Artículo original de investigación

Treatment of piggery wastewater in experimental high rate algal ponds

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Abstract

The objective of this work was to evaluate the efficiency of high rate algal ponds (HRAP) for the treatment of piggery wastewater pretreated with an electroflocculation system. Experiments were conducted in two experimental raceway ponds with a surface area of 1.54 m^2 and a water depth of 0.26 m. The efficiency of both ponds was compared as a function of the surface organic loading rate and ammonia loading rate. Pretreated piggery wastewater had average COD and ammonia concentrations of 3000 mgO_2/L and 790 $mgNH_4^+$-N/L, respectively. The COD removal was 90 % with an organic loading equal to or below 20 g O_2/m^2d. The ammonia removal was 90 % with an ammonia load of 2.5 gNH_4^+-N/m^2d, however it decreased throughout the experiments when ammonia accumulated in the mixed liquor. Simultaneous COD and ammonia removal was limited by ammonia removal. From a mass balance it was determined that the main pathway for ammonia removal was nitrification.

Keywords: *High rate ponds, high rate oxidation ponds, microalgae, wastewater, culture, settling, swine slurry*

Tratamiento de aguas residuales porcícolas en lagunas de algas de alta tasa a nivel experimental

Resumen

El objetivo principal de este estudio fue evaluar la eficiencia de las lagunas de algas alta carga para el tratamiento de purines de cerdo previamente tratados con un sistema de electroflocculation. Los experimentos se realizaron en dos lagunas en forma de carrusel, con una superficie de 1,54 m^2 y una profundidad de 0.26 m. La eficiencia de ambas lagunas se comparó en función de la carga orgánica y de amonio. Los purines de cerdo tenían una concentración media de DQO de 3000 mgO_2/L y de amonio de 790 mgN-NH_4^+/L. La eficiencia de eliminación de DQO fue del 90% cuando la carga orgánica fue de 20 g O_2/m^2d o menor. La eficiencia de eliminación de amonio fue del 90% cuando la carga de amonio fue de 2.5 gN-NH_4^+/m^2d, pero disminuyó a lo largo de los experimentos debido a la acumulación de amonio en el líquido de mezcla. La eliminación simultánea de DQO y amonio estuvo limitada por la eliminación de amonio. A partir de un balance de masas se estimó que la principal vía de eliminación de amonio fue la nitrificación.

Palabras clave: *Lagunas de alta tasa, microalgas, aguas residuales, cultivo, decantación, residuos porcícolas*

1. Introduction

Piggery wastewater is generated as a result of intensive pig breeding. The uncontrolled disposal of pig slurries and manure prompts surface water eutrophication and groundwater pollution due to their high concentration of organic matter and nutrients. Piggery wastewater can be treated by means of microalgae-based processes such as high rate algal ponds (HRAP) or other types of photobioreactors (González *et al*., 2008; de Godos *et al*., 2009). HRAP can be seen as a modification of conventional waste stabilisation ponds commonly used for sewage treatment, with a lower depth and some energy requirements to stir the mixed liquor (Abeliovich, 1986; García *et al*., 2006). HRAP were developed as an efficient system to take profit of solar energy (Oswald, 1977). This study evaluates the potential of HRAP for piggery wastewater treatment, comparing the organic matter and ammonia removal as a function of the surface organic loading and ammonia loading rates. For this purpose, two experimental HRAP were operated during 5 months. The main pathways involved in nitrogen removal were also investigated.

