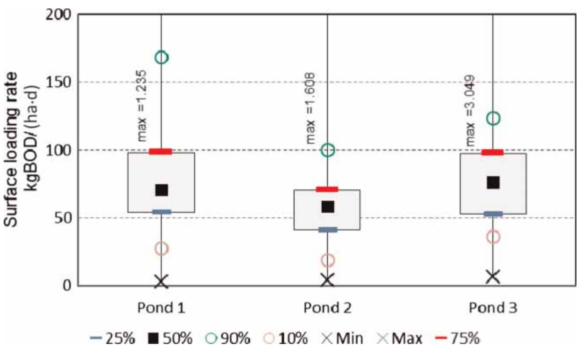

Figure 8 | Box-plot of surface loading rate of BOD throughout the ponds.

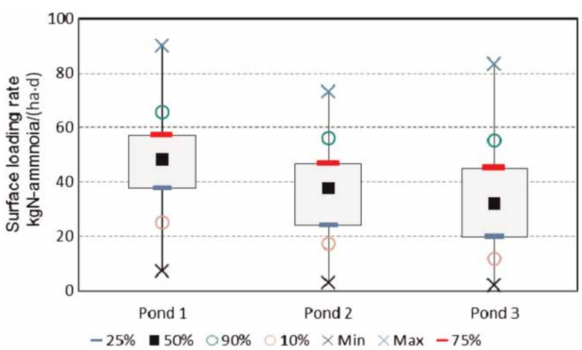

Figure 9 | Box-plot of surface loading rate of ammonia throughout the ponds.

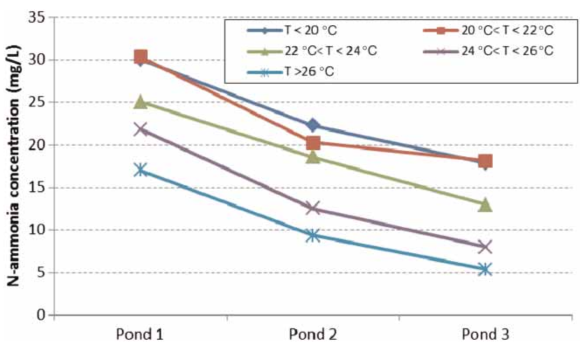

Figure 10 | Concentration of ammonia as a function of temperature ranges in the ponds.

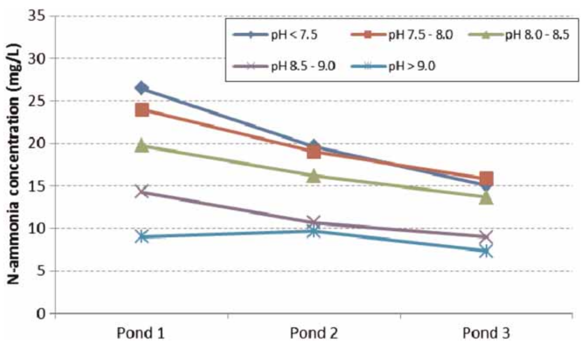

Figure 11 | Concentration of ammonia as a function of pH ranges in the ponds.

The influence of pH can be seen from Figure 11, which separates the mean effluent ammonia concentrations for five different pH ranges (<7.5; 7.5–8.0; 8.0–8.5; 8.5–9.0; >9.0). Lower average concentrations of ammonia were observed when the pH was higher. Again, the Kruskal–Wallis test was applied in order to see whether there are significant differences between the median values of effluent ammonia concentration among the five different pH ranges. The *p*-values obtained were all below 0.05 (0.0293 for Pond 1; 0.0492 for Pond 2; 0.0018 for Pond 3), indicating that, for all the ponds, the median effluent ammonia concentrations were significantly different in the five pH ranges.

