Performance evaluation of an Anaerobic Migrating Blanket Reactor in the biodegradation of perchloroethylene from industrial wastewaters

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ABSTRACT

Aims: The aim of this study is to determine the PCE biodegradation potential in an Anaerobic Migrating Blanket Reactor (AMBR) that has not been used so far for the bioremediation of this compound, in high concentration, and to evaluate the system performance.

Materials and Methods: This study was an Experimental – Interventional study that was done from April 2010 to March 2011, in the Isfahan University of Medical Sciences. The AMBR was used in a type of laboratory scale, with a volume of 10 L, which was divided into four compartments, for the biological degradation of PCE in a synthetic substrate. The startup was done using anaerobic digested sewage sludge. The performance of the reactor was evaluated during four periods, with a PCE loading rate of 3.75 until 75 mg PCE/L.d. The hydraulic retention time (HRT) was 32 hours.

Results: Optimum chemical oxygen demand (COD) removal efficiency was obtained, 98%, with an organic loading rate (OLR) equal to 3.1 g COD/L.d. For PCE removal, the optimum efficiency was observed to be 99.8%, with a PCE loading rate equal to 37.5 mg PCE/L.d. The average COD and PCE removal rates for the whole activity period of the reactor were 91.4 and 99.5%, respectively; $1.1 \pm 0.7\%$ from the influent PCE was adsorbed on the biomass and 20% was found in the headspace.

Conclusions: The AMBR reactor, which provides full-scale studies and uses real industrial wastewater polluted with PCE, is a simple, efficient, and reliable method for the treatment of PCE.

Key words: Anaerobic Migrating Blanket Reactor, industrial wastewater, perchloroethylene, reductive dechlorination

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INTRODUCTION

Throughout the world, chloroethenes are among the most common contaminants observed in the groundwater environment.[1] Perchloroethylene (PCE) and trichloroethylene (TCE) are widely used as solvents, dry cleaning and de-greasing agents, and chemical feedstock.[2] The International Agency for Research on Cancer (IARC) has classified PCE as a priority pollutant and carcinogenic type 2A.[3] PCE provokes a wide concern, because it is a possible carcinogen to humans and recalcitrant in the environments.[2] The maximum contaminant level (MCL) for PCE is 5 µg/L. The half-life of PCE in air and groundwater is 47 days and 108 days, respectively.[2] PCE cannot be converted under aerobic conditions because of its high electron negative character. In contrast, PCE has been demonstrated to degrade anaerobically via reductive dechlorination to the less chlorinated ethenes, TCE, dichloroethenes (DCEs),

vinyl chloride (VC), and ethene.[1] The MCL of intermediate compounds, including TCE, 1,1-DCEs, Cis-1, 2-DCEs, trans-1, 2-DCEs, and Vinyl Chloride in drinking water is determined to be 5, 7, 70, 100 and 2 μg/L, respectively, by the *Environmental Protection Agency* (EPA).[4]

The AMBR is a continuously fed, compartmentalized reactor, without the requirement of elaborate gas–solid separation and feed-distribution systems. Effluent recycling is not necessary, but gentle intermittent mixing is needed to maintain sufficient contact between the biomass and substrate due to the absence of an upflow hydraulic pattern. The influent flows horizontally into one end of the reactor and the effluent leaves from the other end. Consequently, the final compartment receives the lowest substrate concentration, and therefore, the substrate utilization rate of the microbes in this compartment is low. The final compartment serves as an internal clarifier, preventing biomass loss in the effluent. Due to the flow pattern and the observed biomass migration, the biomass accumulates in the final compartment.[5]

The AMBR utilizes the advantages of the Anaerobic Sequencing Batch Reactor (ASBR), such as, mechanical mixing, biomass retention, a simple design (no gas–solids separation and feed-distribution systems required because of the absence of a hydraulic upflow pattern), and granulation. In addition, the hydraulic retention time (HRT) in a continuously fed AMBR can be shortened (and thus the reactor volume can be decreased) compared with the batch-fed ASBR.[6]

In several studies, PCE has been degraded by anaerobic reactors such as the Upflow Anaerobic Sludge Blanket (UASB),[1,6] the Anaerobic Sequencing Batch Biofilm Reactor (AnSBBR),[7] and the Anaerobic Attached Film Expanded Bed (AAFEB),[8] in concentrations and different operating conditions.

