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Innovative anaerobic upflow sludge blanket filtration combined bioreactor for nitrogen removal from municipal wastewater

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ABSTRACT: In this research, a novel laboratory scale anaerobic/upflow sludge blanket filtration combined bioreactor was designed and operated to improve the efficiency of the upflow sludge blanket filtration process for the simultaneous removal of phosphorus and nitrogen from wastewater. The anaerobic/upflow sludge blanket filtration technique was developed by adding an anaerobic reactor to its influent and operated by varying the main process parameters in order to gain the optimum conditions. The results showed that biological removal efficiency of nitrogen and preservation of sludge blanket strongly depend on wastewater characteristics, hydraulic retention time, sludge age and process controlling parameters. The combined bioreactor performed a total nitrogen removal efficiency of 96.6 % with the sludge age of 25 days, total hydraulic retention time of 24 h and optimum "chemical oxygen demand/nitrogen/phosphorus" ratio of 100/5/1. This ratio also improved the compaction quality of sludge blanket in the upflow sludge blanket filtration clarifier. The average specific nitrification and denitrification rates occurred during the process can be expressed as 4.43 mg NOx-N produced/g VSS.d and 5.50 mg NOx-N removed/g VSS.d at the optimum ratio, respectively. To avoid sludge rising due to denitrification process, the optimum total hydraulic retention time of 16 to 24 h was achieved based on the effluent quality. This study suggested that the anaerobic/upflow sludge blanket filtration bioreactor at the optimum operational conditions can be an effective process for removal of nutrients from municipal wastewater.

Keywords: *Bioreactor; Municipal wastewater; Nutrients; Upflow sludge blanket filtration*

INTRODUCTION

Biological nitrogen and phosphorus removal from wastewater is an effective approach for prevention of eutrophication in water bodies (Lu and Huang, 2010; Babel *et al.*, 2009). The adverse effects of eutrophication have frequently been discussed by many authors and vary from decrease in aesthetic and quality depletion of the affected receiving water bodies to increase in treatment costs (Gerardi, 2002; Hu *et al.*, 2003; Seviour *et al.*, 2003; Yang *et al.*, 2005; Zaman, 2010). Biological removal of nitrogen and phosphorus is usually integrated in wastewater treatment systems whenever treated effluent is to be discharged to sensitive receiving water bodies or to be exploited for reuse (Tchobanoglus *et al.*, 2003; WEF *et al.*, 2006; Akpor *et al.*, 2008; Suthar and Singh, 2008; Hooshyari, 2009). There are several varieties of configurations such as the University of Cape Town treatment process and modified bardenpho in combined nitrogen and phosphorus removal processes based on influent characteristics, effluent limits (WEF *et al.*, 2006) and desired operational conditions. All of these configurations consist of the same basic anaerobic/anoxic/aerobic components to achieve nitrification/denitrification and enhanced biological phosphorus uptake. In these configurations, chemical compounds addition and filtration of final effluent through the sand or other media are required for the removal of particulate matter when low nitrogen and phosphorus in the effluent are desired (Tchobanoglus *et al.*, 2003; Priadi *et al.*, 2011).

Nitrification and denitrification are the well known biological processes which primarily remove nitrogen from its solutions (Tchobanoglus *et al.*, 2003). Nitrification is the two-step biological conversion of ammonia to nitrite and then to nitrate under aerobic

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conditions by one group of autotrophic bacteria include nitrosomonas and nitrobacter. Denitrification involves the biological reduction of nitrate to nitrogen gas in the absence of dissolved oxygen under anoxic conditions by a wide range of heterotrophic bacteria species, for example achromobacter, bacillus and flavobacterium and some autotrophic bacteria, such as nitrosomonas europaea (Tchobanoglus *et al.*, 2003; Gerardi, 2006; Henze *et al.*, 2008; Abdulsalam *et al.*, 2011).