Fitting of existing models to the experimental data

The experimental data were fitted to the Pano & Middlebrooks (1982) model for estimating mean effluent ammonia concentrations (Equation (2) or (3), depending on the measured temperature). These equations are based on the temperature, pH and hydraulic load in the pond. Figure 12 presents the plot of observed versus estimated ammonia values in each of the maturation ponds. Despite the natural dispersion of the observed data, the model gives a reasonably good fit, without tendencies of over or under estimation. Based on the coefficients of determination (CoD) presented in the figures, the model was able to explain 46, 47 and 66% of the variances of the data observed in Ponds 1, 2 and 3, respectively.

Similarly, the suitability of the model developed by Reed (1985) for completely mixed conditions (Equation (1)) was tested in the estimation of the total nitrogen concentration in the maturation ponds under study. Figure 13 presents the plot of observed versus estimated nitrogen values in each of the ponds. The CoD indicate that the model explained 47, 71 and 85% of the variances in Ponds 1, 2 and 3, respectively. It may be considered that the model gave a good fit, mainly in the last two ponds.

CONCLUSION

The three maturation ponds in series presented good efficiency in the removal of nitrogen forms, with overall average removal efficiencies of 60, 59 and 59% for ammonia, TKN and total nitrogen, respectively. The average effluent concentrations in the last pond in the series were:

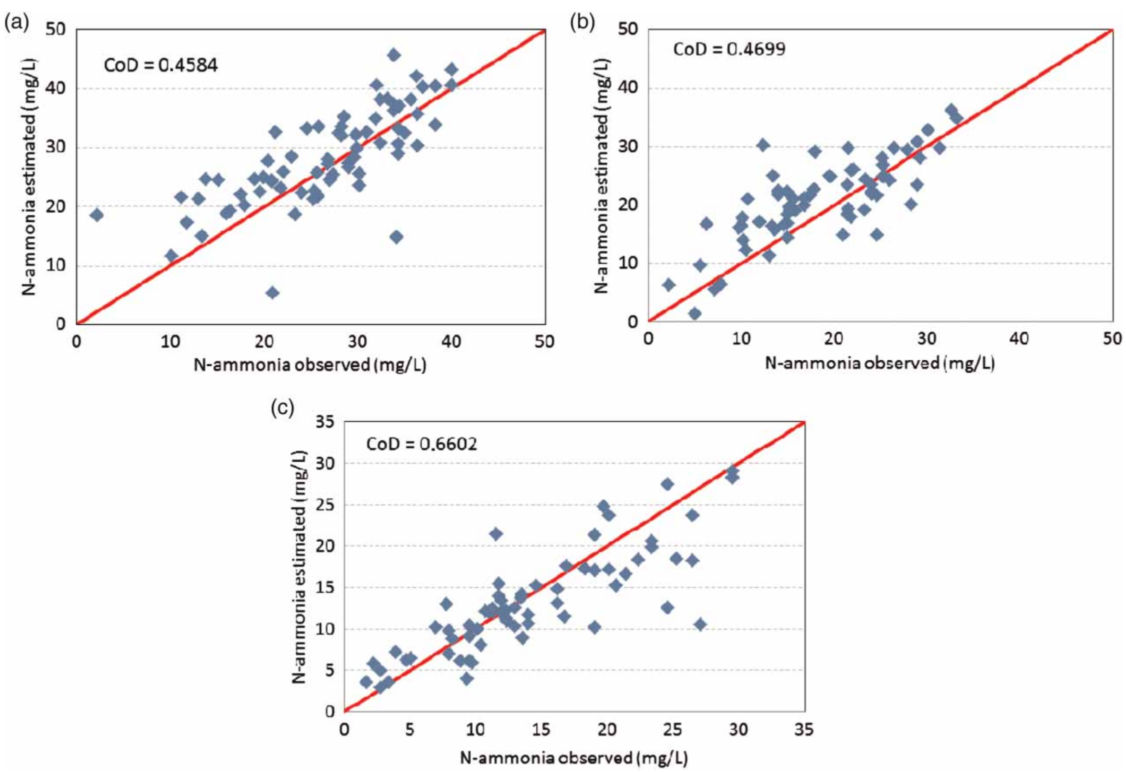

Figure 12 | Observed values vs estimated values of ammonia in Ponds 1, 2 and 3, according to the Pano and Middlebrooks model. (a) Pond 1, (b) Pond 2 and (c) Pond 3.