Hwu examined PCE removal efficiency in the UASB reactor in 2008. In this experiment, the PCE and COD loading rates were 3 mg PCE/L.d and 3125 mg COD/L.d, respectively, in the presence of lactate and sucrose.[1] Prakash also removed PCE in another study, by using the UASB reactor, in 2000. In this study, sodium acetate, methanol, and acetone were used as the carbon source.[6] Dehalorespiration PCE, using the Anaerobic Sequencing Batch Biofilm Reactor (AnSBBR), with lactate and acetate, and an input PCE of 10.5 mg/L, was assessed in 1997 by Hirl.[7] In the study by Chu, the biodegradation ability of PCE was evaluated in a concentration of 8.2 – 26 mg/L by Anaerobic Attached Film Expanded Bed (AAFEB) at 35°C, in the presence of sucrose as an electron donor, in 1994.[8]

The purpose of this study was to determine the biodegradation ability of PCE by the Anaerobic Migrating Bed Reactor (AMBR) that has so far has not been used for the biological degradation of PCE, in higher concentrations than in other studies, and to observe the system performance in this research.

MATERIALS AND METHODS

This was an Experimental–Interventional study that was done from April 2010 to March 2011, in the Isfahan University of Medical Sciences.

Specifications of the anaerobic migrating blanket reactor

This process includes a feeding tank, diaphragm injection pump (Etatron, Italy) with the capacity of 5 L/hour (adjustable) and 10 bar pressure, gas meter (Elster, Germany), and a reactor. The AMBR consists of a rectangular; Plexiglas reactor (internal dimensions, length 43 cm, height 23.5 cm, and width 10 cm) with an active volume of 10 L, which is divided into four compartments. The flow over the horizontal plane of the reactor is reversed once every three days [Figure 1]. Four mixers are mounted at a rotational speed of 80 rpm with intermittent operation (15 minutes on/15 minutes off), to ensure a gentle mixing of wastewater and sludge.

To prevent a sludge washout, the last mixer was off. The temperature of the AMBR was kept constant at 37°C ± 1.

Chemicals

The chlorinated organic compounds used in this study were TCE (Merck, 99%), PCE (Merck, 99.5%), 1, 1-Dichloroethylene (Supelco, 99.9%), Cis-1, 2 - Dichloroethylene (Supelco, 98.5%), Trans-1, 2 - Dichloroethylene (Supelco, 99.9%), and Vinyl Chloride (Supelco, 99.9%). The volatile fatty acids were acetic acid (Merck, 99.5%), propionic acid, and butyric acid (Merck, 99%).

Startup and operation

Seeding of the reactor up to 20 g VSS/L was done using 5 L of anaerobic, digested, sewage sludge with 75 g TSS/L and 39 g VSS/L. It was first sieved (<5 mm), to remove any debris and large particles, and was then introduced into the four compartments of the reactor. The remaining parts of each
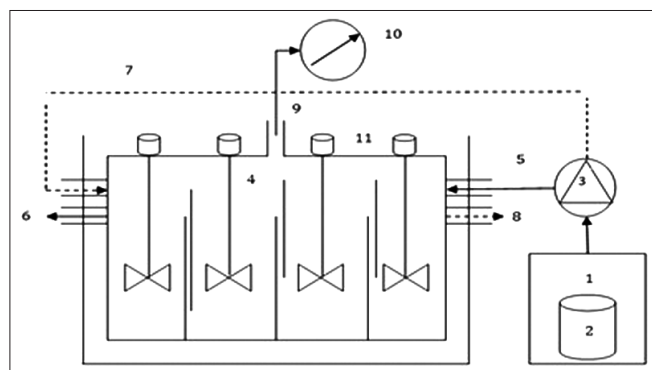

