

Assessment of an artificial free-flow wetland system with water hyacinth (*Eichhornia crassipes*) for treating fish farming effluents[□]

*Evaluación de un humedal artificial con Jacinto de agua (*Eichhornia crassipes*) para el tratamiento de efluentes piscícolas*

*Avaliação de uma zona húmida artificial com Jacinto de água (*Eichhornia crassipes*) no tratamento de efluentes piscícolas*

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Summary

Background: fish farming effluents are mainly composed of organic matter and are considered a source of environmental pollution. **Objective:** to evaluate the efficiency of an artificial free-flow wetland system using water hyacinth (*Eichhornia crassipes*) to treat fish farming effluents under various hydraulic loadings. **Methods:** effluents generated from fingerling ponds of *Oreochromis* sp. and *Piaractus brachypomus* were passed through a constructed wetland system (40 m long and 7.7 m wide) to measure NO₂⁻, NO₃⁻, NH₄⁺, total phosphorus (TP), and Biochemical Oxygen Demand (BOD₅) removal efficiency. The hydraulic retention time was measured for six months in five assessment phases under real production conditions by using five hydraulic loadings (44.9, 45.3, 43.1, 41.6, 42.0 cm/day). **Results:** the hydraulic retention time of the constructed wetland system was 1.6 days, and its removal efficiency rates were: 67.9% for NH₄⁺, 32.1% for BOD₅, 27.1% for NO₂⁻, 23.0% for TP, and 16.7% for NO₃⁻. Removal rate was positively correlated with the loading rate of total inorganic nitrogen during the five phases of this study (r=0.956). Also, highest removal values and efficiency increase were reached in phase 5. **Conclusions:** the free-flow wetland with *E. crassipes* is efficient for removing nitrogen compounds, TP and BOD₅.

Key words: fish waste water, macrophytes, nitrogen compounds, nutrient removal.

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Resumen

Antecedentes: el efluente piscícola se compone principalmente de materia orgánica y es la principal fuente de impactos ambientales negativos. **Objetivo:** evaluar la eficiencia de un humedal artificial de flujo libre con Jacinto de agua (*Eichhornia crassipes*) en el tratamiento de efluentes piscícolas bajo diferentes cargas hidráulicas. **Métodos:** efluentes generados por estanques de alevinaje de *Oreochromis* sp. y *Piaractus brachyomus* se pasaron por el humedal artificial (40 m de largo y 7,7 m de ancho) y se determinó la eficiencia de eliminación de NO_2^- , NO_3^- , NH_4^+ , fósforo total (TP) y BOD_5 (Demanda Bioquímica de Oxígeno). Durante seis meses se determinó el tiempo de retención hidráulica en cinco fases de evaluación en condiciones reales de producción con cinco cargas hidráulicas (44,9, 45,3, 43,1, 41,6, 42,0 cm/día). **Resultados:** el tiempo de retención hidráulica del humedal artificial fue 1,6 días y registró eficiencias de eliminación de: NH_4^+ (67,9%), BOD_5 (32,1%), NO_2^- (27,1%), TP (23,0%) y NO_3^- (16,7%). La velocidad de eliminación se correlacionó positivamente con la velocidad de carga del nitrógeno inorgánico total en las cinco fases de estudio ($r=0,956$); los mayores valores de eliminación y el incremento de su eficiencia se alcanzaron durante la fase 5. **Conclusiones:** el humedal artificial a flujo libre con *E. crassipes* es eficiente en la eliminación de compuestos nitrogenados, TP y BOD_5 .

Palabras clave: agua de residuo piscícola, compuestos nitrogenados, macrófitas, remoción de nutriente.

