

TREATMENT OF LOW-STRENGTH INDUSTRIAL WASTEWATER USING ANAEROBIC BAFFLED REACTOR

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ABSTRACT

The performance of an anaerobic baffled reactor at the pilot scale, with a 100-L volume and six compartments, that is used to treat low-strength industrial wastewater (671.5±49.9 mg COD/L, 350.1±36.8 mg BOD₅/L and 443.8±60.7 mg SO₄⁻²/L) was studied. The reactor was started with a hydraulic retention time (HRT) of 25 h at 35 °C, which was gradually reduced to 3.33 h. The best reactor performance was observed with an organic loading rate (OLR) and a sulfate loading rate (SLR) of 4.45 g COD/L.d and 3.32 g SO₄⁻²/L.d, which was obtained at a HRT of 4 h. The COD and SO₄⁻² removal efficiencies were 78.6% and 89.2%, respectively. Additionally, the majority of the COD and SO₄⁻² removal occurred in the first compartment, up to 51.2% and 69.1%, respectively. Moreover, the pH in the first compartment was also the lowest. Subsequently, when the temperature was reduced to 20 °C at a HRT of 4 h, the maximum removal efficiencies for COD and SO₄⁻² decreased to 59.4% and 66.1%, respectively. In this case, the highest COD and SO₄⁻² removal efficiencies were observed in the third and fourth compartments, respectively, and these compartments had lower pH values. This phenomenon indicates that decrease in temperature causes transference of the acidogenic phase toward subsequent reactor compartments. In addition, these findings further show the potential for sulfate removal of the acidogenic phase.

Key words: Anaerobic baffled reactor; COD removal; Low-strength industrial wastewater; Low temperature effects; SO₄⁻² removal

INTRODUCTION

The successful application of anaerobic reactors for the treatment of industrial wastewaters depends on the development of high-rate bioreactors, which achieve a high reaction rate per unit reactor volume by retaining the biomass in the reactor for long periods of time (Movahedyan *et al.*, 2007); Naimabadi *et al.*, 2009).

Aerobic Baffled Reactor is a modification of Upflow Anaerobic Sludge Blanket (UASB) and it is a staged reactor where biomass retention is

enhanced by forcing the water flow through several compartments (between 3 and 8 compartments) (Barber and Stuckey, 1999; Sponza and Isik, 2002; Kaksonen, and Puhakka, 2007). This reactor has numerous advantages, including good resilience to hydraulic and organic shock loads, long biomass retention times, low sludge yields, simple design, cheap construction, and the ability to separate the various phases of anaerobic catabolism longitudinally down the reactor (Barber and Stuckey, 1999; Liu *et al.*, 2007; Feng *et al.*, 2008). Krishna and co-workers with scrutiny of Volatile Fatty Acid (VFA) profiles and SEM images reported that compartmentalization in ABR

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served to separate acidogenic and methanogenic activities longitudinally along the reactor, with the highest portion of acidogenic activity occurring in the first compartment (Krishna *et al.*, 2007). The separation of two phases causes an increase in protection against toxic material and a higher resistance to changes in environmental parameters such as pH, temperature and organic loading (Wang *et al.*, 2004). Furthermore, the ABR for well operation needs neither the sludge blanket nor the granular and flocculent biomass by virtue of its configuration (Bodkhe, 2009).

Anaerobic digestion of low-strength wastewater (<1000 mg COD/L) results in the production of significantly smaller amounts of biological sludge, as compared to aerobic systems, thus resulting in less sludge requiring disposal. However, when treating low-strength waste, one must be careful that the biomass washout does not exceed the biomass production inside the reactor. In addition, the treatment of low-strength wastewaters results in low gas production with a concomitant poor biomass-substrate contact and low COD degradation (Langenhoff and Stuckey 2000; Langenhoff *et al.*, 2000). Generally, lower substrate concentrations and reduced temperatures result in a deterioration of the process performance when compared to the case of high substrate concentrations and high temperatures (Nachaiyasit and Stuckey, 1997).

The Arrhenius equation predicts that a decrease in temperature will result in a decrease in reaction rate, and therefore, the biological activity will decrease by a factor of about 3 with a temperature drop of 15 °C (Levenspiel, 1972). However, Nachaiyasit observed that when the temperature of an ABR was reduced from 35 °C to 25 °C, there was no significant reduction in the overall COD removal efficiency (Nachaiyasit, 1995). In contrast, according to Arrhenius kinetics, lower catabolic rates caused by elevated K_s values at the front of the reactor caused a shift in acid production towards the rear, although the overall removal remained unaffected. Nachaiyasit and Stuckey further reduced the temperature to 15 °C, and a decrease in overall efficiency of 20% was noted after one month (Barber and Stuckey, 1999).

Sulfate is a common constituent of many industrial wastewaters, and sulfate reduction causes major several problems in the anaerobic digestion that

are: (a) sulfate is reduced to hydrogen sulfide which is a strong inhibitor of methanogenesis (Vossoughi *et al.*, 2003), can serve as the precursor for corrosive sulfur compounds (Khanal and Huang, 2003), is malodorous (the rotten egg smell) (Hilton and Archer, 1998) and is toxic for methane producing bacteria (MPB) (Hulshoff pol *et al.*, 2001); (b) sulfate reduction promotes competition between sulfate reducing bacteria (SRB) and methane producing bacteria (MPB) because of substrate utilization (Moosa *et al.*, 2002).