Figure 1: Schematic diagram of Anaerobic Migrating Blanket Reactor

compartment were filled with tap water. After closing the lid, the synthetic substrate was injected. The synthetic substrate consisted of three short chain volatile fatty acids (acetic, propionic, and butyric) as co-substrate, nutrients, and trace elements that were stored at 4°C, to prevent pre-acidification. The HRT was 32 hours for the entire period of startup and operation. The input pH was adjusted between 7 and 8 by potassium chloride (KCl) and sodium hydroxide (NaOH), 2N. In the startup period, the COD of the substrate and OLR were between 1000 and 4000 mg/L and 0.75 to 3 g COD/L.d.

The reactor operation was conducted in four stages, during the three months that PCE was used as the main substrate. The input PCE concentration and PCE loading rate increased in the four periods from 5 to 100 mg/L and 3.75 to 75 mg/L.d, respectively.

Analytical methods

Soluble COD, *Total suspended solids* (TSS), *Volatile suspended solids* (VSS), pH, and alkalinity were determined according to the procedures described under Standard Methods.[9]

Quantification of perchloroethylene (PCE), trichloroethylene (TCE), cis-1,2-dichloroethylene (cis-1,2-DCES), 1,1-Dichloroethylene (1,1-DCES), Trans-1,2-Dichloroethylene (Trans -1,2-DCES), and Vinyl Chloride was accomplished by the injection of a 500 μl headspace sample in split mode 2:1 into the gas chromatograph (GC), equipped with a mass spectrometry detector[3] and a Chrompack capillary column DB-5 (30 m long, 0.25 mm i.d, 0.5 μ film thickness). The operating conditions of the headspace were: Incubation time: 10 minutes, incubation temperature: 80°C, and magnetic stirring speed: 500 rpm. The column oven temperature was set at 36°C and remained constant for six minutes. After this time, the temperature rose up to 90°C, at 3°C/minute. Helium was employed as the carrier gas in a constant flow mode at 1 mL/minute. The syringe and injector temperature was set at 100°C and 160°C, respectively.

Perchloroethylene extraction from the biomass

To determine the adsorption rate of PCE on the biomass, the extraction method was used in the following steps: Ten grams of sewage sludge mixture was weighed in 100 mL glass Erlenmeyer flasks and extracted with 25 mL of a cyclohexane/dichloromethane (1:5, v/v) mixture. The extraction was conducted at 20°C in an ultrasonic bath for 40 minutes. After extraction, the samples were centrifuged at 3500 rev/minute for 15 minutes. The lower solution was concentrated under a nitrogen stream to 2 mL. It was then purified with silica gel columns. The columns were conditioned with 4 × 3 mL of cyclohexane/dichloromethane mixture (1:5, v/v). The collected leachate was concentrated to 2 mL under a nitrogen stream.[10] The extracts were analyzed for PCE by the method described earlier, which was carried out using a direct inject.

Sludge preparation for scanning electron microscope and X-Ray fluorescence

The samples for the Scanning Electron Microscope (SEM) were collected on the PCE loading of 75 mg/L.d. They were washed with a phosphate buffer (pH 7.2) and fixed overnight in 6% v/v glutaraldehyde. The sludge flocs were frozen and then cut. They were dehydrated through a graded series of ethanol solutions (10, 30, 50, 70, and 100% v/v). The solvent was removed by critical point drying and the dried samples were sputter-coated with gold[6] and examined using a scanning electron microscope (SERON Technology 2008, AIS-2100, South Korea).