The upflow sludge blanket filtration (USBF) process is a novel configuration that incorporates an anoxic selector zone, an aeration unit and an upflow sludge blanket filtration clarifier in one integrated bioreactor (Wang *et al.*, 2008; Rajakumar *et al.*, 2011). In the USBF plant, wastewater enters the anoxic compartment where it mixes with activated sludge recycled from the bottom of the clarifier. The mixed liquor eventually underflows into the aerobic compartment. After aeration, a stream of the mixed liquor enters the bottom of a prism or cone-shaped clarifier and, as it rises, upward velocity decreases until the flocs of cells become stationary. Then, sludge flocs are separated from liquid by upflow sludge blanket filtration and clear effluent overflows into a collection trough and is discharged from the system (Su *et al.*, 2004; Wang *et al.*, 2008). A recently published paper about USBF process indicates that the efficiency of single stage USBF for nitrogen removal is about 80.2 % at the aeration time of 6 h (Mahvi *et al.*, 2008). Due to undesired efficiency of single stage USBF for phosphorous removal (Mahvi *et al.*, 2008; Wang *et al.*, 2008), the novel Anaerobic/USBF combined bioreactor was developed to promote the simultaneous removal of nitrogen and phosphorous from wastewaters. The objective of this paper is nitrogen removal with the anaerobic/USBF combined bioreactor. It is worth something as prior to this research, no study has been published about biological removal of nutrients by anaerobic/USBF process technique.

This research was conducted in pilot center of Isfahan University of Medical Sciences in Isfahan, Iran during 2009.

MATERIALS AND METHODS

Experimental setup

The experiments were conducted using a laboratory scale Anaerobic/ USBF combined bioreactor (Fig. 1) and the operational parameters for the lab-scale Anaerobic/USBF combined bioreactor are listed in Table 1.

In the Anaerobic/USBF process technique, anaerobic/aerobic configuration was installed as an integrated unit for performance of enhanced biological phosphorus removal (EBPR). The anoxic zone was built for dissimilarity nitrate reduction by denitrifier species, such as *Achromobacter*, *Acintobacter* and phosphorus uptake by polyphosphate accumulating organisms e.g., Pseudomonas and Enterobacter (Hu *et al*, 2002; Carvalho *et al.*, 2007). Function of the aeration zone was nitrification and phosphorus luxury uptake.

The recycling sludge from the USBF clarifier was directed to the anoxic zone by a submersible pump. The amount of return activated sludge (RAS) from the clarifier was controlled and monitored by a full automatic timer, which in turn controlled the amount and time of sludge returning.

Mixed-liquor from anoxic zone was recycled to anaerobic reactor by an Etatron pump for EBPR implementation. The RAS and anoxic recirculation rates were typically four and two times respectively as many as the influent flow rate.

Anaerobic/USBF combined bioreactor was placed into a water bath equipped with aquarium heaters and thermocouple to operate at the constant temperature of 28±1°C. Required air for aeration and mixing in the aerobic zone was supplied by the Hailea air compressor with maximum discharge of 90 L/min and injected via three parallel tube diffusers. The airflow rate was

Table 1: Operational parameters for the lab-scale Anaerobic/USBF combined bioreactor

Parameters	Anaerobic reactor	Anoxic reactor	Aerobic reactor	USBF clarifier
Volume (L)	3	6	9	2
Flow rate (L/day)			10-60	
HRT (h)	1.2-7.2	2.4-14.4	3.6-21.6	0.8-4.8
SRT (day)	-	-	10-30	-
Average MLSS (mg/L) *	2605	3290	3735	6200
Average MLVSS (mg/L) *	2115	2575	2865	-

*At the optimum COD/N/P ratio of 100/5/1 regulated with three manual valves to supply the dissolved oxygen demand (DO) at a concentration of 4± 0.5 mg/L in the mixed-liquor of aerobic zone. The mixing of anaerobic and anoxic reactor contents was carried out by a mixer with the speed of 32 rpm.

Operational procedure

The synthetic wastewater containing glucose as the main organic source, NH_4HCO_3 as nitrogen (N) source and KH_2PO_4 and K_2HPO_4 as phosphorus (P) sources was introduced to the system during operation. The synthetic wastewater characteristics have been depicted in Table 2 (Smolders *et al.*, 1994; Hu *et al.*, 2003; Kishida *et al.*, 2006). The sludge which obtained from Isfahan municipal wastewater treatment plant was used as a seed. The composition of ingredients in synthetic wastewater was determined on the basis of desired chemical oxygen demand (COD) concentration, COD/N and COD/P ratios. In order to evaluate the effects of COD/N/P ratios on the efficiency of the system and reach the optimum ratio, COD/N and COD/P ratios were ranged from 25 to 6 and from 100 to 30 respectively, based on constant COD concentration of 750 mg/L.