Some scientists have observed that there is competition between SRB and MPB for acetate and hydrogen, but others have reported the existence of syntrophic relationships between the two groups of bacteria (Vossoughi *et al.*, 2003). Mizuno and co-workers observed that sulfidogenesis competes with methanogenesis for the same substrate; but that sulfidogenesis has an advantage due to the lower Gibbs free energy needed the reaction to proceed (Mizuno *et al.*, 1998). Activity partitioning between sulfidogenesis and methanogenesis should occur in the ABR. Hence, the first compartment could be used as a sulfate-reducing reactor, which will provide a more suitable environment for methane production in subsequent compartments (Saritpongteeral and Chairapat, 2008).

During the past decade, industrial parks have been unexpectedly constructed in developing countries like Iran. Environmental concerns have spurred the construction and operation of more than 70 industrial park wastewater treatment plants in Iran. The main objective of this study was to use a six-compartment ABR at the pilot scale for the treatment of wastewater from a typical industrial park.

MATERIALS AND METHODS

Reactor set-up

A plexi-glass ABR at the pilot scale, with a rectangular shape, external dimensions of 100 cm in length, 25 cm in width and a depth of 40 cm, and a working reactor volume of 100 L, was used in this study. As shown in Fig. 1, the reactor was divided into six identical 16.67-L compartments by vertical standing baffles, with each compartment possessing downflow (down comer) and upflow (up comer) regions created

by a vertical hanging baffle. The width of the up comer was 2.6 times of the width of the down comer (the widths of the up comer and down comer were 12.2 and 4.6 cm, respectively). The lower portions of the hanging baffles were bent 3 cm above the reactor's base at a 45° angle to route the flow to the center of the up comer, thus allowing for better contact and biosolid mixing at the base of each riser.

Liquid sampling ports were located about 10 cm from the top of each compartment. This reactor was equipped with a temperature control chamber (water bath) to adjust the reactor temperature. During the start-up and steady-state periods, the operating temperature remained constant at 35 ± 0.5 °C. The temperature was then decreased to 20 ± 0.5 °C to evaluate the effects on the reactor.

The influent feed was pumped from an equalization tank from Kashan's Amirkabir industrial park wastewater treatment plant to an ABR pilot using an adjustable diaphragm pump (Ethatron, HRS technology, Italy).

Seed sludge

The ABR was initially seeded with anaerobic digested sludge taken from the anaerobic digester of a municipal wastewater treatment plant (North of Isfahan, Iran). Before seeding the reactor, large particles and debris from the sludge were removed by passing it through a sieve (<5 mm). The clean anaerobic sludge was then introduced uniformly into all six compartments of the reactor, so that each compartment was filled with 35% sludge with a concentration of solids of 36.7 g SS/L and 25.1 g VSS/L, giving a total of 878 g VSS in the reactor. This value (8.78 g VSS/L of reactor volume) agreed with the initial VSS values used in other studies undertaken on ABRs (Barber and Stuckey, 1999). The remaining part of each compartment was filled with industrial park wastewater taken from an equalization tank. After seeding the reactor, the lids were sealed and the operating temperature was maintained constant at 35 ± 0.5 °C.

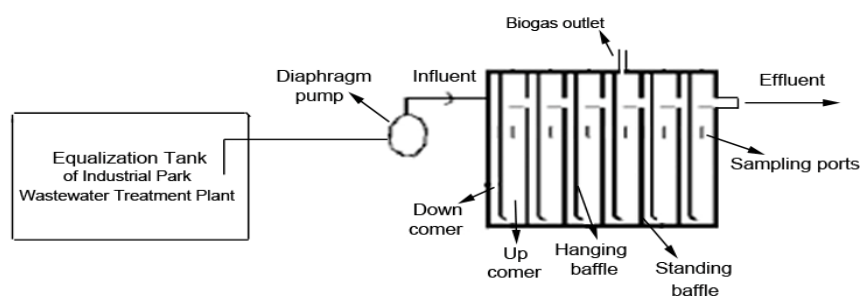


Fig. 1: Schematic diagram of the pilot-scale anaerobic baffled reactor used in this study

Wastewater characteristics

The characteristics of wastewater from Kashan's Amirkabir industrial park wastewater treatment plant are shown in Table 1. Indeed, the 25% of the mixture of this wastewater was effluents from textile, cardboard, meat processing and dairy industries; and the main part of it was sanitary effluents from different factories. Generally, during the reactor operation period (continuous running at 35 °C and 20 °C), experimental results showed no need to add nitrogen or phosphorous to the influent of the reactor.

Analysis

Liquid samples were taken from the influent, six compartments, and effluent of the reactor, beginning at the last compartment and moving towards the first, to prevent air intrusion and to maintain anaerobic conditions. COD, SO_4^{2-} , pH and TSS were measured every two days, while influent total nitrogen (TN), total phosphorous (TP), orthophosphate (Ortho-P) and BOD_5 were measured weekly, and the temperature was monitored daily (APHA, 2005). Photometer AL-250 of Aqualytic for analyzing of COD, BOD_5 -system Oxi-Direct of Aqualytic for analyzing of

Table 1: Characteristics of industrial park wastewater fed to the ABR

Parameter	COD (mg/L)	BOD ₅ (mg/L)	TSS (mg/L)	SO ₄ ⁻² (mg/L)	TN (mg N/L)	TP (mg P/L)	Ortho-P (mg PO ₄ /L)	pH
Values	671.5 ± 49.9	350.1 ± 36.8	258.8 ± 51.6	443.8 ± 60.7	57.4 ± 8.03	5.22 ± 0.94	17.05 ± 1.36	7.57 ± 0.19

BOD₅ and photometer Multi-Direct of Aqualytic for analyzing of SO₄⁻², TN, TP and Ortho-P were used. Meanwhile Senso-Direct pH200 of Aqualytic was used for measuring of pH (Aqualytic devices was made in Germany).