Resumo

Antecedentes: o efluente piscícola se compõe principalmente de matéria orgânica e essa é a principal fonte de impactos ambientais negativos. **Objetivo:** avaliar a eficiência de uma zona húmida artificial de fluxo livre com Jacinto de água (*Eichhornia crassipes*) para o tratamento de efluentes piscícolas sob diferentes cargas hidráulicas. **Métodos:** efluentes gerados por viveiros de alevinagem de *Oreochromis* sp e *Piaractus brachyomus* se passaram pela zona húmida (40 m de comprimento e 7,7 m de largura) e foi determinada a eficiência da eliminação de NO_2^- , NO_3^- , NH_4^+ , fósforo total (FT) e BOD_5 . Durante seis meses determinou-se o tempo de retenção hidráulica em cinco estágios de avaliação em condições reais de produção com cinco cargas hidráulicas (44,9; 45,3; 43,1; 41,6 e 42,0 cm/dia). **Resultados:** o tempo de retenção hidráulica da zona húmida artificial foi de 1,6 dias e registrou eficiências de eliminação: NH_4^+ (67,9%), BOD_5 (32,1%), NO_2^- (27,1%), FT (23,0%) e NO_3^- (16,7%). A velocidade de eliminação correlacionou-se positivamente com a velocidade de carga do nitrogênio inorgânico total durante os cinco estágios de estudo ($r=0,956$); os valores de eliminação maiores e o incremento da sua eficiência se alcançaram durante o estágio 5. **Conclusões:** a zona húmida artificial a fluxo livre com *E. crassipes* é eficiente na eliminação de compostos nitrogenados, FT e BOD_5 .

Palavras chave: água de residuo piscícola, compostos nitrogenados, macrófitas, remoção de nutrientes.

Introduction

Effluents produced by fish farming are usually composed of organic matter (feces, urine, excreta, food residues, dead organisms and pathogens) and are the main cause of negative environmental changes in aquatic ecosystems (Gentelini, 2007). To solve this problem, aquacultural processes require cleaner production technologies aimed at reducing environmental pollution while maintaining economic viability (Pardo-Carrasco *et al.*, 2005). Improved production systems require alternatives to reduce the risk of polluting water bodies. A possible solution is treating aquaculture effluents in constructed wetland systems (Spieles and Mitsch, 2000; Lee *et al.*, 2009), thus improving water quality with biological, economic and practical processes (Yang *et al.*, 2001;

Schulz *et al.*, 2003; Vinatea, 2005). In addition, this process should be capable of turning an unwanted product into something useful and even profitable. Such a process is called biotransformation (Troell *et al.*, 2005).

Constructed wetland systems have been used for treating acid mine drainages, municipal surface water, industrial water, and livestock effluents. Constructed wetland systems have proven their ability to remove significant amounts of suspended solids, organic matter, nitrogen, phosphorus, trace elements, and microorganisms present in wastewater (Gentelini, 2007; Lee *et al.*, 2009; Jing *et al.*, 2001; Luna and Ramírez, 2004). The use of aquatic plants is becoming increasingly important for removing carbon compounds (measured as Biochemical Oxygen

Demand (BOD_5) from effluents and wastewater. *Eichhornia crassipes* is one of the most studied macrophytes used for the treatment of effluents. It is an outstanding species among freshwater hydrophyte communities from South America. This plant is widely used for treating wastewater, as it can assimilate and store pollutants, transport oxygen to the root area and foster a perfect medium for bacterial activity (Wedler, 1998). Moreover, it has high nutrient absorption capacity, especially for ammonium, nitrate and nitrite nitrogen (Wedler, 1998). Thus, constructed wetland systems are becoming increasingly used for the treatment of aquaculture effluents all over the world (Jing *et al.*, 2001; Kadlec *et al.*, 2000; Posadas, 2001; Lin *et al.*, 2002; Lin *et al.*, 2005). They are also a cleaner, more sustainable production alternative (Vinatea, 1999; New, 2003). Hence, this study evaluated the capabilities of water hyacinth in a constructed wetland system to treat fish farming effluents in northern Colombia. The efficiency of a free-flow constructed wetland system planted with water hyacinth was assessed for removing nitrogen compounds, total phosphorus, and BOD_5 while operating under commercial fingerling culture conditions.

Materials and methods

Ethical considerations

This study was approved by the Animal Experimentation Ethics Committee of the Fish Research Center (CINPIC), Universidad de Córdoba, Colombia (CINPIC 002 - May 18, 2008).

Layout

The wetland system was built in Aquacaribe farm (Córdoba, Colombia.), located at latitude $9^{\circ}13'54''$ N and longitude $75^{\circ}49'11''$ W, at 7 m.a.s.l. The annual mean temperature is 28°C . The wetland was built on the ground (length: 40 m, width: 7.7 m; depth: 0.9 m). The bottom and slopes were covered with a 20 mm thick geomembrane (Figure 1) to isolate soil from water. The wetland was planted with water hyacinth (plants were the same size, age and color) collected from a nearby area. Plants were cleaned before planted in the wetland for further propagation. Water hyacinth was planted at a density of 5 ± 2 plants/ m^2 , and the average weight of plants was 2.2 ± 0.9 kg. Thus, a total of 1,500 macrophytes were planted during the study, reaching a biomass of 3.4 ton.