The main biochemical reaction related to the removal of organic matter in HRAP is aerobic degradation. By means of this reaction, organic matter is transformed into new microorganisms and inorganic end products such as carbon dioxide and water (Abeliovich, 1986; García *et al*., 2006). Nitrogen removal in HRAP is achieved mainly by two processes: photosynthetic assimilation and ammonia stripping (Nurdogan and Oswald, 1995; García *et al*., 2000a). Nitrification followed by denitrification is assumed not to be an efficient process in these systems. Many studies have demonstrated that nitrification is not significant, despite the availability of oxygen (Koopman *et al*., 1980; Shelef *et al*., 1982; El Halouani *et al*., 1993). Recent research indicates that nitrifying bacteria and microalgae may compete for inorganic carbon in HRAP, and that the higher affinity of microalgae for inorganic carbon could explain the low rates of nitrification (de Godos *et al*., 2009). Photosynthetic assimilation does not produce a net nitrogen decrease if algal biomass is not harvested from the mixed liquor (García *et al*., 2000a). Indeed, complete treatment in HRAP requires an efficient separation of algae and bacteria biomass from the mixed liquor (García *et al*., 2000b). Many authors indicate that the main reaction involved in nitrogen removal is ammonia stripping (Shelef *et al*., 1982; El Halouani et al., 1993; García *et al*., 2000a).

2. Material and Methods

This study was performed at the laboratory of the GEMMA research group (Department of Hydraulic, Maritime and Environmental Engineering, Universitat Politècnica de Catalunya-BarcelonaTech) in Barcelona, North-East Spain. The experimental set-up was located outdoors, at the roof of the building. It included the following units: storage tank, pumping system, two parallel HRAP (namely 1 and 2) and two settling tanks for subsequent algal biomass separation. The HRAP were constructed with PVC (surface area of 1.54 m^2 and water depth of 0.26 m). Length and width of HRAP were 2.65 m and 1.0 m. respectively. A paddle-wheel moved the mixed liquor in the ponds (Figure 1). The surface area of each settling tank was 0.0255 m^2. Settling tanks were only used during the experiments corresponding to the second period, with the aim of harvesting biomass and recycling the effluent of the settlers into the HRAP. An effluent volume corresponding to 45 % and 30 % of the pond volume was daily recycled in HRAP 1 (185 L/day) and HRAP 2 (120 L/day), respectively.

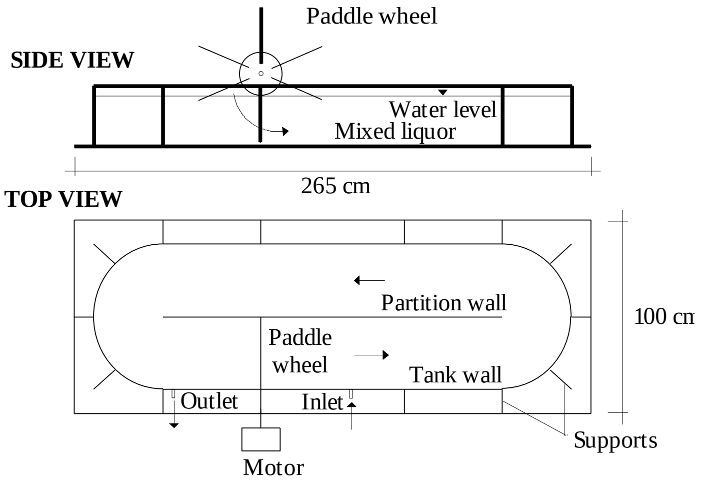

Figure 1. Schematic diagram of the top and side view of the HRAP.

A detailed description of the HRAP can be found in García *et al*. (2000a,b, 2006). Prior to experiments, ponds were filled with a mixture of tap and urban wastewater, and inoculated with microalgae from an ornamental pond located near the laboratory. Most of the microalgae species present were Chlorophyta (*Scenedesmus*, *Chlorella*, etc.).

The experiments were carried out from August 2002 to December 2002. The hydraulic retention time (HRT) of the HRAP ranged from 40 to 80 days. The ponds were operated semi-continuously: a certain volume of mixed liquor (*i.e.* effluent) was daily removed at midday (when the pH and dissolved oxygen were the highest), and the ponds were subsequently fed with piggery wastewater pretreated with an electroflocculation process which removed almost all suspended components. The influent was pumped into the ponds during a period of two hours. Pretreated piggery wastewater was received monthly from a farm located in Toledo (center of Spain). Water evaporation was taken into account in the influent/effluent balance. Periodical addi-tions of phosphorus (K_2HPO_4) to the mixed liquor were needed to maintain a concentration around 2 mg P/L.

