Pilot study of a sequencing batch reactor for the treatment of wastewater from an animal food factory

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Estudio piloto de un reactor secuencial batch para tratamiento de aguas residuales de una fábrica de alimentos veterinarios

Estudi pilot d'un reactor seqüencial batch per a tractament d'aigües residuals d'una fàbrica d'aliments veterinaris

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RESUMEN

Se estudió la eliminación de nitrógeno y materia orgánica de las aguas residuales de una empresa de procesado de alimento para animales utilizando un reactor piloto secuencial tipo batch (Sequencing Batch Reactor o SBR). Las pruebas se llevaron a cabo con 2 tipos de agua residual: aguas de lavado caracterizadas por un alto contenido en materia orgánica, y aguas de condensado con una elevada concentración de nitrógeno amoniacal. El tiempo de operación del reactor fue de 252 días utilizando ocho etapas distintas que dependen del índice de carga orgánica (Organic Loading Rate o OLR) y del índice de carga amoniacal (Ammonia Loading Rate o ALR). Los rendimientos de eliminación más elevados se obtuvieron para un OLR de 3.24 g COD_F/L.d y un ALR de 1.102 g NH_4^+-N/L.d, con una relación agua de lavado / aguas de condensados de 9:1, y con una relación BOD_5 / NH_4^+-N en un rango de 2.0 a 4.0.

Palabras clave: Índice de carga amoniacal (ALR); Agua residual industrial; Reactor Secuencial de Batch (SBR); Índice de carga orgánica (OLR).

SUMMARY

The removal of organic matter and nitrogen in wastewater from an animal food processing company was studied using a pilot Sequencing Batch Reactor (SBR). Trials were carried out with 2 types of waste water; washing water which is characterized by a high content of organic matter and condensed water which has a high concentration of ammoniacal nitrogen. The time of operation of the reactor was 252 days using eight different stages depending on the organic loading rate (OLR) and ammoniacal loading rate (ALR). The highest removal efficiencies were obtained for an OLR of 3.24 g COD_F/L.d and an ALR of 1.102 g NH_4^+-N/L.d, with a ratio of 9:1 of washing water:condensed water and with the BOD_5/ NH_4^+-N relationship in a range of 2.0 - 4.0.

Keywords: Ammoniacal Loading Rate (ALR); Industrial wastewater; Sequencing Batch Reactor (SBR); Organic Loading Rate (OLR).

RESUM

S'ha estudiat l'eliminació de nitrogen i de matèria orgànica de les aigües residuals d'una empresa de processament d'aliments per a animals utilitzant un reactor pilot seqüencial tipus batch (Sequencing Batch Reactor o SBR). Les proves es van dur a terme amb 2 tipus d'aigua residual; aigües de rentat caracteritzades per un alt contingut en matèria orgànica i aigües de condensat amb una elevada concentració de nitrogen amoniacal. El temps d'operació del reactor va ser de 252 dies utilitzant vuit etapes diferents que depenen de l'índex de càrrega orgànica (Organic Loading Rate o OLR) i l'índex de càrrega amoniacal (Ammonia Loading Rate o ALR). Els rendiments d'eliminació més elevats es van obtenir per un OLR de 3.24 g COD_F/L.d i un ALR d'1.102 g NH_4+-N/L.d, amb una relació aigua de rentat / aigües de condensats de 9:1 i amb una relació BOD_5 / NH_4+-N en un rang de 2.0 a 4.0.

Paraules clau: Índex de càrrega amoniacal (ALR); Aigua residual industrial; Reactor Seqüencial de Batch (SBR); Índex de càrrega orgànica (OLR).

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1. INTRODUCTION

Wastewater in the food sector possesses high protein, nitrogen and COD contents (Dapena et al., 2006). In this work, we studied the treatment of wastewater from an animal food factory. In such factories, animal food is prepared using meat from the meat sector industry and slaughterhouse waste. The production of flour and fat is the main source of contamination from the food prepared in this type of industry. Animal food is made from viscera, feathers, tallow, blood, bone and fat originating from slaughterhouses, chicken and pig farms and other meat sector industries using continuous cooker batch and cooker systems (Deyanira, 2005). Cooking is performed at temperatures ranging from 110°C to 150°C, which causes frying and hydrolysis processes. The vapors generated during these processes are directed towards air-condenser systems and cooling towers, which generate water with high organic material and ammonium content (Jhons, 1995). Furthermore, the washing of vehicles, packaging, recipients and equipment for the storage of raw materials produces wastewater containing a large amount of organic matter. This water is easily treated, whereas the water from the cooking processes requires complex procedures to remove the organic matter and nitrogen.