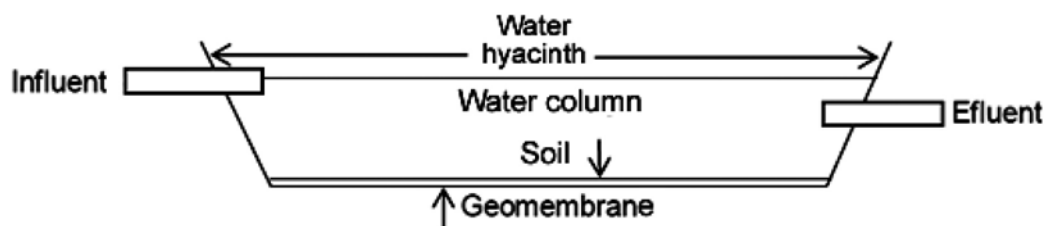


Figure 1. Diagram of the free flow constructed wetland system planted with *Eichornia crassipes* for treating effluents generated by fish farming.

Wetland system operation

The system was monitored for 24 weeks (6 months) at two sampling locations (influent and effluent). During this time the fish farm effluent was added to the free flow wetland system (FWS) via gravity flow ditches. These entry points were not constant in the system, as they depended on the way in which water was replaced in the fish farm. The average

flow rate of the wetland was estimated using weekly gauging with Bos equation (Bos, 1986), which uses the height and diameter of the stream to determine flow:

$$Q = 5.47D^{1.25} H^{1.35}$$

Where, D is stream diameter, H is stream height (m), and Q is flow (m^3/s).

Efficiency assessment

The processes of pollution removal of the wetland were calculated using a first order kinetic model with piston flow, as established by the International Water Association (Kadlec *et al.*, 2000).

$$C_o/C_i = \exp(-K*t)$$

Where C_i is pollutant concentration in the influent (mg/L); C_o is pollutant concentration in the effluent (mg/L); t is nominal hydraulic retention time (days) and K is the first order removal rate constant.

The loading rate of pollutants (LRP, g/m²/day) was estimated using the following equation:

$$LRP = HLR * C_i$$

Where HLR is the hydraulic loading rate (mg/L) and HRL was estimated using the following equation:

$$HRL = Q_i * A_w$$

Where Q_i is the influent and A_w is the wetland area.

The pollutant removal rate (PRT, g/m²/day) was calculated using the following equation:

$$PRT = HLR * (C_i - C_o)$$

The average rate of influent and effluent (Q) was also determined, and the hydraulic loading (q) was measured as the average flow rate (Q) divided by the wetland area. Finally, the nominal hydraulic retention time (t) was calculated by dividing the depth of the wetland system by the average flow rate.

Sample analysis

Physical and chemical parameters were measured three times per week via *in situ* readings. Parameters measured were pH, dissolved oxygen (DO), and temperature (T) at the influent and effluent points of the wetland. Measurements were taken once per day from 8:00 am to 10:00 a.m. with a digital oximeter (YSI, 550A, Yellow Springs, Ohio, USA) and a digital potentiometer (YSI, pH100), calibrated in accordance with the manufacturer's instructions. Measurements

were taken at an average depth of 25 cm at the influent and effluent points of the system. Water was sampled at two points to measure nutrients using 2-L amber bottles, which were packed and sent to the Regional Water Institute of the University of Córdoba (IRAGUAS) where concentration of BOD₅, NO₂⁻, NO₃⁻, NH₄⁺, and total phosphorus (TP) were determined using procedures and techniques given by the 24 American Public Health Association (APHA, 1980). Results on total ammonia nitrogen (TAN) were determined as the sum of the values for NO₂⁻, NO₃⁻, and NH₄⁺.

A regression analysis between removal rate and loading rate of TAN was carried out to obtain the curve and best-fit equation.

Results

Wetland system setting

Hydraulic conditions in the wetland system depended on the water replacement and removal dynamics of the fish farm. The wetland started operation at phase 1 with a hydraulic loading of 44.9 cm/day (Table 1).

Table 1. Hydraulic conditions of the wetland system planted with *Eichhornia crassipes* throughout five phases.