Table 1 shows the operating strategies evaluated in this study. The first month included the start-up and stabilization of the ponds (when a conspicuous algal-bacteria culture was observed). During periods 1 and 2, the HRAP were operated with different flow rates, hence with different surface organic loading rates (OLR) and surface ammonia loading rates (ALR). During period 2, both HRAP operated with biomass separation and settlers effluent recycling. The aim of this system was to improve process performance by providing conti-nuous biomass removal from the mixed liquor, while maintaining the HRT by recycling the effluent of the settlers.

Organic matter removal was measured in terms of dissolved chemical oxygen demand (COD). pH, temperature, dissolved oxygen (DO), dissolved COD, ammonia and total suspended solids (TSS) were analyzed from influent and mixed liquor (*i.e.* effluent) samples. During period 2, the nitrogen removal rate by biomass separation in settling tanks was also estimated. 1 L of biomass was daily purged; and total solids (TS) were determined using gravimetric methods. The values of TS were assumed to be representative of algal biomass. The amount of nitrogen (ammonia) removed by the biomass purge was calculated considering that the nitrogen weight of microalgae is approximately 7.5 % (Greenwell *et al.*, 2010). All analyses were carried out following the procedures described in the Standard Methods (APHA-AWWA-WPCF, 1995).

Table 1. Operating strategies in both HRAP. OLR is surface organic loading rate. ALR is surface ammonia loading rate.

Period (Date)	**HRAP 1**			**HRAP 2**		
	Flow rate, L/d	**OLR g COD/m^2d**	**ALR g NH_4^+-N /m^2d**	**Flow rate, L/d**	**OLR, g COD/m^2d**	**ALR, g NH_4^+-N /m^2d**
Start-up and stabilization 1 (09/08 to 16/08)	10	20	5.0	20	40	10
Stabilization 2 (17-08 to 27-08)	5.0	10	2.5	10	20	5.0
Stabilization 3 (28-08 to 04-09)	5.0	10	2.5	15	30	7.5
Period 1-1 (05-09 to 16-09)	5.0	10	2.5	7.5	15	3.7
Period 1-2 (19-11 to 31-11)	10	20	5.0	10	20	5.0
Period 2-1 (17-09 to 27-09)	(a)	(a)	(a)	7.5	15	3.7
Period 2-2 (28-09 to 15-10)	(a)	(a)	(a)	5	10	2.5
Period 2-3 (16-10 to 18-11)	10	20	5.0	10	20	5.0
Period 2-4 (02-12 to 31-12)	6.5	13	3.3	6.5	13	3.3

(a) Breakdown of the system.

3. Results and Discussion

Piggery wastewater was pretreated by electro-flocculation with the aim of reducing the COD and TSS concentration.

Table 2. Composition of pretreated piggery wastewater.

Parameter	**Average ± s.d.**
pH	8.2 ± 0.5
Alcalinity, mg $CaCO_3$/L	1,400 ± 53
TSS, mg/L	290 ± 50
COD, mg O_2/L	3,400 ± 280
Dissolved COD, mg O_2/L	3,000 ± 8
Ammonia, mg NH_4^+-N/L	790 ± 10

As shown in Table 2, pretreated piggery wastewater was characterized by a relatively low TSS content and high dissolved organic matter, ammonia and alkalinity.

3.1 HRAP performance

Table 3 shows the main results obtained in each HRAP during experimental periods 1 and 2. As it can be observed, DO and pH were slightly higher during period 2 (comparing periods with the same loading rate) as a result of the separation-recycling system.

Table 3. Effluent (mixed liquor) physico-chemical parameters of both HRAP in different periods. Average ± s.d.