Prepared synthetic wastewater was continuously pumped into the Anaerobic/USBF combined bioreactor with the flow rate of 20 L/day under the aforementioned conditions. Using this flow rate resulted in the hydraulic retention time (HRT) of 3.6 h, 7.2 h and 10.8 h, in the anaerobic, anoxic and aerobic reactors, respectively. In the series of experiments assessing the influence of various HRT and COD/N/P ratios on system efficiency, the sludge retention time (SRT) of 25 days was maintained. At the optimum COD/N/P ratio, overall HRT was set variably from 12 to 48 h to select the optimum HRT.

Mass balance calculations were developed to determine the actual changes of nitrogen and other parameters in each reactor on the basis of influent, effluent and return flows.

At the end of experiments, to estimate the values of the selected kinetic parameters, continuous feeding of the system was interrupted and the system was run under the batch mode by hydraulic isolation of each single tank. Instant addition of nitrate (about 30 mg NO_3 –N /L) and organic substrate (200 mg COD/ L) took place directly in the anoxic compartment. At the same time, ammonia was added in excess amount (30 mg NH_4-N /L) into the aerobic tank. Samples of mixed liquor were taken from each reactor at fixed time intervals and were immediately analyzed (Warner *et al*., 1986; Harremoës and Sinkjaer 1995; Ekama and Wentzel 1999; Dincer and Kargi 2000; Kapagiannidis *et al*., 2006).

Sampling and Analysis

The system was monitored for about one month by allowing the synthetic wastewater to reach steady state conditions and then operated in seven months. At least three runs of steady state data were collected

Table 2: Composition of synthetic wastewater used in this study

Chemicals	Concentrations
$C_6H_{12}O_6.H_2O$	773.43 mg/L
NH_4HCO_3	variable as COD/N
KH_2PO_4	variable as COD/N
K_2HPO_4	variable as COD/N
$MgSO_4.7H_2O$	as Mg/P= 0.56
$CaCl_2.2H_2O$	as Ca/P= 0.32
$FeCl_3.6H_2O$	as Fe/COD= 0.5/100
Trace elements *	0.5 mL/L

*Trace element compounds include: $FeCl_3$.6H2O 1.5 g/L, H_3BO_3 0.15 g/L, $CuSO_4.5H_2O$ 0.03 g/L, KI 0.03 g/L, $MnCl_2$.$4H_2O$ 0.12 g/L, $NaMoO_4.2H_2O$ 0.06 g/L, $ZnSO_4$ .H_2O 0.12 g/L, $CoCl_2.6H_2O$ 0.15 g/L.

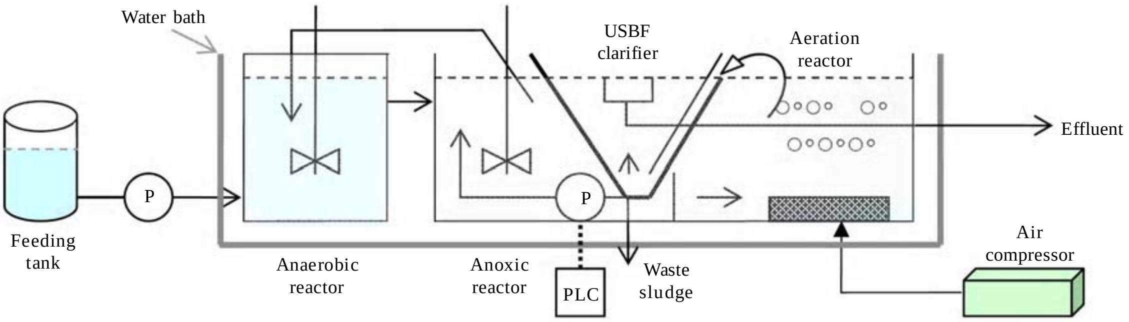

Fig. 1: Schematic diagram of the lab-scale Anaerobic/USBF combined bioreactor

from each reactor during each phase of experiments to characterize each of them.