RESULTS

Reactor start-up and performance

Prompt start-up is essential for the highly efficient operation of ABR, due to slow growth rates of anaerobic microorganisms, especially MPBs, establishment of the most suitable microbial population is critical to the prompt start-up of ABR (Liu *et al.*, 2010). Table 2 shows a summary of the reactor operation conditions. For the ABR start-up, the system was initially run on batch for 10 days. During this time, the content of the reactor was recycled once for homogeneity. After this period, the ABR was run continuously and was fed the industrial park wastewater.

Throughout the study, the organic loading rate (OLR) and the sulfate loading rate (SLR) were increased by decreasing the hydraulic retention time (HRT).

The reactor was started with a HRT of 25 h (corresponding OLR= 0.58 ± 0.02 g COD/Ld and SLR= 0.36 ± 0.02 g SO₄⁻² /Ld). It was gradually decreased to 20, 10, 6.67, 5, 4 and 3.33 h in steps. Corresponding OLRs and SLRs are shown in Table 2. As shown in Fig. 2 and Table 2, the OLR and SLR values were finally increased to 5.44 g COD/Ld and 4.06 g SO₄⁻² /Ld, respectively (HRT of 3.33 h).

For each HRT, the steady condition was marked by relatively stable effluent COD values with less than 5% variation. In this study, the optimum ABR operation conditions were observed at a HRT of 4 h (at 35 °C). To investigate temperature reduction effects, the HRT was returned to 4 h (from 3.33 h) and the temperature of the reactor was reduced to 20 °C.

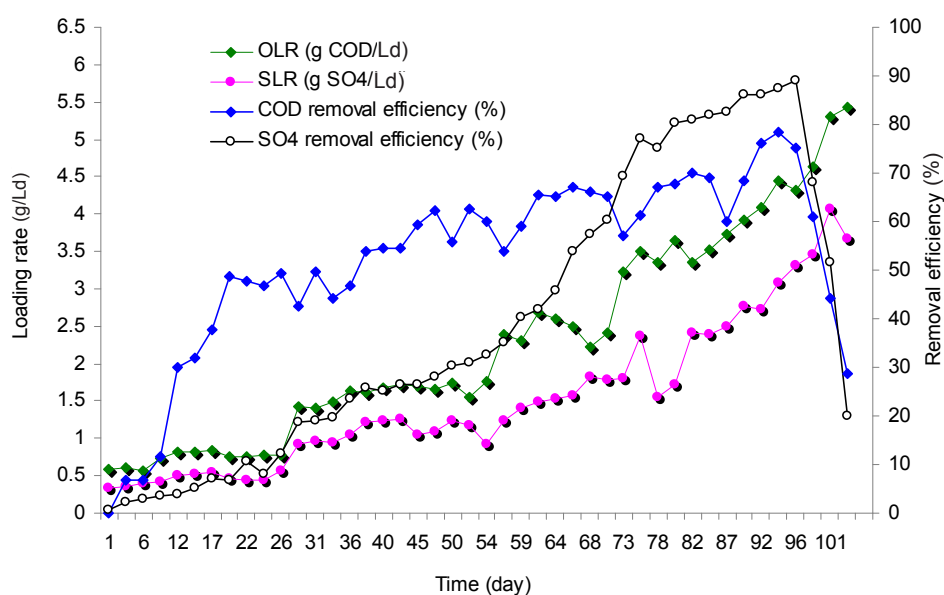
Fig. 2: COD and SO₄⁻² removal efficiencies based on loading rates

Table 2: ABR reactor operation conditions

Parameter		Operation days	HRT (h)	Temperature (°C)	upflow liquid velocity (m/h)	OLR (g COD/Ld)	SLR (g SO ₄ ²⁻ /Ld)	COD removal (%)	SO ₄ ²⁻ removal (%)	pH (first-sixth compartments)	Effluent TSS (mg/L)
Continuous running*	Start-Up periods	1-6	25	35	0.157	0.58 ± 0.02	0.36 ± 0.02	4.52 ± 3.2	1.9 ± 0.99	7.875-7.93	24 ± 0.89
		7-26	20	35	0.196	0.79 ± 0.03	0.49 ± 0.05	38.1 ± 12.3	7.18 ± 2.9	6.557-6.98	27.3 ± 2.19
	Steady-State periods	27-54	10	35	0.392	1.61 ± 0.11	1.09 ± 0.13	53.8 ± 6.5	25.6 ± 4.5	6.92-7.31	34.4 ± 1.85
		55-71	6.67	35	0.588	2.44 ± 0.15	1.6 ± 0.19	63.2 ± 4.43	47.8 ± 8.7	6.82-7.1	39.9 ± 2.11
		72-85	5	35	0.784	3.43 ± 0.13	2.04 ± 0.36	65.4 ± 4.66	77.5 ± 4.4	6.347-6.783	42.01 ± 1.5
		86-96	4	35	0.980	4.1 ± 0.26	2.89 ± 0.29	71.6 ± 6.67	86.3 ± 2.18	6.253-6.74	46.4 ± 1.41
		97-105	3.33	35	1.176	5.13 ± 0.35	3.73 ± 0.25	44.6 ± 13.1	46.7 ± 19.9	7.073-7.373	59.3 ± 3.27
		106-121	4	20	0.980	3.89 ± 0.35	2.79 ± 0.26	51.5 ± 7.43	50.4 ± 14.96	7.267-6.927	58.6 ± 0.77

* Before continuous running, the batch operation was applied for up to 10 days.