Measurement of perchloroethylene in the gas phase

Due to the volatility of PCE, to achieve the real efficiency of biological removal of PCE, the PCE concentration was measured in the gas phase via the National Institute for Occupational Safety and Health (NIOSH) method, No. 1003, for analysis of hydrocarbons. In this method, granulated activated carbon was used as a sampler. The adsorbed PCE on activated carbon was extracted by carbon disulfide (CS_2) for 30 minutes.[11] The solvent was analyzed by the same method that was mentioned to detect PCE concentration in the biomass, with the difference being, the injection volume was 3 μL.

RESULTS

Table 1 shows the AMBR performance during startup and the steady state periods. During these periods, total of COD removal efficiencies for compartments 1 – 4 were 84, 11, 5, and 4%, respectively. The average OLR and COD removal in these periods were 2.2 ± 0.9 g COD/L.d and $89 \pm 15\%$, respectively.

The performance of the reactor throughout the operation stage is summarized in Table 2. Each increase in the PCE loading rate was followed by a short-term decrease in COD removal, but the removal efficiency increased quickly. Table 3 lists the measurements of the PCE and intermediates existing in the liquid effluent.

In stages 2 and 4, the concentrations of the PCE and its intermediates were measured in the liquid effluent of the four compartments, and Table 4 shows those results.

The PCE removal for stages 5–8 were 99, 99.7, 99.8, and 99.5%, respectively. Therefore, an average PCE removal was obtained at 99.5% in this period. During the operation period, COD removal efficiencies for compartments 1–4 were 75, 68, 38, and 22%, respectively. The average COD removal and OLR in this period were $97 \pm 1.6\%$ and 3.1 ± 0.1 gCOD/L.d, respectively. An optimum OLR of 3.1 g COD/L.d was obtained during the operation days 231 – 270. The maximum COD and PCE removal efficiencies obtained were up to 98% and 99.8%, respectively, (corresponding OLR = 3.1 gCOD/L.d and PCE loading

Table 1: AMBR performance in startup and steady state periods before PCE injection

Stage	Operation days	OLR (g COD/L.d)	COD removal (%)	Alkalinity (mg/L CaCO₃)	pH (first-fourth compartment)
Startup periods					
1	1-45	0.8 ± 0.05	65 ± 28.5	845 ± 35	6.6-7.9
2	46-80	1.5 ± 0.03	94 ± 3.5	1070 ± 184	6.9-7.8
Steady state periods					
3	81-110	2.3 ± 0.03	97 ± 0.55	1777 ± 117	6.9-7.9
4	111-210	3.04 ± 0.03	95 ± 1.34	2439 ± 321	6.7-7.9

Table 2: AMBR operation after PCE injection

Stage	Operation days	OLR (g COD/L.d)	PCE in, mg/L	PCE removal (%)	COD removal (%)	Alkalinity (mg/L CaCO₃)	pH (first-fourth compartment)
5	211-230	3 ± 0.03	5	99	96 ± 3	2556 ± 62	7.2-7.8
6	231-250	3.1 ± 0.01	20	99.7	98 ± 0.3	3015 ± 7	7.5-8.2
7	251-270	3.1 ± 0.01	50	99.8	98 ± 0.3	3043 ± 11	7.1-8.6
8	271-290	3.2 ± 0.01	100	99.5	97 ± 0.4	3290 ± 99	7.4-8.6

Table 3: PCE and intermediates existing in the liquid effluent

Stages	1	2	3	4
PCEin (mg/L)	5	20	50	100
PCEout (mg/L)	0.05	0.05	0.1	0.5
TCEout (mg/L)	<0.05	<0.05	<0.05	<0.05
1,1-DCESout (mg/L)	<0.05	<0.05	<0.05	<0.05
Trans-1,2-DCESout (mg/L)	<0.05	<0.05	<0.05	<0.05
Trans-1,2-DCESout (mg/L)	<0.05	<0.05	<0.05	<0.05
VCout (mg/L)	NDᵃ	NDᵃ	NDᵃ	NDᵃ

NDᵃ: Not Detectable

Figure 2: COD removal efficiencies based on OLR during the reactor operation period