Phase	Weeks in operation	Q (m ³ /day)	q (cm/day)	t (day)
1	1 to 7	137.3	44.9	1.50
2	8 to 11	138.6	45.3	1.49
3	12 to 15	131.8	43.1	1.57
4	16 to 20	127.2	41.6	1.62
5	21 to 24	128.5	42.0	1.61

Q: average rate of influent and effluent, q: hydraulic loading rate, t: nominal hydraulic retention time (porosity 0.75).

Vegetation grew rapidly. Its initial density was 5 ± 2 plants/m², and its density in phase 3 was 13 ± 3 plants/m². In this phase, the differences between the values for nitrogen compound concentration, total phosphorus and BOD₅, as well as the difference between the influent and effluent were low. However, an increase in the removal rate of nitrogen compounds was observed in phase 5. Similarly, from phase 3 onward, the studied parameters

had a removal trend, with hydraulic loadings ranging from 41.6 to 45.3 cm/day (Table 2). This removal rate

became observable after week 7 for inorganic nitrogen and BOD₅, and after week 10 for total phosphorus.

Table 2. Water quality at the sampling locations during all the assessment phases.

Phase	pH	T (°C)	DO (mg/L)	BOD ₅ (mg/L)	TAN (mg/L)	NH ₄ ⁺ (mg/L)	NO ₃ ⁻ (mg/L)	NO ₂ ⁻ (mg/L)	TP (mg/L)
1									
In	7.1±0.2	28.8±0.5	0.32±0.15	3.36±0.96	3.74±7.0	2.69±7.10	1.04±0.18	0.008±0.00	0.29±0.06
Ef	6.9±0.1	30.1±1.0	1.27±0.83	3.45±0.90	1.73±1.23	0.74±1.26	0.98±0.09	0.005±0.00	0.29±0.08
2									
In	7.5±0.2	27.6±0.1	0.20±0.07	4.27±0.83	2.83±2.74	1.83±2.79	0.99 ±0.14	0.005±0.00	0.47±22
Ef	7.3±0.1	28.6±0.4	0.34±0.14	2.78±0.50	1.60±0.66	0.73±0.86	0.86±0.35	0.005±0.00	0.49±0.61
3									
In	8.0±0.2	27.7±0.5	0.19±0.03	5.33±0.91	1.49±0.67	0.33±0.64	1.15±0.16	0.007±0.00	0.31±0.20
Ef	7.7±0.2	28.2±0.3	0.28±0.10	2.74±0.61	1.48±0.94	0.41±0.80	1.07±0.15	0.008±0.00	0.19±0.08
4									
In	8.3±0.1	27.8±0.4	0.19±0.06	4.97±2.21	2.30±2.30	1.06±2.10	1.26±0.37	0.010±0.01	0.32±0.21
Ef	7.9±0.2	28.7±0.4	0.19±0.05	2.94±0.28	0.92±0.28	0.01±0.00	0.90±0.27	0.007±0.00	0.18±0.08
5									
In	8.3±0.3	28.3±0.8	0.43±0.20	7.62±3.24	1.49±0.50	0.01±0.00	1.45±0.47	0.029±0.04	0.48±0.12
Ef	7.9±0.0	28.4±0.3	0.43±0.22	5.45±2.45	1.18±0.44	0.01±0.00	1.15±0.41	0.018±0.02	0.29±0.11

In: influent, Ef: effluent, T: temperature, DO: dissolved oxygen, BOD₅: biochemical oxygen demand, TAN: total ammonium nitrogen, NH₄⁺: ammonium nitrogen, NO₃⁻: nitrate nitrogen, NO₂⁻: nitrite nitrogen, TP: total phosphorus.

Nitrogen Removal

Pollutant concentration in the influent during the study period ranged from 0.005 to 0.029 mg/L for NO₂⁻; 0.8 to 1.8 mg/L for NO₃⁻; and 0.99 to 1.45 mg/L for NH₄⁺.

The average value for NH₄⁺ removal was 0.36 ± 0.38 g/m²/day, which represents 67.9% efficiency throughout the entire study. Phase 1 had the highest removal value for NH₄⁺: 0.88 g/m²/day, while the lowest value, -0.03 g/m²/day, was observed during phase 3 (data not shown).