The following nitrogen forms, which are of great environmental interest, are listed in descending order of their oxidation state: nitrate, nitrite, ammonia and organic nitrogen. They can be transformed biochemically; the ammonium ion is oxidized by autotrophic bacteria to nitrite and then to nitrate in the presence of oxygen and inorganic carbon (nitrification). Nitrate is reduced by heterotrophic bacteria to molecular nitrogen (N_2) in the absence of oxygen and the presence of organic carbon (denitrification). Nitrogen is an inert gas and is the main component of the atmosphere (Mahvi, 2008).

Wastewater can be treated under aerobic, anoxic or anaerobic conditions with different microbial communities, which can result in denitrification (Wilderer, 2001) or nitrification processes. The sequencing batch reactor (SBR) operates discontinuously while conducting sequential phases of nitrification and denitrification in the same treatment tank (Coromidas, 2006). Basic sequential SBR phases include filling, aeration, mixing, sedimentation, emptying, purging and inactivity (the latter is applied when the SBR is comprised of two reactors in parallel); each phase is performed for a set period of time (Wilderer, 2001; Mahvi, 2008). The phases are combined in different ways depending on the required water effluent quality.

A correlation between the nitrification capacity of the activated sludge and the ratio of BOD_5:NKT was observed. When this ratio increases, the amount of nitrifying bacteria decreases and the nitrification process thus loses efficiency. With a high BOD_5:NKT ratio, there is an excess of organic matter and a decrease in the amount of nitrogen-containing compounds, which favors the rapid growth of heterotrophic microorganisms (Cheng and Chen, 1994; Niel et al., 1993) to the detriment of autotrophic organisms. Conversely, various bacterial groups compete with the denitrificants for nitrate and transform it into products other than N_2. For this reason, an appropriate C/N relationship and a readily biodegradable carbon source are important factors for effective denitrification. Several reports of wide ranges of organic loading rates (OLR) (0.13-9.40 g COD_F/L.d) and ammoniacal loading rates (ALR) (0.01-5.95 g NH_4^+-N/L.d) in SBR reactors (Tables 1 and 2) have been published and describe the different percentages of OLR and ALR removal.

Table 1. *OLR values from different studies using SBR systems*

OLR (g COD_F/L.d)	COD_F REMOVAL (%)	REFERENCES
1.34 *	79.9	Sirianuntapiboon and Ungkaprasatcha, 2001
1.00 *	89.4	
0.68 *	95.6	
0.50 *	97.4	
1.20	96.0	Li et al., 2008
0.55	81.0-99.0	
0.92	-	Fongsatitkul et al., 2007
0.15-6.00	90	
3.20	80	
0.50-2.00	80-90	Arrojo et al., 2004
6.25	96	Ruiz et al., 2001
7.20	>86	
1.46-1.72	90-95	Figueroa et al., 2008
0.20-1.20	-	Timur and Ozturk, 1999
0.13-0.84	-	
0.4-9.4	64-85	Sunil et al., 2008

**g BOD_5/L.d*

Table 2. *ALR values from different studies using SBR systems*

ALR (g NH_4^+-N/L.d)	N-NH_4^+ REMOVAL (%)	REFERENCES
1.40	82	Fongsatitkul et al., 2007
2.40	-	
0.3-0.87	>95	
0.08-0.2	30-80	Arrojo et al., 2004
0.72	>85	
0.18-0.25	20-45	Figueroa et al., 2008
0.063-1.12*	94	Timur and Ozturk, 1999
0.01-0.08*	92-99	
1.00	-	Doyle et al., 2001
1.20	-	
5.91	-	
0.70	-	

**g NTK-N/L.d*

This study describes one example of the influence of variations in the OLR and ALR on the removal of ammonia and organic matter. The SBR effluents were monitored for COD, nitrogen and solid content. The experiment described in this study provides a useful reference for defining adequate conditions for performing this type of water treatment process.