Figure 3: Alkalinity variation profiles during the reactor operation period (P.P: Phenolphthalein alkalinity, T: Total alkalinity)

rate=37.5 mgPCE/L.d). Figure 2 demonstrates the COD removal profile based on OLR during the performance of the reactor. Throughout the performance of the reactor, the COD in the liquid effluent was lower than 1000 mg/L.

pH and alkalinity

The pH of the influent was maintained between 7.1 and 8.5 and the effluent pH varied between 6.8 and 8.7. The range of the pH in the compartments during the performance of the reactor is shown in Tables 1 and 2. The average pH for the compartments 1–4 were 7.2, 7.28, 7.29, and 7.32, respectively. Comparing the pH in the different compartments in the AMBR reactor showed that the pH in first compartment was the lowest. During the system's performance, the alkalinity gradually increased from 845 to 3290 mg/L, and these variations are shown in Figure 3.

Total suspended solids and volatile suspended solids

The sSludge wash out was increasing with rising OLR. *Total suspended solids* (TSS) and *volatile suspended solids* (VSS) in the effluent were between 46 and 303 mg/L and 26 and 211 mg/L, respectively. The effluent TSS and VSS profiles are shown in Figure 4.

The results show that until OLR was 1.5 g COD/L.d, the effluent TSS was less than the standard value of 100 mg/L for discharge treated industrial wastewaters within the water resources.
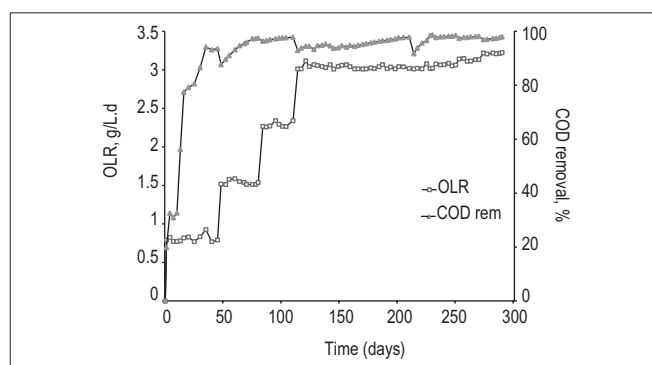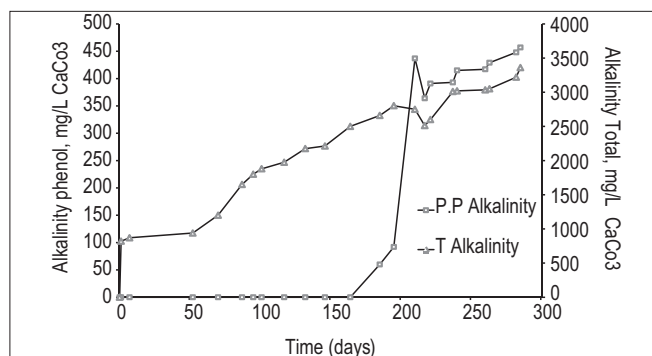
Adsorption rate of perchloroethylene on the biomass

The adsorption rate of PCE on the biomass in four influent PCE concentrations 5, 20, 50, and 100 mg/L were equal to 26, 210, 320, and 2100 μg/L, respectively. Thus, 0.52, 1.05, 0.64, and 2.1% from the influent PCE, with an average of 1.1 ± 0.7%, were adsorbed on the biomass.

Perchloroethylene concentration in the headspace

The PCE concentration in the headspace was found to be approximately 20% of the total PCE fed to the reactor.