COD and SO₄²⁻ removal at 35 °C

According to Figs. 2 and 3, the maximum of COD and SO₄²⁻ removal efficiencies were obtained as up to 78.6% and 89.2%, respectively, with a HRT of 4 h (corresponding OLR= 4.45 g COD/Ld and SLR= 3.32 g SO₄²⁻/Ld). The COD and SO₄²⁻ variation profiles for different compartments of the ABR system at 35 °C are illustrated in Fig. 4 and Fig. 5, respectively. Each decrease in HRT was followed by a temporary increase in the COD and SO₄²⁻ concentration in the effluent, but in these cases, the reactor quickly regained its removal efficiency.

As shown in Fig. 6, for the best reactor performance, which was achieved at HRT of 4 h and 35 °C, the maximum of the COD removal occurred in the first compartment (51.2%) and the rest of the COD was removed in the other compartments (27.4%). This phenomena shows that about 0.667 h (40 min) is sufficient for the removal of 51.2% COD and probably we could enter wastewater to more than one compartment. As the COD decreased in the preceding compartment, reduction in the substrate utilization rate of the microorganisms in the subsequent compartments occurred, leading to lower removal efficiency. This phenomenon could be well supported by the bacterial kinetics that lower substrate concentration will cause lower growth rate (Saritpongteerala and Chairapat,

2008).

The pH profiles for the ABR at HRT of 4 h are shown in Fig. 7. The earlier compartments had lower pH as acidogenesis and acetogenesis occurred in these compartments (Dama *et al.*, 2002). Thus, due to the high concentration of volatile fatty acids (VFAs), the sudden drop in the pH, especially in the first compartment is quite noticeable. Fig. 7 shows that the pH in the first compartment was the lowest. The pH values increased down the reactor due to the conversion of intermediate products, i.e. the VFAs in the

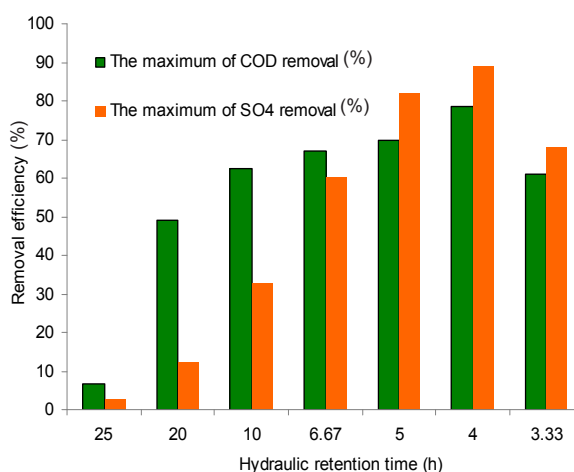


Fig. 3: Comparison between COD and SO₄²⁻ removal efficiencies based on HRTs

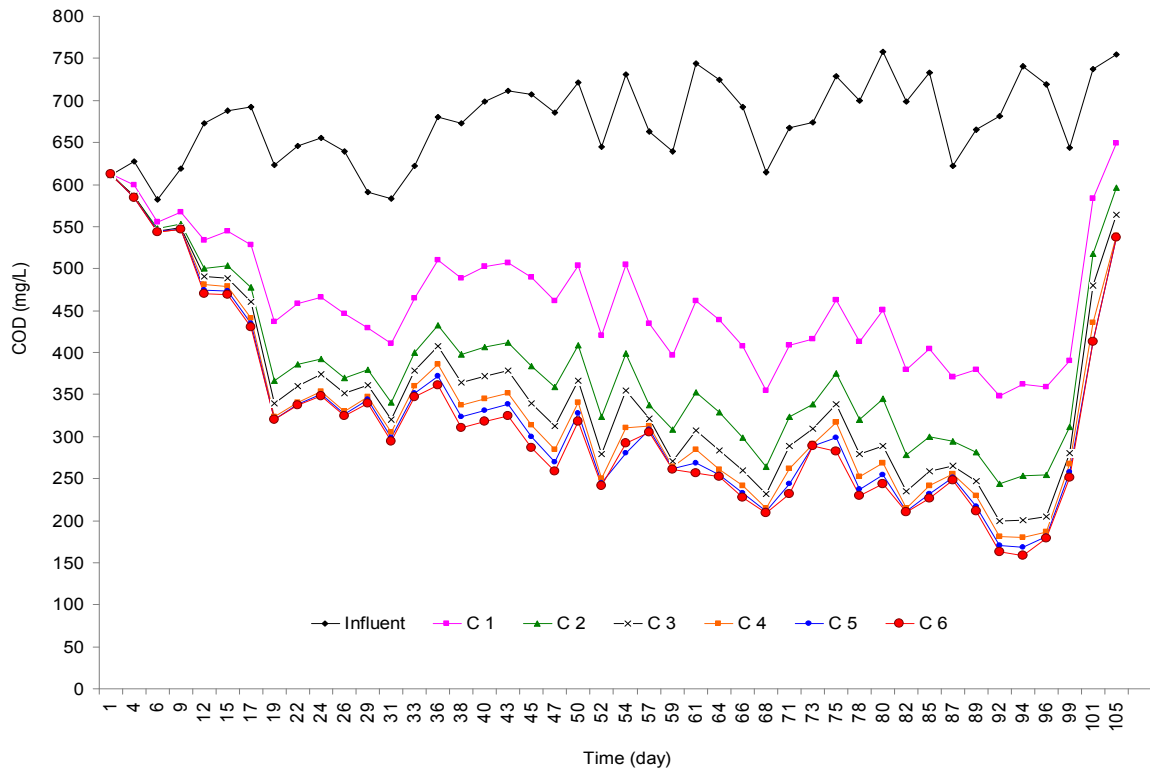


Fig. 4: COD variation profiles for different compartments of the ABR during the reactor operation period at 35 °C (C_i: Compartment)