Samples were collected from influent, effluent and sampling port of each reactor. Temperature, DO and pH were daily measured in each reactor immediately before sampling. DO measurements were carried out using a YSI 55 DO meter (YSI Company Inc., USA) and a Schott pH meter model CG-824 was used for pH analysis.(Schott UK Ltd). The samples were analyzed immediately after centrifuge. Soluble chemical oxygen demand (sCOD), ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), soluble phosphorus (PO_4-P), mixed liquor suspended solid (MLSS) and mixed liquor volatile suspended solid (MLVSS) were analyzed in accordance with standard methods for the examination of water and wastewater (APHA, *et al.*, 2005).

RESULTS AND DISCUSSION

The novel Anaerobic/USBF combined bioreactor was developed to promote the simultaneous removal of nitrogen and phosphorous from wastewater. At this paper, it was focused on evaluation of nitrogen removal using Anaerobic/USBF combined bioreactor.

Nitrogen removal was carried out using preanoxic denitrification. In order to evaluate the influence of COD/N/P ratios on system efficiency and reach to the optimum ratio, the COD/N ratios of 20, 16, 14, 12, 10, 8 and 6 were examined at the constant COD of 750 mg/L, total HRT of 24 h and SRT of 25 days. The average total Kjeldahl nitrogen (TKN) and average total nitrogen (TN) removal efficiency at varying COD/N ratio are shown in Figs. 2 and 3. It can be observed in Figs. 2 and 3 that the average TKN removal efficiency and the average effluent TKN were approximately constant but the TN removal efficiency was decreased with decreasing COD/N ratio. The results also indicated that the average total nitrogen and the average TKN removal efficiency are 96.61 % and 99.68 % respectively, which was obtained at the optimum COD/N/P ratio of 100/5/1 and the compaction of sludge blanket at this ratio was better than that in other ratios.

Tay *et al*. (2003) examined the effects of COD/N/P ratio on nitrogen and phosphorus removal in a single upflow fixed-bed filter provided with anaerobic, anoxic, and aerobic conditions. The authors revealed that phosphorus removal efficiency was affected more by its own concentration than that of COD and N concentrations, while nitrogen removal efficiency was unaffected by different phosphorus concentrations. At the COD/N/P ratio of 300/5/1, both nitrogen and phosphorus were effectively removed using the filter, with removal efficiencies of 87 % and 76 %, respectively (Tay *et al.*, 2003).

Figs. 4 and 5 illustrate the average TKN and average TN removal efficiency in the anaerobic/USBF combined bioreactor at the optimum COD/N/P ratio of 100/5/1 respectively. The similar average removal efficiency (H”33.2 %) was observed in the anaerobic unit for both TKN and TN. However, the highest average removal efficiency for TKN in aerobic unit was found to be 94.7 % as compared to highest average removal efficiency for TN in anoxic unit (60.01 %). The above results confirmed that nitrification and denitrification processes have been taken place in the aerobic and anoxic reactors respectively.

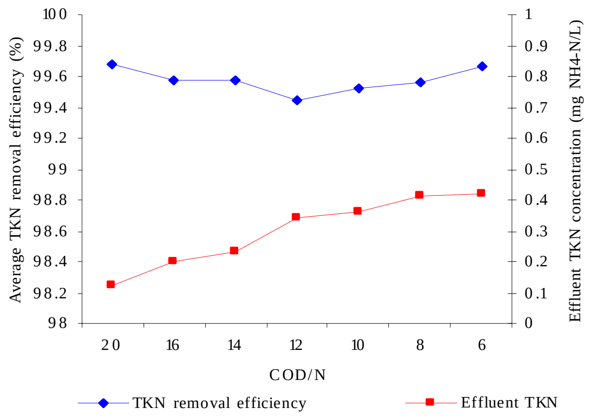

Fig. 2: The average TKN removal efficiency versus COD/N variations (HRT=24 h, SRT=25 days)