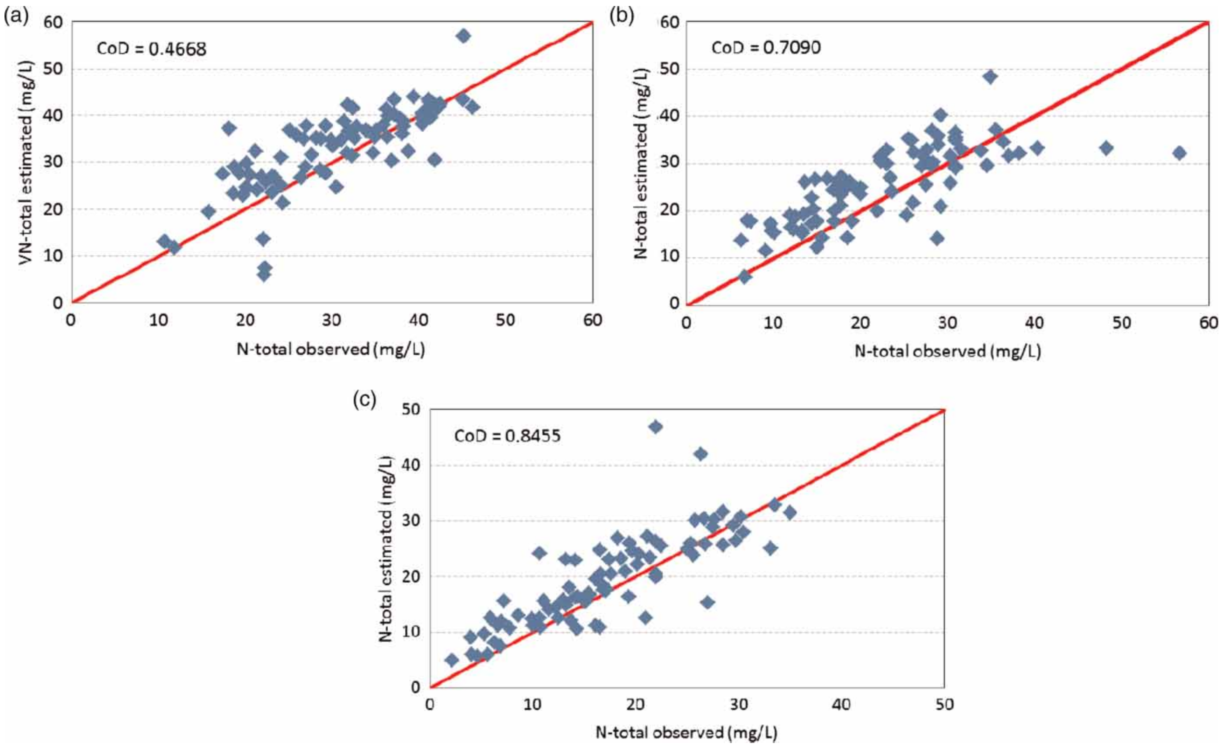

Figure 13 | Observed values vs estimated values of total nitrogen in Ponds 1, 2 and 3, utilizing the Reed model. (a) Pond 1, (b) Pond 2 and (c) Pond 3.

organic nitrogen = 4 mg/L, ammonia = 12 mg/L, nitrite = 1.0 mg/L, nitrate = 0.3 mg/L.

Temperature and pH showed a significant relationship with the effluent ammonia concentrations from the three ponds. The concentrations of ammonia observed in the ponds' effluents were lower in periods in which the temperature and pH were higher. As expected, such parameters are closely related to the removal of this fraction of nitrogen in pond systems.

Although the models developed by Pano–Middlebrooks and Reed were based on studies in facultative ponds, they gave good fit to the observed values in the maturation ponds, having demonstrated good predictive capacity for effluent concentrations of ammonia and total nitrogen.

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