Parameter	**HRAP1**			
	Period 1		**Period 2**	
	1-1 (5 L/d)	**1-2 (10 L/d)**	**2-4 (6.5 L/d)**	**2-3 (10 L/d)**
DO, mg O_2/L	6.5 ± 1.7	7.2 ± 1.7	11.0 ± 2.0	9.3 ± 1.8
Temperature, ºC	20 ± 2.2	13 ± 1.1	11.9 ± 1.4	16.1 ± 2.9
pH	7.2 ± 0.2	7.4 ± 0.2	7.7 ± 0.2	7.7 ± 0.2
TSS, mg/L	220 ± 60	204 ± 124	149 ± 77	274 ± 75
Ammonia, mg NH_4^+-N/L	161 ± 6	187 ± 27	232 ± 8	131 ± 14
COD, mg O_2/L	203 ± 16	270 ± 23	152 ± 11	170 ± 20
Ammonia removal, g NH_4^+-N/m^2.d	2.0 ± 0.1	3.9 ± 0.2	2.5 ± 0.1	4.3 ± 0.1
Ammonia removal, %	81.6	78.0	76.7	86.0
N removed by biomass harvesting, g N/d	----	----	0.30	0.13

Parameter	**HRAP 2**					
	Period 1		**Period 2**			
	1-1 (7.5 L/d)	**1-2 (10 L/d)**	**2-2 (5 L/d)**	**2-4 (6.5 L/d)**	**2-1 (7.5 L/d)**	**2-3 (10 L/d)**
DO, mg O_2/L	6.7 ± 1.3	10.1 ± 0.9	10.2 ± 1.0	12.1 ± 2.0	9.5 ± 1.8	9.8 ± 1.8
Temperature, ºC	20 ± 1.1	12 ± 1.0	18 ± 1.3	11 ± 1.4	22 ± 2.3	17 ± 3.2
pH	7.2 ± 0.2	7.5 ± 0.4	7.9 ± 0.2	7.8 ± 0.2	7.6 ± 0.2	7.7 ± 0.2
TSS, mg/L	180 ± 67	110 ± 10	234 ± 64	118 ± 69	200 ± 55	231 ± 98
Ammonia, mg NH_4^+-N/L	186 ± 12	240 ± 18	143 ± 32	251 ± 24	161 ± 23	201 ± 27
COD, mg O_2 /L	140 ± 15	160 ± 35	198 ± 8	203 ± 6	158 ± 2	207 ± 9
Ammonia removal, g NH_4^+-N/m^2d	2.9 ± 0.1	3.6 ± 0.1	2.1 ± 0.1	2.5 ± 0.1	3.0 ± 0.1	3.8 ± 0.2
Ammonia removal, %	78.5	71.4	84.0	74.7	81.7	76.0
N removed by biomass harvesting, g N/d	----	----	0.93	0.34	1.00	0.75

The average dissolved COD concentration in the effluent was 198 mg O_2/L in HRAP 1 and 178 mgO_2/L in HRAP 2; ranging from 130 to 296 mgO_2/L in both HRAP. Dissolved COD removal efficiencies above 90 % were observed in both HRAP for all OLR. However, there was no clear relationship between the OLR and effluent dissolved COD concentration. For instance, in period 1-1 HRAP 1 operated with a lower OLR than HRAP 2 and the dissolved COD concentration was higher in HRAP 1. On the other hand, in period 1-2 both HRAP operated with the same OLR and the effluent dissolved COD concentration was slightly different. The results indicate that when HRAP are operated with OLR equal to or lower than 20 gO_2/m^2d, the system can remove almost all influent dissolved COD regardless of the load.

In this way, the effluent concentration seems to be related with unpredictable variables such as the amount of influent refractory compounds or exo-polysaccharides produced by algal biomass, among others.

During the stabilization period, when an OLR of 40 gO_2/m^2d was used in HRAP 2, a sudden drop in the efficiency and DO concentration was observed (Figure 2).