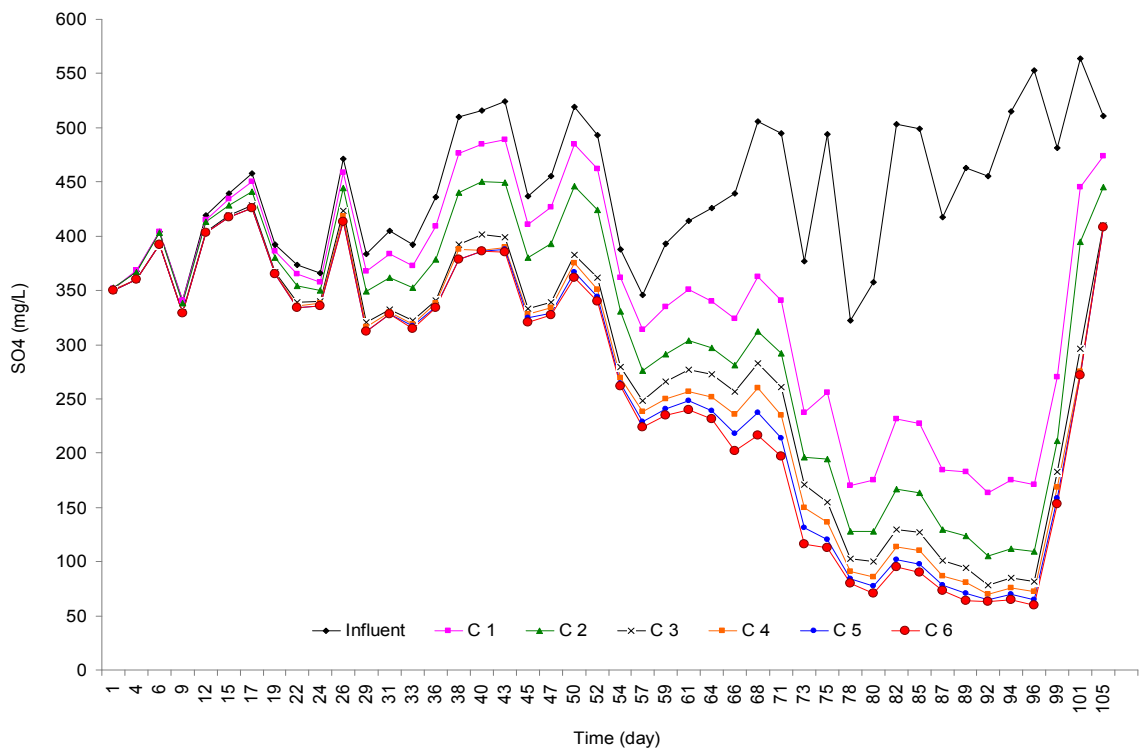


Fig. 5: SO₄²⁻ variation profiles for different compartments of the ABR during the reactor operation period at 35 °C (C_i: Compartment)

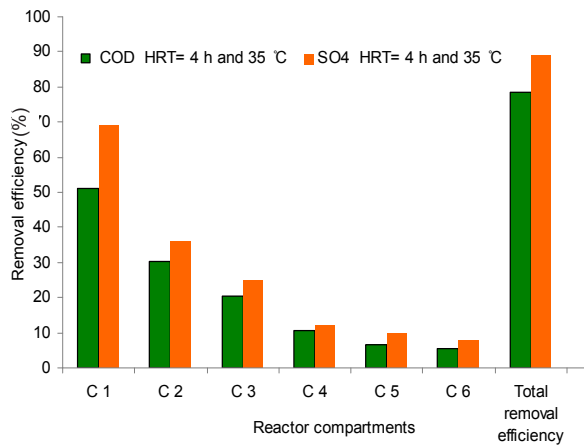


Fig. 6: Comparison between COD and SO₄⁻² removal efficiencies at HRT of 4 h and 35 °C (C_i: Compartment)

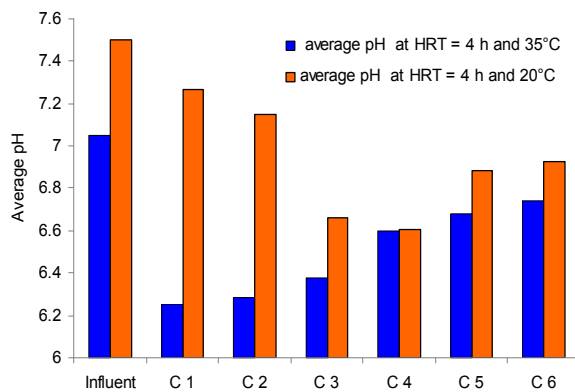


Fig. 7: pH variation profile at HRT of 4 h (C_i: Compartment)

latter compartments (Krishna *et al.*, 2007). According to Fig. 6, it is clear that the majority of the sulfate was removed in the first compartment (69.1%) at a HRT of 4 h and 35 °C, which proved to be the best performance of the reactor. However, only 20.1% of the SO₄⁻² removal was observed in the other compartments. This result demonstrates that the acidogenic phase was able to remove the sulfate because most of the conversion occurred in the first compartment (Vossoughi *et al.*, 2003). The effluent total suspended solids (TSS) variation profile based on the HRTs is shown in Fig. 8. After each decrease in the HRT, the effluent TSS increased. However, during the periods in which the HRT was kept constant, the effluent TSS

slightly decreased. Thus, sludge washout was negligible in the experiments since the effluent TSS was in the range of 24-65 mg/L. These results demonstrate that the ABR can withstand short HRTs without causing a substantial washout of the biomass, and hence, the ABR is a robust design for industrial use (Langenhoff *et al.*, 1999).