2. MATERIALS AND METHODS

2.1 Experimental description

A circular tank with a volume of 2.96 m^3 was placed in an animal food factory located in the municipality of Amagá (Antioquia), Colombia. The tank was divided into 2 chambers: the first served as the primary settler and the second housed the SBR. Each SBR cycle included filling, reaction, sedimentation and emptying steps. In total full-cycle time of 8 hours, the cycle was divided into a 6-hour reaction phase, alternating between an intermittent ventilation phase (8 minutes) and an anoxia phase (mixture, 15 minutes), and a 2-hour sedimentation phase. The SBR was filled in an average time of 35 minutes during a cycle of mixing and aeration. The unloading was performed in 5 minutes. Additionally, to provide organic carbon for the denitrification phase, short filling times were performed every 2 hours during the reaction.

2.2 Wastewater

Two types of wastewater were studied. The first type of wastewater was generated by washing the vehicles, recipients, equipment and packaging, and the second was generated from the condensate generated after transforming raw materials into fats and meal for animals by cooker processes. Washing water entered the SBR after a preliminary treatment consisting of a skimmer, a system of coagulation-flocculation and a sedimentation system. The properties of the two wastewater types are listed in Table 3.

PARAMETER	UNITS	WASHING WATER	CONDENSATE WATER
		Average ± Std. Dev.	Average ± Std. Dev.
COD_T	mg/L	8308.33 ± 1823.38	1381.14 ± 483.64
COD_F	mg/L	3922.44 ± 1539.83	822.47 ± 215.33
BOD_5	mg/L	2684.54 ± 1686.49	563.42 ± 219.39
TSS	mg/L	1710.70 ± 973.84	7.19 ± 3.12
VSS	mg/L	1242.15 ± 817.43	6.13 ± 2.91
NH_4^+-N	mg/L	365.14 ± 85.66	615.54 ± 129.39
pH	-	6.11 ± 0.40	9.64 ± 0.47
BOD_5/NH_4^+-N	-	7.45 ± 4.59	0.94 ± 0.36

2.3 Sludge

The reactor was inoculated with 1.0 g/L of volatile suspended solids (VSS) from an UASB (upflow anaerobic sludge blanket) reactor located in the same factory, which was acclimated to high organic loading with a sludge volume index (SVI) of 16.8 mL/g, indicating a mud with good settling capacity and 1,075 g of VSS/L originating from the mixed liquor of the activated sludge system at the municipal treatment plant in Medellín, Colombia with an SVI of 142.97 mL/g (i.e., a mud with an acceptable settling capacity).

2.4 SBR operation

Experiments were divided into eight different stages that varied in the ratio of washing water and condensate (Table 4). The sludge age (θc) was 30 days to enhance oxidizing bacterial growth.

Table 4. SBR operating conditions

Stages	Time of Operation (d)	Mix ratio	
		Washing water (%)	Condensate water (%)
I	0 - 21	100	0
II	22 - 43	100	0
III	44 - 77	100	0
IV	78 - 98	90	10
V	99 - 154	80	20
VI	155 - 189	50	50
VII	190 - 231	30	70
VIII	232 - 252	0	100

2.5 Chemical analysis

The chemical oxygen demand of the filtrate (COD_F), total chemical oxygen demand (COD_T), biochemical oxygen demand (BOD), total solids (TS), volatile solids (VS), sedimentable solids (SSE) and the SVI were determined according to the established protocols of the Standard Methods (APHA, 2005). The ammonium (NH_4^+-N) content was determined with a Kjeldahl instrument (Büchi), and the pH was determined with a Schott handylab pH 11/SET. The protein concentration was determined by Lowry's colorimetric method (Lowry et al., 1951) modified by Peterson (Peterson, 1977).

2.6 Statistical analysis

The experimental protocol was designed to examine the effects of different OLR and ALR values on the operational efficiency of the SBR, and the results were subjected to the Statgraphics Plus 5.1 program. The results are represented as the average ± standard deviation.