Table 4: PCE and intermediates existing in the liquid effluent of compartments in stages 2 and 4

Stages	Compartment	PCE (mg/L)	TCE (mg/L)	1,1-DCES (mg/L)	Trans-1,2-DCES (mg/L)	Trans-1,2-DCES (mg/L)	VC (mg/L)
2	1	0.2	<0.05	<0.05	<0.05	<0.05	ND[a]
	2	0.1	<0.05	<0.05	<0.05	<0.05	ND[a]
	3	0.08	<0.05	<0.05	<0.05	<0.05	ND[a]
	4	0.06	<0.05	<0.05	<0.05	<0.05	ND[a]
4	1	1.2	<0.05	<0.05	<0.05	<0.05	ND[a]
	2	0.93	<0.05	<0.05	<0.05	<0.05	ND[a]
	3	0.81	<0.05	<0.05	<0.05	<0.05	ND[a]
	4	0.75	<0.05	<0.05	<0.05	<0.05	ND[a]

ND[a]: Not Detectable
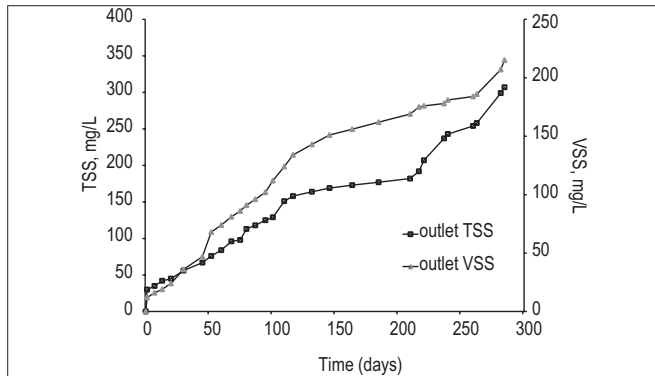
Figure 4: Effluent TSS and VSS variation profiles during the reactor operation period

Figure 5: SEM photographs of the flocs

Results of scanning electron microscopy and X-ray analysis

The SEM photographs of the sludge are shown in Figure 5. An examination of the granular biomass showed that the granules were black in color, having a spherical shape. The SEM images revealed that the granule surface was rough and uneven. Filament bacteria were observed on the surface of the flocs. In the study by Prakash, a heterogeneous bacterial population including *Methanothrix*, *Methanosarcina*, and *Methanospirillum* was observed on the surface of the granules.[6]

The XRF analysis of the sludge samples [Figure 6] showed a high content of sodium, potassium, and phosphorous. The containment of such elements in the sludge samples is indicative of the precipitation of these minerals within the granules. In the study by Debolina Basu, the XRF analysis of the sludge samples showed a high content of calcium, iron, and phosphorous.[12]

Figure 6: Biomass sampling points for XRF analysis

DISCUSSION

The addition of PCE 5 mg/L was followed by a short-term decrease in the COD removal deal of 6.2%, but the COD removal showed a trend of rising after three days and the average of COD removal increased to 96 ± 3. Therefore, injection of PCE showed a non-inhibitory effect, but the dehalogination by-products of PCE, such as TCE and DCES, appear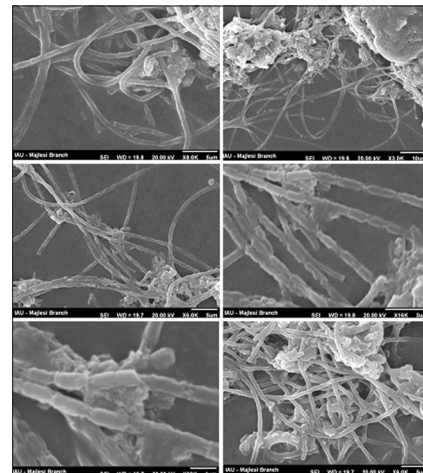ed in the 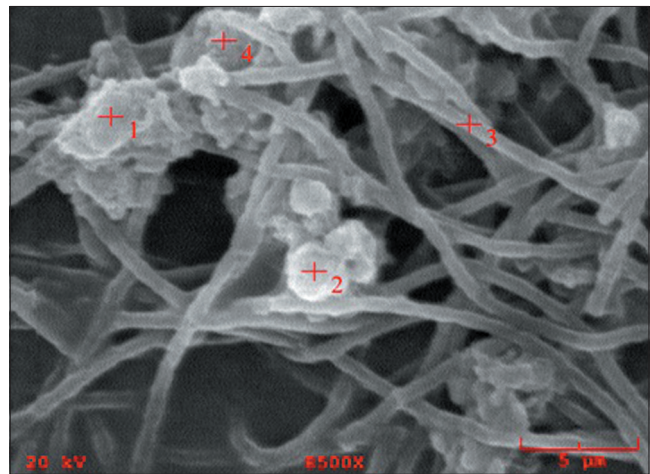effluent. By increasing the OLR and PCE loading rates, the COD removal efficiency had little fluctuations. The AMBR reactor showed a high ability to accept shocks resulting from organic and toxic substances. The removal of PCE was reductive dechlorination, wherein a chlorine atom was replaced by a hydrogen atom at each step, and the products of PCE were TCE and DCEs, and VC was not detected, which was consistent with some results.[1,2,8] Therefore, it was difficult to determine whether the DCEs were the end products. Most of studies of anaerobic dehalogenation of PCE have centered on the argument that it merely gets transformed to VC, which is a compound far