The average rate of NO₃⁻ removal was 0.08 ± 0.05 g/m²/day, which corresponds to 16.7% efficiency. Additionally, a peak in this rate was observed in phase 4, with a value of 0.15 g/m²/day, which is equivalent

to 31% efficiency (values calculated using data from Table 2). On the other hand, NO₂⁻ had an average of 0.001 ± 0.002 g/m²/day, that is, 27.1% efficiency. Negative values were recorded during phases 2 (-0.001 g/m²/day) and 3 (-0.003 g/m²/day). However, the highest removal value was reached in phase 5: 0.004 g/m²/day, corresponding to 37.9% efficiency.

The concentration of NO₂⁻ and TAN in the effluent was highly correlated with the loading rate of the pollutant, their r-values being 0.697 and 0.546, respectively, during the evaluation period. However, nitrogen compounds maintained low values in the effluent: less than 0.11 mg/L for NO₂⁻; less than 1.8 mg/L for NO₃⁻; and less than 2.9 mg/L for NH₄⁺. The TAN loading rate for each study phase had a high correlation with the TAN removal rate: r=0.956 (Figure 2).

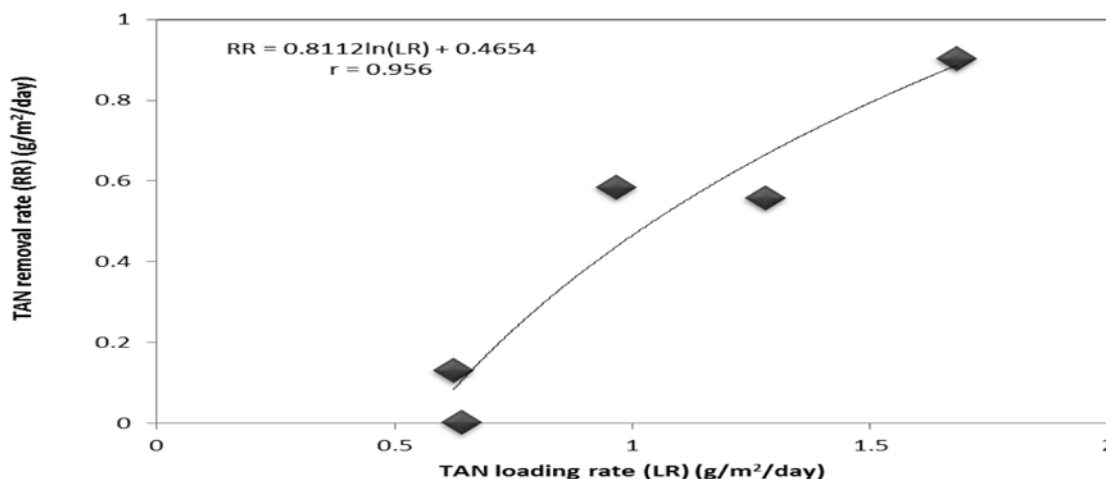


Figure 2. Equation and best fit curve for removal and loading rates of total ammonia nitrogen (TAN) in the constructed wetland system.

Total phosphorus removal

TP concentration in the influent during the study ranged from 0.29 to 0.48 mg/L. The average P removal was 0.034 ± 0.038 g/m²/day, which represents 23% efficiency. The removal data were negative in phases 1 (-0.002 g/m²/day) and 2 (-0.010 g/m²/day), and the last phase had the highest TP removal rate: 0.077 g/m²/day, corresponding to 33.9% efficiency. The efficiency values of the system had a strong tendency to improve as the pollutant rate of hydraulic loading decreased.

There was a low positive correlation ($r=0.271$) between rate of hydraulic loading and TP concentration in the effluent. A low linear correlation ($r=0.07$) was observed during all phases of the study when relationships between variations in rate of loading and rate of TP removal in the wetland were established. However, a high correlation ($r=0.96$) was observed when the same correlation did not include values from phases 1 and 2 or from the stabilization period.

BOD₅ removal

Pollutant concentration in the influent during the study period ranged from 3.36 to 7.62 mg/L for BOD₅. The average BOD₅ removal during the period was 0.70 ± 0.44 g/m²/day, which corresponds to 32.1% efficiency. Although this value was negative in phase 1 (-0.04 g/m²/day), it ranged from 0.67 to 0.91 g/m²/day in the subsequent phases, and reached its maximum

in phase three (1.11 g/m²/day), which corresponds to 47.6% removal efficiency.