3. RESULTS AND DISCUSSION

3.1 Organic and ammoniacal loading rate variation

Different ratios of washing water and condensate were used to obtain different OLR and ALR values (Figure 1). During the first 3 stages, the SBR used only washing water to adapt the bacteria to the organic substrate and to avoid high ammonium concentrations that would be inhibitory. For this reason, the condensed water was added during the later stages. The OLR for these three early stages ranged from 2.26 to 4.25 g COD_F/L.d, whereas the ALR ranged from 0.33 to 1.01 g NH_4^+-N/L.d, with a lower ALR (0.33 g NH_4^+-N/L.d) occurring during stage I. During stages IV though VII, the condensed and washing waters were mixed, which resulted in an ALR increase and OLR decrease. Notably, the OLR peaked in stage V, an event caused by an increase in the concentration of organic material in the wastewater due to overloading of the cooker systems. Stage VIII contained only condensate, which re-

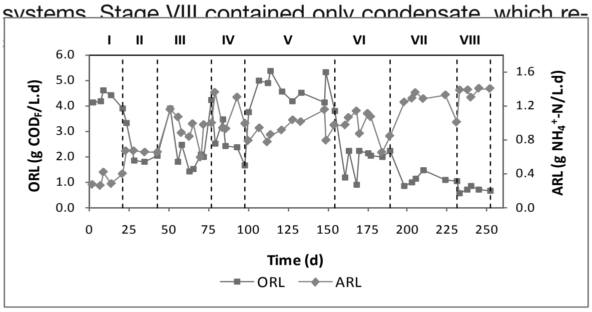


Figure 1. *Relationship between the OLR and ALR*

The OLR values in this study varied from 0.71 to 4.55 g COD_F/L.d, and the ALR values varied from 0.33 to 1.37 g NH_4^+-N/L.d. Both ranges have been observed in previous experiments cited in the bibliography (Tables 1 and 2).

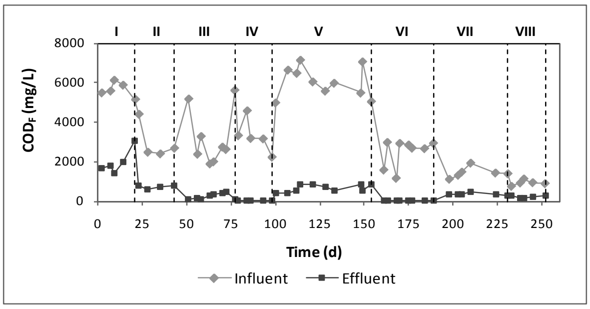
3.2 SBR efficiency

The COD_F values of the influent ranged from 948 mg/L to 6,065 mg/L, with the latter value occurring during stage V. Conversely, the effluent values ranged from 42 mg/L to 1,987 mg/L (Figure 2). Therefore, the maximum percentage removed was 98.7% and 97.6% during phases IV and VI, respectively, with OLR values of 2.49 and 1.87 g COD_F/L.d and an ALR value ranging from 1.10 to 0.96 g NH_4^+-

N/L.d. In contrast, the lower percentages removed were observed during phases I, II and VIII and were 64.35%, 74.79% and 74.72%, respectively. The low efficiencies in stages I and II were attributed to the adaptation of the biomass to the substrate. The low efficiency in stage VIII (condensate only) was attributed to bacterial inhibition, which occurred due to a high concentration of ammonia and a low concentration of organic carbon. These concentrations resulted in an accumulation of ammoniacal nitrogen in the reactor, which was confirmed by the characterization of the substrate (Table 3) and matched the minimum OLR (0.71 g COD_F/L.d) and the maximum monitored ALR (1.37 g NH_4^+-N/L.d) during the aforementioned stage.