COD and SO₄⁻² removal at 20 °C

The OLR and SLR values, at the reactor performance at HRT of 4 h and 20 °C, were in the range of 3.89 ± 0.35 g COD/Ld and 2.79 ± 0.26 g SO₄⁻² /Ld, respectively, and are shown in Table 2 and Fig. 9. According to Fig. 9 and Fig. 10, the maximum of the COD and SO₄⁻² removal efficiencies were obtained up to 59.4% and 66.1%, respectively. The maximum of COD removal was observed in the third and fourth compartments (26.5% and 20.72%, respectively). These results show that the ABR system probably requires a longer retention time for the degradation of organic wastes at lower temperatures.

As shown in Fig. 7, the pH values were the lowest in the fourth and third compartments. According to Arrhenius kinetics, low temperatures reduce catabolic rates, and lower catabolic rates, which were caused by elevated K_s values at the front of the reactor, caused a shift in acid production towards the subsequent compartments (Barber and Stuckey, 1999). Therefore, the acidogenic phase occurs in the third and fourth compartments. Fig. 10 shows that most of the sulfate removal occurred in the fourth and third compartments (28.98% and 23.23%, respectively). These findings demonstrate the ability of the acidogenic phase to remove sulfate.

Effects of temperature decrease from 35 °C to 20 °C on removal efficiencies at the same HRT of 4 h is shown in Fig. 11, in which the COD removal efficiencies at the end of the reactor operation period at a HRT of 4 h were 75.1% and 58.8% at 35 and 20 °C, respectively. The Arrhenius equation predicts that a decrease in temperature will result in a decrease in reaction rate, and therefore, the biological activity will decrease by a factor of about 3 with an associated temperature drop of 15 °C (Levenspiel, 1972).

As shown in Fig. 11, a change in the temperature

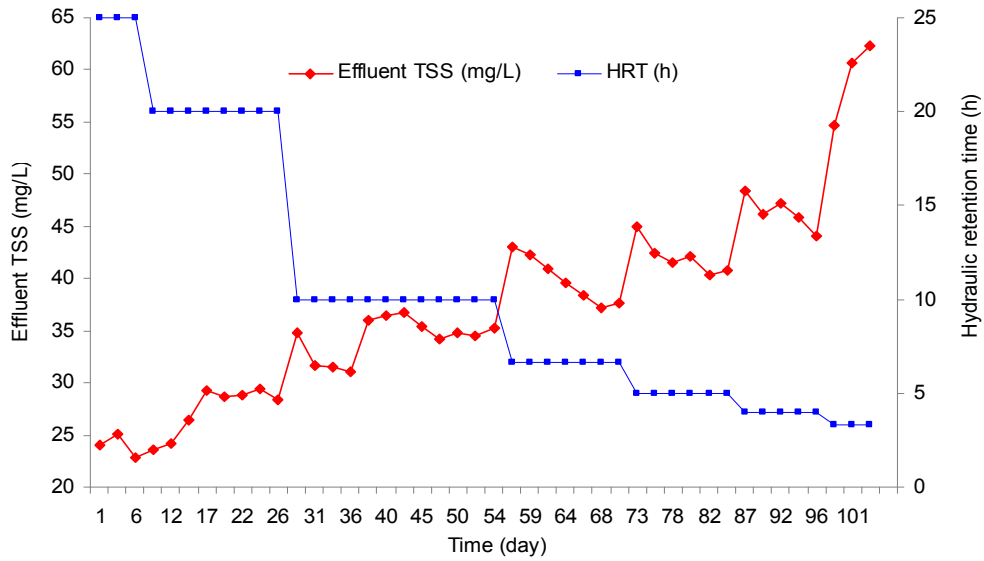


Fig. 8: Effluent TSS variation profile based on HRTs at 35 °C

from 35 °C to 20 °C reduced the removal efficiency by only 16.3% (75.1% → 58.8%), which is less than the amount predicted by the Arrhenius equation. This shows that the reactor contained more than enough active biomass to treat the incoming waste, and this was not degrading the incoming COD at its maximum rate at 35 °C (Langenhoff and Stuckey, 2000). These findings indicate that ABR systems are resistant to shocks like a decrease in temperature.

As shown in Fig. 12, the SO_4^{-2} removal efficiencies

at the end of the reactor operation period at a HRT of 4 h were 89.2% and 64.99% at 35 °C and 20 °C, respectively. The SO_4^{-2} removal efficiency was reduced by as much as 24.21% (89.2% to 64.99%) with a temperature decrease of 15 °C. These results demonstrate that ABR systems are quite capable of sulfate removal, even at low or ambient temperatures.