A positive linear correlation ($r=0.494$) was observed when comparing the loading rate with BOD₅ concentration in the effluent. The average removal rate of BOD₅ was greater for higher hydraulic loadings, with values approaching 3 mg/L.

Discussion

Hydraulic conditions

Constructed wetland systems function better with a constant water flow allowing for appropriate removal of entering pollutants (Kadlec *et al.*, 2000; Lin *et al.*, 2002). Water inflow in the wetland depended upon the actual production conditions of the fish farm where the study took place. Thus, influent and effluent were affected by emptying, drying and replacement processes. In this study, the wetland flow ranged from 127.2 m³/day to 136.8 m³/day, and the estimated average value was 132.7 ± 5.1 m³/day. The average flow decreased 6.08 m³/day in the section between influent and effluent. The hydraulic retention time (HRT), also known as hydraulic residence time or t (τ), is a measure of the average time that a soluble compound remains in a constructed wetland.

As hydraulic retention time increased so did the removal rate of pollutants such as BOD₅ (Llagas

and Gomez, 2006), since pollutants had more opportunities to interact with plants, bacteria, and the wetland's substratum. The average hydraulic loading rate (q) during this study was 43.4 ± 1.68 cm/day, and the nominal hydraulic retention time (t) was 1.6 ± 0.06 days. Retention time started at 1.5 days (with a flow of 137.3 m³/day), and ended at 1.6 days (with a flow of 128.5 m³/day). Lin *et al.* (2002) conducted an experiment on an FWS under controlled conditions in a laboratory. They reported an average time of 4.5 days and a decreasing trend. This is not consistent with our study, which had a lower time and an increasing trend. However, Lin *et al.* (2005) conducted another study under operating conditions in a shrimp plant, and reported an average time of 2 days, which is consistent with our findings. Gentelini (2007) assessed three hydraulic retention times (0.16, 0.33, and 0.5 days) by treating the effluents in 1.2 m³ tanks. The hydraulic retention times observed in our study increased the probability of effluents to come into contact with the bacteria in the macrophyte roots present in the water column and bed of the wetland system, thus favoring the removal processes.

Wetland system stabilization

A constructed wetland system generally requires an extended period of time to stabilize bacterial communities and removal processes (Kadlec *et al.*, 2000). The soil added to the wetland bed provides ideal environments for the development of microbial processes such as nutrient nitrification, denitrification, and mineralization.

In this study, a maximum density of 13 ± 3 plants/m² was achieved at the end of phase 4, five months after water hyacinth were planted. This correlates with higher nutrient removal efficiency rates. It was suggested that plants did not cover the system completely at the beginning and the associated bacterial communities did not have favorable conditions for organic matter decomposition. Lin *et al.* (2002) planted *Ipomoea aquatica* on the front side of a FWS and *Paspalum vaginatum* on the other side under controlled conditions. They obtained good retention rates between the second and third months, but the densities used were greater than 30 plants/m². Likewise, Lin *et al.* (2002) explained that their wetland system required approximately seven months

to reach vegetation coverage approaching 80%, whereas in our study the vegetation covered more than 80% within five months, given the characteristics of the species used (*E. crassipes*) and the local weather conditions. This suggests that performance level established for pollutant removal may be achieved without full vegetation coverage, confirming the work by Lin *et al.* (2002). The results of this study suggest that replacing the plants five months after planting them would maintain the pollutant removal tendency and create macrophyte-free zones followed by plant-covered zones, thus allowing for high levels of dissolved oxygen, thereby increasing nutrient removal values.

Posadas (2001) stated that constructed wetland systems with 25% of the total size of the production ponds and 2-day retention time significantly improved channel catfish (*Ictalurus punctatus*) production. In this study, the size of the constructed wetland system was only 0.9% of the total size of the farm's reflecting pool, yet good removal rates were achieved due to climatic conditions and effluents had the largest loading of nitrogen compounds because they originated from fish and fingerling feeding processes. This is consistent with the results reported by Schwartz and Boyd (1995), who estimated that the area to treat aquaculture effluents should be 0.7 to 2.7 times the size of the pond.