The BOD_5 varied from 616 mg/L to 4,305 mg/L in the influent and from 33 mg/L to 391 mg/L in the effluent (Figure 2b). The maximum COD_F efficiencies were obtained in phases IV and VI and were 98.14% and 94.54%, respectively.

a)



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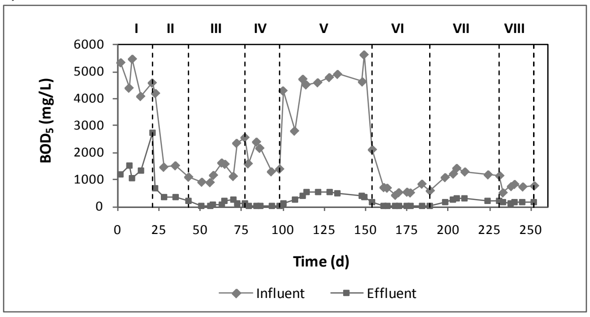


Figure 2. *Temporary variations of a. COD_F and b. BOD_5 in*

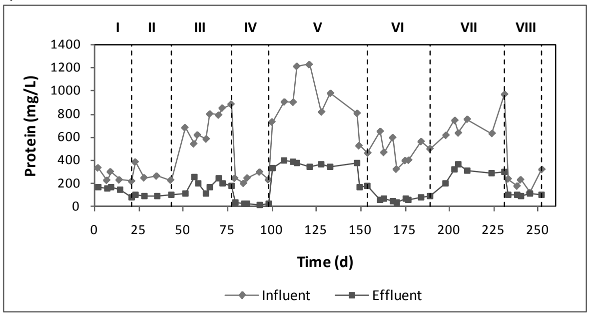
SBR influent and effluent

Table 5 illustrates that the removal of organic matter gradually increased until stage IV. Therefore, the bacteria were acclimating to the influent and were not inhibited by the gradual increase in ammoniacal nitrogen. However, the efficiencies decreased in stage V, which correlated to a significant increase in the organic loading in the influent caused by failures in the industrial processes. Despite this increase, the SBR was able to remove much of the incoming organic matter, as demonstrated by the high capacity of the SBR to operate with discharges of strong functional load variations. In stage VI, the OLR decreased and thus increased the SBR efficiency, but the rate of removal of organic matter declined in phases VII and VIII as a concurrent OLR decrease and ALR increase occurred (Table 5). These two final stages were the key to the industrial wastewater process studied, as they demonstrated high nitrogen loads and low carbon loads (extremely low C/N ratios), which inhibited the bacteria. Therefore, the condensate from this company cannot be treated without mixing it with washing water or, in its absence, without the addition of an external carbon source.

Stages	ORL (g COD_F/L.d)	ARL (g N-NH_4^+/L.d)	Removal (%)		
			COD_F	BOD_5	NH_4^+-N
I	4.25 ± 0.28	0.33 ± 0.08	64.35 ± 3.69	66.47 ± 5.78	29.39 ± 5.14
II	2.26 ± 0.71	0.66 ± 0.01	74.69 ± 5.43	79.26 ± 4.12	49.69 ± 6.83
III	2.43 ± 1.07	0.94 ± 0.17	89.85 ± 7.25	91.33 ± 6.95	56.25 ± 8.09
IV	2.49 ± 0.63	1.10 ± 0.21	98.68 ± 0.45	98.14 ± 0.47	70.51 ± 7.56
V	4.55 ± 0.58	0.92 ± 0.12	88.76 ± 0.61	90.91 ± 2.70	19.18 ± 2.64
VI	1.87 ± 0.52	0.96 ± 0.17	97.57 ± 1.33	94.54 ± 0.99	60.89 ± 7.80
VII	1.09 ± 0.20	1.25 ± 0.13	82.94 ± 4.20	80.50 ± 2.32	40.98 ± 2.08
VIII	0.71 ± 0.10	1.37 ± 0.04	74.72 ± 8.28	76.78 ± 5.26	58.52 ± 1.89

The protein concentration ranged from 218.72 mg/L to 858.12 mg/L in the influent and from 25.49 mg/L to 328.27 mg/L in the effluent (Figure 3a). Stage V demonstrated the highest concentrations of protein and organic matter. Conversely, the NH_4^+-N variation was between 435.62 mg/L and 686.83 mg/L in the influent and between 163.82 mg/L and 363.95 mg/L in the effluent (Figure 3b).

a)