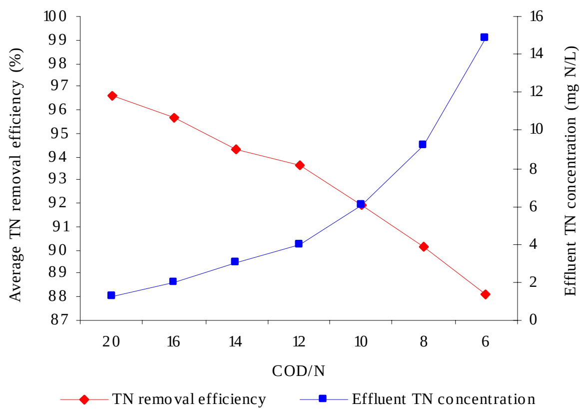

Fig. 3: The average TN removal efficiency versus COD/N variations (HRT=24 h, SRT=25 days)

Nitrification rates at different aerobic TKN loading rates are shown in Fig. 6. Nitrification rate has increased with increasing ammonium loading. By a TKN loading rate of 18.18 g NH_4-N/m^3.d, nitrification rate at the optimum ratio was 17.88 g NH_4-N removed/m^3.d and 12.688 g NO_X-N produced/m^3.d. Because some of the aerobic loading rate was consumed for cell anabolism, nitrification as g NO_X-N produced/m^3.d was less than that of as g NH_4-N removed/m^3.d.

During the experimental work, the average MLSS and MLVSS concentration were 3735 mg/L and 2865 mg/L at the optimum ratio, respectively. Thus, the average specific nitrification rate in the aerobic reactor can be expressed as 4.428 mg NO_x-N produced/g VSS.d at the optimum ratio. Nevertheless the maximum specific nitrification rate in the aerobic reactor was equal to 33.912 mg NO_x-N produced/g VSS.d at the COD/N ratio of 6.

According to experiments and Table 1, the average specific denitrification rate was 5.5 mg NO_x-N removed/ g VSS.d at the optimum ratio.

The results obtained from the experiments under batch condition for determination of kinetic parameters of nitrification and denitrification processes were demonstrated in Figs.7 and 8. The maximum specific nitrification rate (SNR) and half saturation constant for ammonium-nitrogen were 1.05 mg oxidized NH_4-N/ g VSS.h and 2.59 mg/L, respectively. Fig. 7 indicates that high NH_4-N concentrations ensure the process description by zero order kinetics. As nitrogen becomes scarce i.e. NH_4-N concentrations below 10 mg/L, the reaction is described by transition between zero and first order kinetics. Fig. 8 confirms that denitrification process follows zero order kinetics with the specific denitrification rate (SDNR) of 3.26 mg reduced NO_3-N/ g VSS.h.

Nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter* exhibit different substrate concentration sensitivities. Media containing low substrate concentrations (10 mg NH_4/L) can give larger most probable number of ammonia oxidizers than media containing higher NH_4 concentrations. Also, ammonia oxidation is inhibited at high substrate concentrations (Suwa *et al.*, 1994; Princic *et al.*, 1998; Gujer, 2010). Based on mentioned principles, nitrogen removal decreases as the influent TKN/COD ratio increases (Henze *et al.*, 2008), which is in agreement with the results obtained from this study (Figs. 2-8).

Biological reduction of nitrate to nitrite and N_2 gas requires a suitable electron donor. The rate of denitrification depends primarily upon the nature and concentration of the organic matter present as electron donor (Plosz, 2007). It is commonly accepted that denitrification is zero-order with respect to nitrate concentration down to very low levels (Sedlak, 1991).

SRT is one of the significant parameters that affects on biological nutrient removal processes. Fig. 9 illustrates SRT effects on average TN removal efficiency. The efficiency of TN removal increased with increasing SRT.