more toxic and volatile than the parent compound.[6] In this study, unlike other studies,[6-8] all isomers of the DCEs were detected in the effluent.

The PCE fed to the AMBR reactor can theoretically be removed by three possible mechanisms: adsorption onto the sludge, biological degradation, or stripping into the gas phase. The production of methane (and other non-determined biogas) creates a stripping effect on the overall removal of chloroethenes. Each of the three mechanisms have to be considered when studying the dehalogenation of PCE fed to the AMBR reactor.

Previous studies[1,3,6-8] have not addressed the adsorption rate of PCE on the biomass. In this study it was observed that $1.1 \pm 0.7\%$ of the total PCE fed to the reactor was adsorbed on the biomass. By considering the Water-Octanol partition coefficient PCE of 2.86, capturing only a small part of it on the biomass can be anticipated. Some studies have not determined the stripping effect,[13] and would have overestimated the treatment efficiency. The PCE concentration in the headspace was found to be approximately 20% of the total PCE fed to the reactor versus 1.5% in the study of Prakash,[6] and 10% in the study of Hwu.[1] Huang observed that approximately 1% of the total TCE fed to the activated carbon fluidized bed system was being stripped to produce gas.[14] The results achieved from this study revealed that influent PCE concentration in the range of $5 - 100$ mg/L, with an HRT of 32 hours, gave an overall PCE removal of around $99.5 \pm 0.4\%$. On subtracting the contribution of stripping and adsorption on the biomass, the biological degradation obtained was $78 \pm 0.7\%$. Hwu investigated the influence of HRT on the performance of complete PCE dechlorination. In this experiment, PCE removal increased from $51 \pm 5\%$ to $87 \pm 3\%$ when the HRT was increased from one to four days. On subtracting the contribution of stripping, the biological conversion ratio was $38 \pm 7\%$ to $76 \pm 4\%$.[1] Prakash assessed the effect of the increased concentration of PCE on the operational parameters of the UASB reactor to dechlorinate PCE, and the effect of HRT on the performance of the process. Influent PCE concentration of $5 - 50$ mg/l decreased to less than 0.23 mg/l ($98.5 \pm 1\%$ removal) in most cases, in an HRT of 8 to 24 hours. The trichloroethylene (TCE), cis-1, 2-dichloroethylene (cis-DCES), vinyl chloride (VC), and ethylene were formed after dehalogenation of PCE. Under steady state operation conditions, the COD removal was $94 \pm 2\%$.[6] Hirl worked on the Anaerobic Sequencing Batch Biofilm Reactor (AnSBBR), wherein, the input of PCE of 10.5 mg/L was converted to TCE and DCE isomers at the end of the 24-hour cycle. The PCE removal efficiency reached up to 95%.[7] In the study by Chu, in which the biodegradation ability of PCE by the Anaerobic Attached Film Expanded Bed (AAFEB) was evaluated, the PCE removal efficiency was more than 98%.[8]