For low-strength industrial wastewater treatment

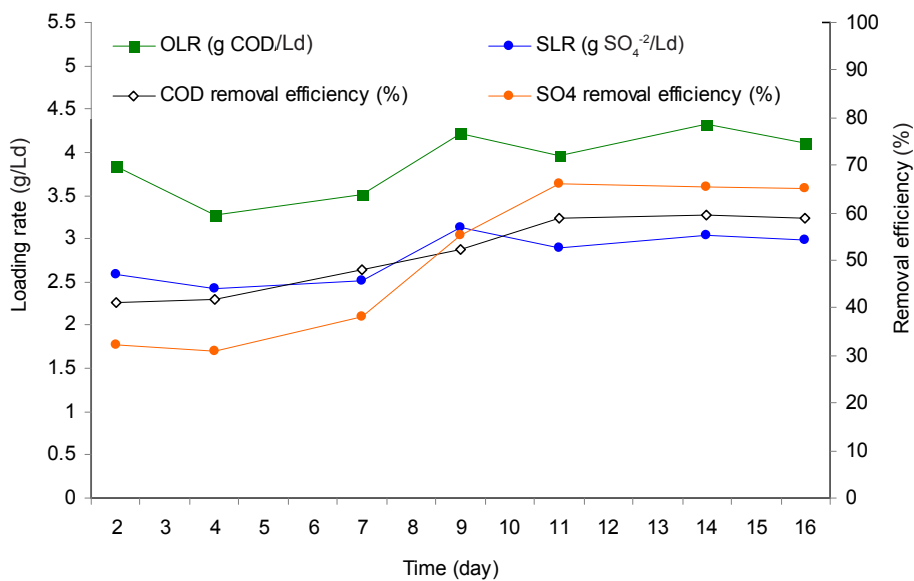


Fig. 9: COD and SO_4^{-2} removal efficiencies based on loading rates at HRT of 4 h and 20 °C

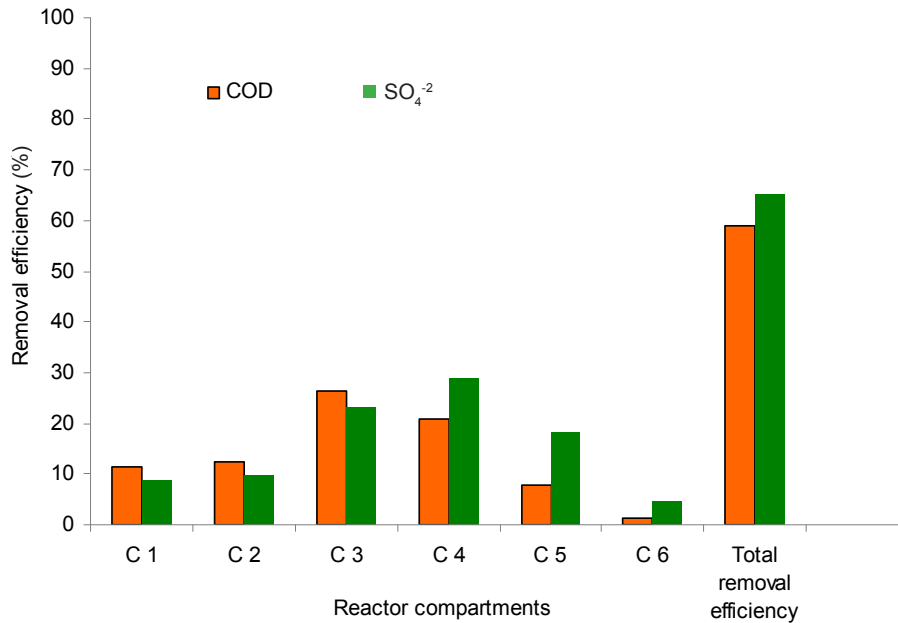


Fig. 10: Comparison between COD and SO_4^{2-} removal efficiencies at HRT of 4 h and 20 °C (C_i : Compartment)

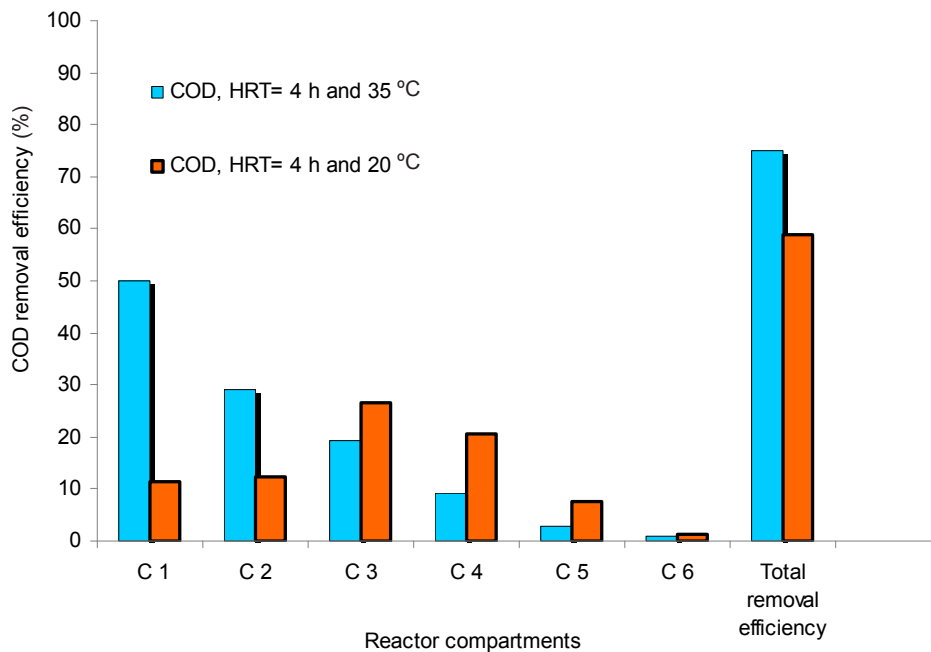


Fig. 11: COD removal efficiencies at 35 and 20 °C at the same HRT of 4 h (C_i : Compartment)

at 35 and 20 °C in this study, the SO_4^{2-} removal efficiency was higher than the COD removal efficiency. Typically, sulfidogenesis competes with methanogenesis for the same substrate, but sulfidogenesis has an advantage because it requires a lower Gibbs free energy for the reaction

to proceed (Mizuno *et al.*, 1998). On the other hand, after a 15 °C temperature decrease, the COD removal efficiency reduction value (16.3%) was lower than the SO_4^{2-} removal efficiency reduction value (24.21%). This result likely indicates that SRB are more sensitive to temperature decreases