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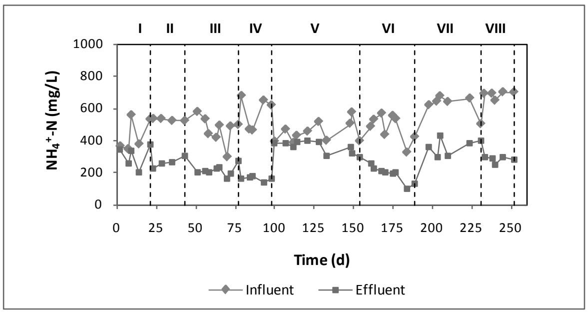


Figure 3. *Temporary variations in a) protein and b) NH_4^+-N concentration*

The NH_4^+-N removal was greater in phases IV and VI and was determined to be 70.51% and 60.89%, respectively. These two stages yielded ALR values of 1.102 and 0.96 g NH_4^+-N/L.d, respectively. Conversely, lower percentages removed were observed in stages I and V with values of 29.39% and 19.18%, respectively (Table 5).

The BOD_5:NH_4^+-N ratio was high in stages I and V (Figure 4), implying a high carbon to nitrogen ratio that did not favor the growth of oxidizing bacteria and thus affected NH_4^+-N removal. Conversely, the BOD_5:NH_4^+-N ratio decreased significantly in stages II, III, IV, VI VII and VIII, an occurrence that favored the removal of ammonia due to an adequate carbon to nitrogen ratio and thus likely decreased the oxidizing bacterial population. We conclude that the appropriate balance between BOD_5 and NH_4^+-N in the treatment of analyzed wastewater falls within the 2.0 to 4.0 range, and similar results were observed by Cheng and Chen (1994), Niel et al. (1993), Verhagen and Laandbroek (1991) and Hanaki et al. (1990).

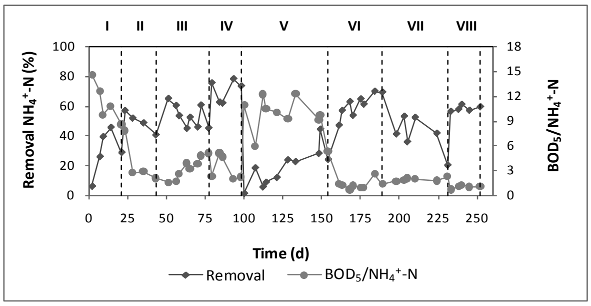
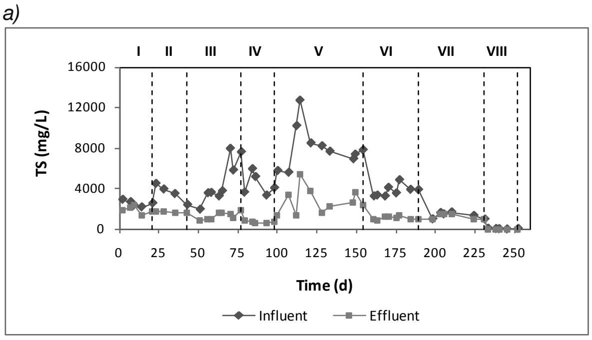


Figure 4. *Relationship between the removal of NH_4^+-N and the ratio of BOD_5:NH_4^+-N*

The TS concentrations ranged from 75.4 mg/L to 8,112.3 mg/L in the influent and from 48.4 mg/L to 2,825.0 mg/L in the effluent. The highest concentrations in the influent and the effluent were observed during stage V, and the lowest concentrations were observed during stage VIII (Figure 5a). This result was expected because phase VIII corresponds to the treatment of condensate water only, which contained a low amount of solids according to the performed analysis (Table 3). The average VS variation (Figure 5b) ranged from 64.0 mg/L to 6,789.9 mg/L in the influent and from 34.7 mg/L to 1,800.9 mg/L in the effluent. Like the TS, the highest VS concentrations in both the influent and effluent were found in stage V, and the lowest concentration were found in phase VIII. Conversely, the SSE ranged from 0 mL/L to 834.5 ml/L in the influent and from 0 mL/L to 31.0 mL/L in the effluent. In both cases, the null values were observed in phase VIII (condensate treatment only) (Figure 5c).