In comparison of the PCE removal efficiency in this research and the mentioned studies, the PCE removal efficiency in the AMBR reactor was the highest. In the AMBR reactor, with the maintenance of biomass in the reactor, independent of the input wastewater, separation of SRT and HRT occurred. In fact, this separation allowed the anaerobic microorganisms with a slow growth to remain inside the system independent of the wastewater, thus, OLR and the removal efficiency increased. Increase in hydraulic turbulence resulted from mechanical mixing, which could lower the apparent K values, thus enhancing treatment efficiency.[15] Therefore, the use of short HRT for the wastewater treatment could allow for a smaller reactor size, and thus, a more economical treatment scheme. The majority of COD removal occurred in the first compartment (82.9%) and the rest of the COD was removed from the other compartments (8.5%). As the COD decreased in the preceding compartment, reduction in the substrate utilization rate of the microorganisms in the subsequent compartments occurred, leading to a lower removal efficiency. This event could be well supported by the bacterial kinetics that lower substrate concentration would cause a lower growth rate.[15]

Majority of the PCE removal took place in the final compartment, which received a minimum concentration of PCE. Angenent *et al.*, observed that staged conditions promoted complete removal of propionic acid in the final compartments of the AMBR reactor.[16] In this study, the PCE removal efficiency was higher than the COD removal efficiency. PCE could be completely transformed to non-chlorinated compounds by anaerobic microorganisms. A number of bacteria, capable of reductive dechlorination of PCE, have been identified.[17] Of these, *Dehalococcoides* are the only known species capable of complete dechlorination of PCE to non-chlorinated compounds.[18] As a result *Dehalococcoides*, which competes with the methanogenesis for the same substrate, dominate these in substrate utilization.

When comparing the compartments, it was seen that the primary compartment always had the minimum pH. The pH decreased in the first compartment because of acidification, the acetate phases, and high concentrations of volatile fatty acids. Due to the anaerobic decomposition process of the intermediate products (volatile fatty acids) to the final products (methane and carbon dioxide) in the next compartment, the pH value kept increasing from compartments one to four. The pH and alkalinity were important parameters to measure the stability of the reactor. Proper pH and alkalinity were very important for the startup of AMBR. In this study, higher pH was applied in the startup period to prevent the souring of the reactor, which could inhibit the increase of methanogenic bacteria. The VSS was found to be $80 \pm 11\%$ of TSS. Prakash found that the VSS was $42 \pm 2\%$ of SS.[6]

The present study demonstrates the ability of the AMBR systems to treat industrial wastewaters polluted with PCE that pass through their compartmentalized structure, allowing for greater removal efficiency. In the AMBR reactors,

due to high concentrations of TSS in the output, the use of a sedimentation unit is required to remove suspended solids, which improves the effluent quality.

CONCLUSIONS

This study describes the dechlorination of PCE in the AMBR reactor. The results of monitoring the Anaerobic Migrating Bed Reactor (AMBR) in the biodegradation of perchloroethylene from synthetic industrial wastewaters show that the reactor performs well in the HRT of 32 hours, in decreasing the concentrations of PCE in the range 5 – 100 mg/L, as the PCE in the effluent reactor is variable between 0.05 – 0.5 mg/L, with an overall removal efficiency of around 99.5 ± 0.4.

Intermediate compound concentrations (trichloroethylene and dichloroethylene isomers) were less than 50 μg/L. Optimum OLR in the reactor was 3.1 gCOD/L.d (±0.01) and COD removal efficiency was 98 ± 0.3%. One of the reactor characteristics was that it could withstand organic and toxic matter shocks.

According to the information obtained from this study, it can be stated that AMBR provides full-scale studies, using real industrial wastewater polluted with PCE, and it is a simple, efficient, and reliable method for the treatment of PCE.

ACKNOWLEDGMENTS

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