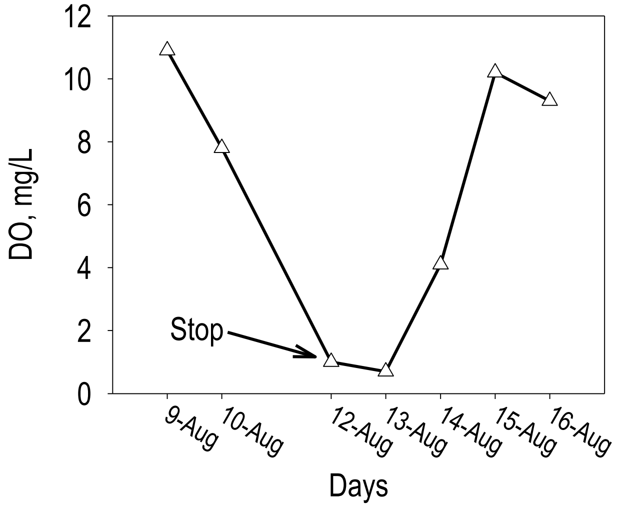

Figure 2. Dissolved oxygen (DO) concentration in HRAP 2 during the stabilization period (40 gCOD/m2d). High DO concentration was recovered as soon as feeding was stopped.

This means that this load exceeded the capacity of the system. During this event, the color of the mixed liquor changed from green to brown. Initial conditions in terms of color and DO concentration were re-established by stopping the feeding for several days. Feeding was re-started with a flow rate of 10 L/d (20 gO_2/m^2d), which did not decrease the DO concentration. The flow rate was then increased to 15 L/d (30 gO_2/m^2d), decreasing the DO content. Therefore, the maximum OLR that the HRAP could withstand was 20 gO_2/m^2d. In practice, an organic matter removal efficiency of 90 % is only feasible if HRAP have an efficient system to separate algae biomass from the effluent. The separation-recycling system used in period 2 was not as effective as expected, since effluent dissolved COD concentrations were not systematically higher or lower than in period 1, even if data from periods with the same loading rate are compared (Table 3).

The average effluent ammonia concentration was of 178 $mgNH^{4+}$-N/L in HRAP 1 and 197 $mgNH_4$+-N/L in HRAP 2. A higher concentration in HRAP 2 is attributed to the fact that loading rates were generally higher in HRAP 2 than in HRAP 1. Figure 3 shows the cumulative distribution of ammonia removal efficiency, which ranged between 68 and 85%. In both HRAP in the ammonia concentration increased during the experiments, therefore the removal efficiency decreased with time. This trend can be observed in Table 3. For example, in HRAP 1 the ammonia removal efficiency was higher in 1-1 than in 1-2; and it was also higher in 2-1 than in 2-3 and 2-4. However, this efficiency decrease cannot be observed when the removal is expressed in terms of load. This is due to the fact that the load removed is mostly dependant on the ALR (Figure 2). The effluent ammonia concentration decreased or remained nearly constant when feeding was stopped or with ALR of 2.5 gNH_4^+-N/m^2d (Figure 4).

Table 3. Effluent (mixed liquor) physico-chemical parameters of both HRAP in different periods. Average ± S.D.

Parameter	**HRAP1**			
	Period 1		**Period 2**	
	1-1 (5 L/d)	**1-2 (10 L/d)**	**2-4 (6.5 L/d)**	**2-3 (10 L/d)**
DO, mg O_2/L	6.5 ± 1.7	7.2 ± 1.7	11.0 ± 2.0	9.3 ± 1.8
Temperature, ºC	20 ± 2.2	13 ± 1.1	11.9 ± 1.4	16.1 ± 2.9
pH	7.2 ± 0.2	7.4 ± 0.2	7.7 ± 0.2	7.7 ± 0.2
TSS, mg/L	220 ± 60	204 ± 124	149 ± 77	274 ± 75
Ammonia, mg NH_4^+-N/L	161 ± 6	187 ± 27	232 ± 8	131 ± 14
COD, mg O_2/L	203 ± 16	270 ± 23	152 ± 11	170 ± 20
Ammonia removal, g NH_4^+-N/m^2d	2.0 ± 0.1	3.9 ± 0.2	2.5 ± 0.1	4.3 ± 0.1
Ammonia removal, %	81.6	78.0	76.7	86.0
N removed by biomass harvesting, g N/d	----	----	0.30	0.13