Under long aerobic SRT, more oxidation of organic matter can be obtained, leading to a higher rate of nitrogen removal (You *et al.*, 2003). However, it may adversely affect the biological removal of phosphorus due to the secondary release of phosphorus because of an increase in endogenous respiration in the aerobic

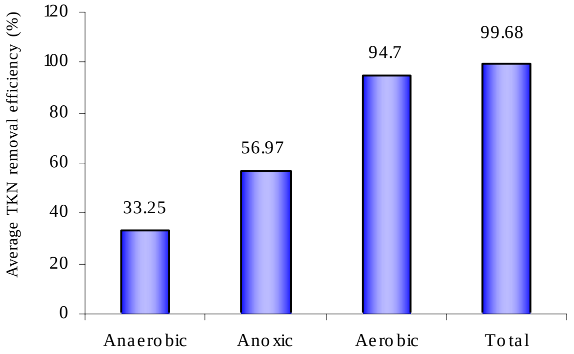

Fig. 4: The average TKN removal efficiency in the reactors at the optimum COD/N/P ratio (HRT=24 h, SRT=25 days)

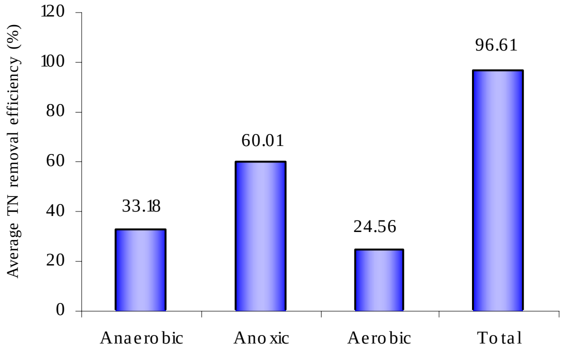

Fig. 5: The average TN removal efficiency in the reactors at the optimum COD/N/P ratio (HRT=24 h, SRT=25 days)

zone. Hence, optimum SRT ought to be selected according to the most optimal settling condition and desirable efficiency for BNR (You *et al.*, 2003). It has been reported that SRT of 10-12 days is an optimal range for the maximum removal of both N and P (Chuang *et al.*, 1997; Kargi and Uygur 2002). The maximum SRT value obtained after 10 days was in conformity with the present studies so that TN and TP removal efficiency were determined 90.4 % and 86.0 % at the sludge age of 10 days. When the sludge age increased to 30 days, these amounts were changed to 96.9 % and 81.33 % respectively.

In order to select optimum HRT, the effect of total HRT on PO_4-P, TN, sCOD removal efficiency and effluent TSS were examined in the lab-scale Anaerobic/USBF combined bioreactor. The compaction of sludge blanket for the present study was weak with a total HRT of less than 16 h and more than 24 h, optimum total HRT can be selected between 16 and 24 h for this configuration, based on effluent quality (Fig. 10). It was obvious that rising sludge due to denitrification in the USBF clarifier has increased with increasing HRT. This conclusion corresponds with researches on other processes of nutrient removal (Tchobanoglus *et al.*, 2003; WEF *et al.*, 2006; Henze *et al.*, 2008).