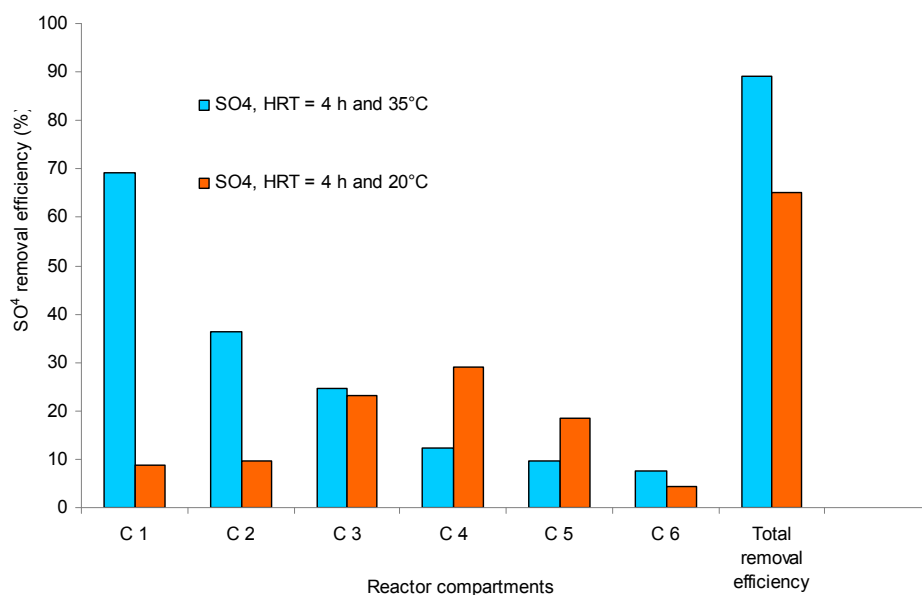


Fig. 12: SO₄²⁻ removal efficiencies at 35 and 20 °C at the same HRT of 4 h (C_i: Compartment)

than MPB.

DISCUSSION

Mizuno and co-workers observed sulfate reduction in the acidogenic phase, even at HRTs as low as 2 h (Mizuno *et al.*, 1998). Fox and Venkatasubbiah observed that sulfate was completely reduced to sulfide within the first compartment, and that a concomitant increase in sulfide levels down the reactor indicated that sulfide preferentially redirected electron equivalents to hydrogen sulfide rather than methane (Fox and Venkatasubbiah, 1996).

Low-strength industrial wastewaters inherently provide a low mass transfer driving force between biomass and the substrate, and biomass activities will be greatly reduced according to Monod kinetics. It appears that biomass retention is significantly enhanced due to lower gas production rates, suggesting that low hydraulic retention times (6→2 h) are feasible during low-strength industrial wastewater treatment (Barber and Stuckey, 1999).

Another important consequence of low retention times is an increase in hydraulic turbulence, which can lower the apparent K_s values, thus enhancing treatment efficiency (Kato *et al.*, 1997). Therefore, the use of short HRTs for the

treatment of low-strength industrial wastewaters can allow for a smaller reactor size and thus a more economical treatment scheme (Langenhoff *et al.*, 2000).

In the steady-state ABR performance, SO₄²⁻ removal efficiency was higher than COD removal efficiency in each of the compartments. Moreover, the majority of COD and SO₄²⁻ removal occurred in the first compartment. Additionally, the pH variation profile showed that sulfidogenesis, which occurs in the acidogenic phase, can be separated from methanogenesis longitudinally the ABR. In the earlier compartments, where COD consumption occurs by SRBs for sulfate reduction, a lower COD concentration remains for MPB, which leads to a decrease in their biological activity in the subsequent compartments. This problem causes more harmful effects to organic degradation when treating low-strength industrial wastewaters. This occurs because a low activity level of MPBs leads to a noticeable reduction in methane production. As a remedial solution, split feeding of the ABR, that is, the addition of wastewater to one of the earlier compartments (with the exception of the first compartment), along with an influent of the ABR, can be effective

to treat low-strength industrial wastewaters containing sulfate at low temperatures. Using this procedure, the substrate concentration is increased, which increases the MPB biological activity. However, it seems that there is no separation of acidogenic and methanogenic phases with a split feeding of ABRs.

The pH profile at low temperatures showed an acidogenic phase transference to the middle compartments, which was caused by the decrease in temperature. Since acidogenic bacteria are less sensitive to temperature reductions with respect to MPB, their biological activity and microbial population increased significantly when compared to MPB. Therefore, they were found in more of the reactor compartments. In this condition, the majority of COD and SO_4^{2-} removal occurred in the middle compartments. These results show that COD conversion requires greater retention times at lower temperatures. Additionally, these results represent further evidence of sulfidogenesis in the acidogenic phase.

The present study demonstrated that the ability of ABR systems to treat sulfate-containing low-strength wastewaters at ambient temperatures comes from the compartmentalization structure of the ABR, which allows for greater resistance to environmental variations.

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