Parameter	**HRAP 2**					
	Period 1		**Period 2**			
	1-1 (7.5 L/d)	**1-2 (10 L/d)**	**2-2 (5 L/d)**	**2-4 (6.5 L/d)**	**2-1 (7.5 L/d)**	**2-3 (10 L/d)**
DO, mg O_2/L	6.7 ± 1.3	10.1 ± 0.9	10.2 ± 1.0	12.1 ± 2.0	9.5 ± 1.8	9.8 ± 1.8
Temperature, ºC	20 ± 1.1	12 ± 1.0	18 ± 1.3	11 ± 1.4	22 ± 2.3	17 ± 3.2
pH	7.2 ± 0.2	7.5 ± 0.4	7.9 ± 0.2	7.8 ± 0.2	7.6 ± 0.2	7.7 ± 0.2
TSS, mg/L	180 ± 67	110 ± 10	234 ± 64	118 ± 69	200 ± 55	231 ± 98
Ammonia, mg NH_4^+-N/L	186 ± 12	240 ± 18	143 ± 32	251 ± 24	161 ± 23	201 ± 27
COD, mg O_2 /L	140 ± 15	160 ± 35	198 ± 8	203 ± 6	158 ± 2	207 ± 9
Ammonia removal, g NH_4^+-N/m^2d	2.9 ± 0.1	3.6 ± 0.1	2.1 ± 0.1	2.5 ± 0.1	3.0 ± 0.1	3.8 ± 0.2
Ammonia removal, %	78.5	71.4	84.0	74.7	81.7	76.0
N removed by biomass harvesting, g N/d	----	----	0.93	0.34	1.00	0.75

The separation-recycling system improved the ammonia removal efficiency only slightly (increasing from 0.1 to 0.5 gNH_4^+-N/m^2d). This was due to the fact that the efficiency of settlers for algal biomass retention was quite low (ranging from 25 to 30%). As can be observed in Table 3, ammonia removal in terms of gN/m^2d was higher in period 2 for the same loading rate.

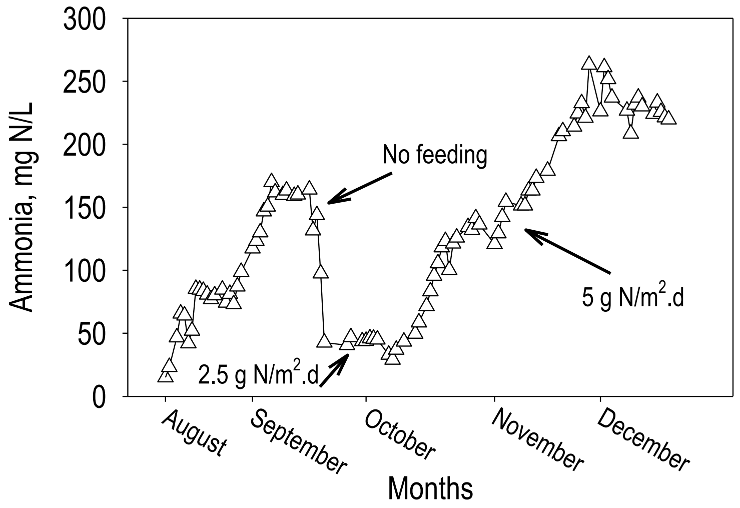

Figure 4. Effluent ammonia concentration in HRAP 1. Ammonia concentration decreased as soon as feeding was stopped; it remained quite constant with an ammonia load of 2.5 g N-NH_4^+/m^{2}d.

3.2Ammonia transformations

During the experiments, the pH of the mixed liquor of both ponds ranged from 7.0 to 8.2. Therefore, a maximum of 10 % over the total ammonia removal could be attributed to stripping (Metcalf and Eddy, 2004). However, removal efficiencies observed in both HRAP were clearly higher (68-85 %). This means that other processes played an important role in the removal of ammonia, including algal uptake and nitrification. A mass balance of each HRAP was carried out in order to estimate the relative contribution of different ammonia removal mechanisms. Data of 6 consecutive days from period 2 were used (during these days both HRAP were operated with a flow rate of 6.5 L/d). The results of the mass balance are shown in Table 4.