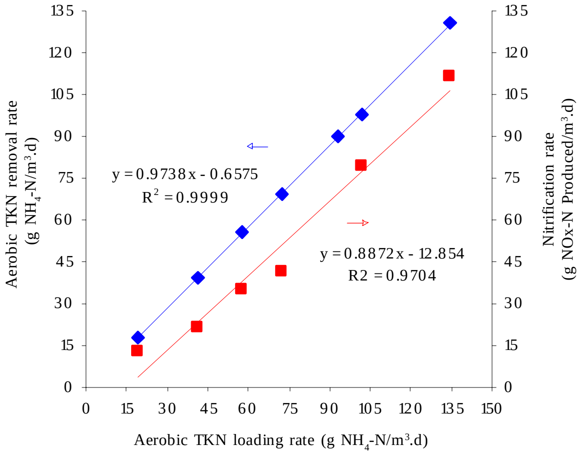

Fig. 6: The average nitrification rates at various aerobic TKN loading rates

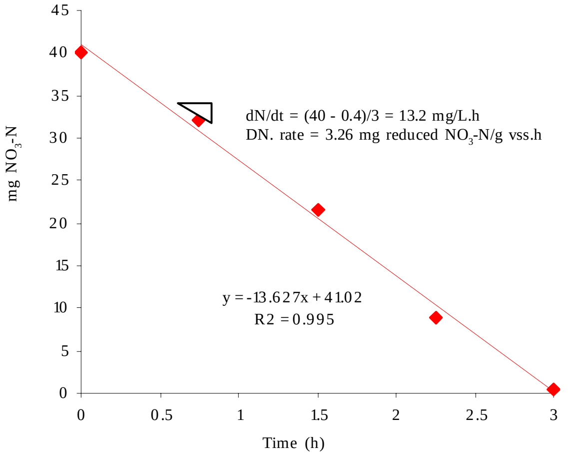

Fig. 8: The specific denitrification rate (SDNR) for nitrate nitrogen

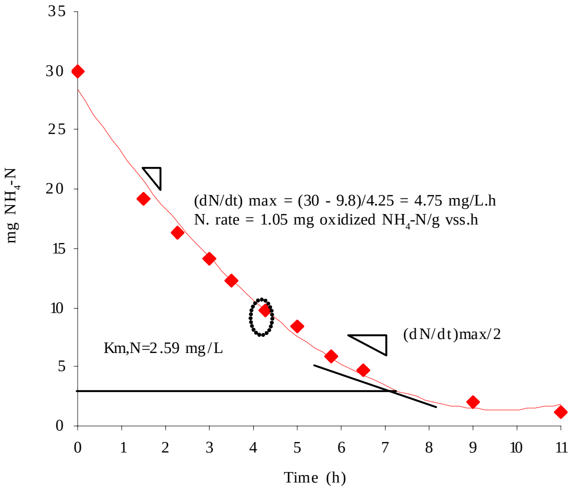

Fig. 7: The maximum specific nitrification rate (SNR) and half saturation constant for ammonium-nitrogen

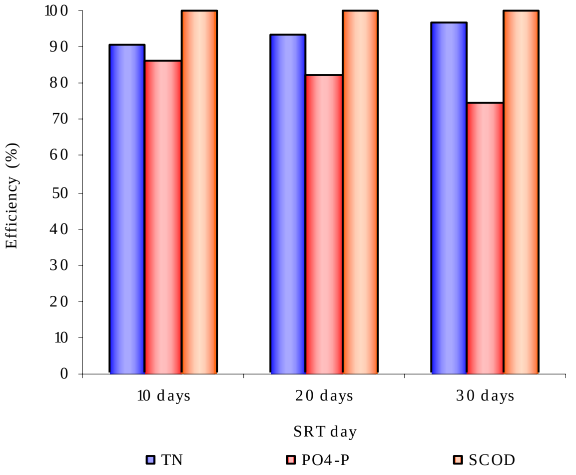

Fig. 9: The average total nitrogen, phosphorus and sCOD removal efficiency at different SRT (HRT=24 h)

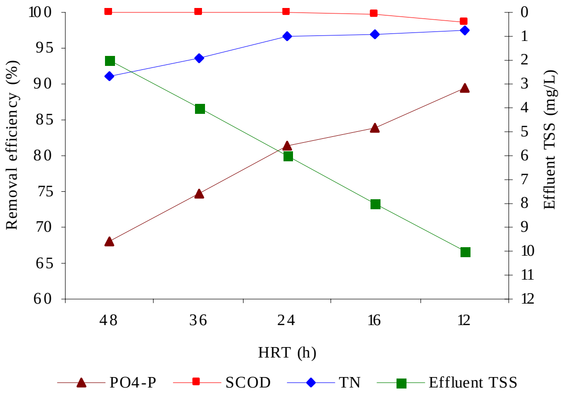

Fig. 10: The effect of total HRT on the average TN, PO_4-P, sCOD and TSS removal efficiency

The influent TKN/COD ratio, clarifier shape and kind of pump strongly affected monotonous sludge recycle, effluent TSS in the USBF clarifier based on operational experiments.

CONCLUSION

Biological removal efficiency of nitrogen and preservation of sludge blanket strongly depend on wastewater characteristics, HRT, SRT and process control. The combined bioreactor performed a total nitrogen removal efficiency of 96.61 % with a sludge age of 25 days, HRT of 24 h and optimum COD/N/P ratio of 100/5/1.The Anaerobic/USBF combined bioreactor at the optimum conditions can be an effective technology for nitrogen removal from municipal wastewater, but it is not suggested for wastewater containing a high TKN/COD ratio because of rising sludge and disordering blanket in the USBF clarifier.

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