The high solid content variability during the 252 days of experimentation with the SBR was consistent with the two types of treated wastewater. The largest solid concentrations were observed in stages I through V, as the largest percentage of water entering the reactor at these stages was washing water. However, phases VI to VIII involved a higher percentage of condensate, which possessed a high nitrogen loading and a low solid concentration. Similarly, the results indicate that the SBR may be used to efficiently remove suspended solids in the reactor during sedimentation and that this process can be performed in the same tank. Therefore, in a full-scale treatment plant, the incorporation of a sedimentation tank after SBR treatment is unnecessary.

a)



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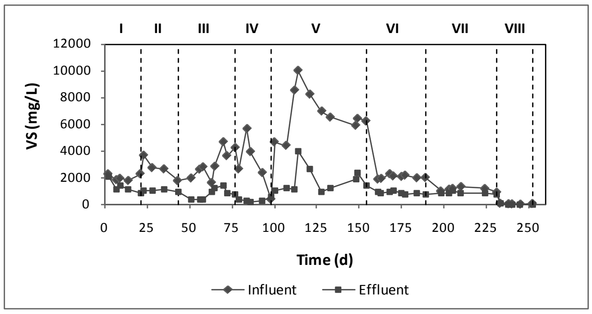

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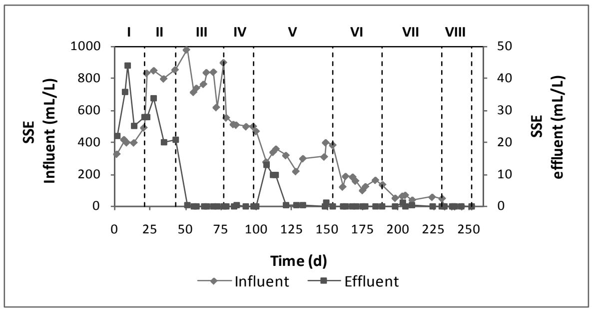

Figure 5. *Temporary variations in a) TS, b) VS and c) SSE*

The average pH ranged from 5.91 to 9.48 in the influent and from 7.12 to 7.84 in the effluent (Figure 6). The highest average value for the influent occurred during stage VIII (condensate only) and the lowest average value occurred during stage III (washing water only). The washing water was characterized by a low pH;, in contrast, the pH was high in the condensate due to the presence of ammonia (Table 3). As the washing water mixes with the condensate in various proportions, the pH tends to peak, corresponding to when only condensate exists (stage VIII) (Figure 6). Conversely, the pH in the effluent was extremely homogeneous, and its lack of variability demonstrates that a buffer solution created in the SBR system can regulate significant changes in pH.

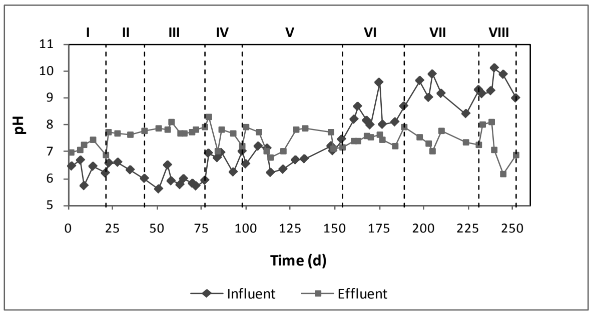

Figure 6. *pH behavior*

However, Dapena et al. (2006) and Rodriguez et al. (2011b) observed that the optimal pH is between 7.5 to 8.5 for nitrifying bacterial growth and between 7.0 and 9.0 for denitrifying bacterial growth. In agreement with this result, the stage that most favored bacterial growth in the present study was stage VI with an average pH of 8.4.

4. CONCLUSIONS

In this experiment where washing and condensed water generated from the food industry were sequentially treated, stages IV and VI yielded the greatest removal of organic matter, NH_4^+-N and TS by the SBR. Therefore, the 2 types of water can be treated together if their ratio (BOD_5:NH_4^+-N) is between 2 and 4. However, the biomass must be adapted to the substrate.

5. ACKNOWLEDGEMENTS

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