Removal of nitrogen compounds

NH₄⁺ removal reached 67.9% efficiency throughout the study, suggesting that the system attained a certain balance due to macrophytes growth and their interrelationship with the microbial biofilm associated to the roots and the organic matter at the bottom of the pond. Phase 4 showed a reduction of 99.1% of NH₄⁺. These results are consistent with those reported by Spieles *et al.* (2000), who suggested that NH₄⁺ removal of a wetland system can range from 25 to 85%. In the present study, it was necessary to wait for two months after planting the water hyacinth in order to obtain sufficient NH₄⁺ removal rates. Moreover, it is possible that at the observed temperature (27 to 30 °C) macrophyte growth might have fostered the development of aerobic nitrifying organisms that could have performed the biological conversion from ammonium to nitrate.

Nitrite is an intermediate product of the nitrification process, which turns ammonium into nitrate (Fernandez *et al.*, 2005). It is removed from wetlands mainly through oxidation by microorganisms of the *Nitrobacter* genus. The mean value of NO_2^- obtained in the influent for the entire process was 0.012 ± 0.01 mg/L, while the value in the effluent was 0.009 ± 0.01 mg/L, which corresponds to 27.1% efficiency. Phase 5 showed the best removal efficiency (37.9%). Therefore, it can be assumed that at this stage the wetland system became stable and bacteria developed, which enabled removal of pollutants and water self-purification.

Nitrate remains in the water column, where it can be either assimilated by the macrophytic bacteria/microorganisms, or reduced to nitrogen gas by heterotrophic anaerobic bacteria. In this study, an average of 1.2 ± 0.2 mg/L NO_3^- was observed in the influent. The effluent, in turn, had a value of 1.0 ± 0.1 mg/L; hence, the removal rate was 14.2%. However, nitrate removal rate ranged from 26.7 to 30.8% in phases 4 and 5. Other authors conducting experiments under similar conditions reported similar values (Lin *et al.*, 2005; Schulz *et al.*, 2004). This proves that this parameter may have low removal efficiency under real production conditions. Comparing these data with studies conducted under similar conditions, we suggest that anaerobic bacteria communities in the bed of the system—responsible for the denitrification process—had limited growth. On the other hand, *Nitrosomonas* and *Nitrobacter*, responsible for the nitrification process that ultimately produces nitrate, experienced much better growth.

Total phosphorus removal

Total Phosphorus removal took place mainly through assimilation mechanisms of macrophytes and precipitation and accumulation of phosphorus on the substratum of the bed (Fernandez *et al.*, 2005). The average performance observed in this study was 23.0%. However, phases 4 and 5 showed removal rates ranging from 39.6 to 43.8%. These values are similar to those reported by Gentelini (2007) and Tilley *et al.* (2002), higher than those reported by Lin *et al.* (2005), and lower than those by Schulz *et al.* (2004) and Henry-Silva and Camargo (2006).

It is suggested that the constructed wetland system started maturing during phase 6, since vegetation covered more than 80% of the total area, which leads to higher phosphorus assimilation rates. Moreover, the hydraulic retention time made it possible for the wetland system to precipitate phosphorus in the effluent and accumulate it at the bottom of the constructed wetland.

BOD₅ removal

BOD₅ determines the availability of dissolved oxygen in the influent and the type of microorganisms participating in the organic matter degradation process (Fernandez *et al.*, 2005). If such microorganisms are aerobic, then the reactions will be quick and efficient. Conversely, if the organisms are anaerobic, the reactions will be slow and inefficient (Fernandez *et al.*, 2005). Therefore, oxygen availability is crucial for the biodegradation of organic matter. The average BOD₅ removal efficiency observed was 19.1% throughout the study. These removal values are lower than those reported by Ramírez *et al.* (2005), but higher than those reported by Lin *et al.* (2005), who used *Phragmites australis* under controlled conditions to obtain averages of 4.6 mg/L in the influent and 4.1 mg/L in the effluent. This constitutes a removal of 10.9% of the BOD₅. Low BOD₅ removal rates could be due to the fact that the transfer by diffusion of oxygen from the submerged parts of the macrophytes (aerenchyma) to the effluents was low. Likewise, the vegetation reduced the rate of atmospheric air incorporation by physical processes.

The results of this study allow us to conclude that the constructed wetland system with water hyacinth (*E. crassipes*) can remove BOD₅, NH_4^+ , NO_3^- , NO_2^- and TP when it is operated with an average flow of 132.7 ± 5.1 m³/day, a mean hydraulic retention time of 1.6 ± 0.1 days, and a mean hydraulic loading of 43.4 ± 1.7 cm/day. This assumes assessed conditions for an area equivalent to 0.9% of the fish production ponds.

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