Table 4. Mass balance of ammonia nitrogen in both HRAP during 6 consecutive days. Calculations from data obtained during period 2 with a flow rate of 6.5 L/d.

Mass of ammonia, g NH_4^+-N	**HRAP 1**	**HRAP 2**
N mass influent	30.5	30.5
N mass removed	23.1	22.8
N mass removed by algal harvesting	3.3 (14.4 %)	2.1 (9.0 %)
N mass removed by stripping	0.5 (2.4 %)	0.8 (3.8 %)
N mass removed by nitrification	19.2 (83.2 %)	19.9 (87.2 %)

Ammonia mass removed through stripping was calculated taking into account the pH. The mass removed by algal uptake was estimated from the biomass harvested in settlers. Finally, ammonia mass removed by nitrification was calculated from difference. Algal biomass in the mixed liquor did not vary significantly during the period evaluated. Note that during this period algal biomass in the mixed liquor remained approximately constant.

From the results it is clear that nitrification was the main mechanism for ammonia removal. Taking into account that nitrate concentration was systematically low in the mixed liquor of both HRAP (2-9 mg NO_3^--N/L), it seems that denitrification was an important reaction for nitrogen removal. These results indicate that it is possible to achieve good removal efficiencies even with pH below 8.5 and stripping being not significant. These findings are in opposition with previous works in which nitrification was reported not to be significant in HRAP (Koopman *et al*., 1980; Shelef *et al*., 1982; El Halouani *et al*., 1993). Nitrification is perhaps a key reaction in the systems evaluated in the present study as a result of the high hydraulic retention time (from 40 to 80 days, which is also the cellular retention time), and also due to the high alkalinity of piggery wastewater which avoids microalgae and nitrifying bacteria competition for inorganic carbon.

4. Conclusions

The results of this study indicate that the efficiency of HRAP for removing COD from pretreated piggery wastewater is higher than 90% if they are operated with a maximum OLR of 20 gO_2/m^2d (hydraulic loading rate of 10 L/m^2d). Taking into account this maximum OLR, the treatment of 100 m^3/d of piggery wastewater (which is a representative flow rate for most farms) would require a surface area of approximately 1.5 ha. The results also indicate that with this maximum OLR, ammonia progressively accumulates in the system (corresponding ALR: 5 gNH_4^+-N/m^2d) and it is not possible to maintain a long term ammonia removal. Thus, simultaneous removal of COD and ammonia is limited by the requirements needed for ammonia. Experimental data showed that HRAP can remove nearly all ammonia with an ALR equal to or below 2.5 gNH_4^+-N/m^2d. Bearing in mind this ALR, the surface area required for removing soluble COD and ammonia from 100 m^3/d of this piggery wastewater would be of approximately 3 ha. In locations with high evaporation rates this treatment system would not be appropriate.

The separation-recycling system for algal biomass harvesting did not improve dissolved COD removal efficiency. Ammonia removal efficiency was not significantly improved because the efficiency of the settlers for algal biomass separation was low (25 to 30% in terms of TSS). In conclusion, the implementation of a separation-recycling system without chemical addition (for promoting biomass flocculation) does not appear to be a good alternative for increasing pollutant removal efficiency.

The pH of the mixed liquor of the HRAP ranged from 7.0 to 8.2 and therefore only a maximum of 10 % over the total ammonia removal could be due to stripping. This result indicates that under the experimental conditions tested other mechanisms for ammonia removal were important. Indeed, from mass balances it was calculated that the main pathway for ammonia removal was nitrification. It was estimated that 80-90 % of ammonia was removed through this pathway.

HRAP treating highly loaded wastewater need a considerable surface area, which could limit their application. In this case, the implementation of combined unit processes may be a good alternative. In other words, HRAP may be used as a complementary secondary treatment to remove the main portion of pollutants. Chemical addition can also be used for reducing algal biomass.

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