Treatment of organic matter and methylated arsenic in landfill biogas condensate

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A B S T R A C T

To explore the feasible treatment alternatives for organic contaminant, especially organic arsenic species in the landfill gas (LFG) condensate, a variety of treatment approaches were examined and evaluated in this study. Biological degradation, conventional and advanced oxidation, and physical absorption showed limited effectiveness to convert the methylated arsenic to inorganic arsenic. Reverse osmosis (RO) was found to be able to remove the organic arsenic and meet the discharge limits. Maximum removal efficiency and cost level were summarized for all treatment approaches tested, which can be a reference for the organic arsenic treatment method selection under different circumstances.

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1. Introduction

Biogas (methane) generation, collection and utilization could have an important impact on future energy and global warming scenarios. Biogas is a renewable biofuel and there is interest in using this to replace fossil fuel. Also, since the global warming potential (GWP) of methane is 25 times of carbon dioxide (Forster et al., 2007), the oxidation of biogas methane to carbon dioxide and water can reduce the GWP of these gases. Biogas originates either from landfills or anaerobic digesters, produced mainly from organic fractions of municipal solid waste (Barlaz et al., 2004; Levis and Barlaz, 2011; Amini and Reinharth, 2011) and sewage sludge (Tchobanoglous et al., 2004). LFG is collected from landfill gas extraction wells, transported via under and above ground piping systems, and physically purified based on temperature and pressure to be suitable for turbine, engine and combustion systems. Through natural or artificial cooling or through physical processes such as volume expansion, water and other vapors are removed from landfill gas based on different boiling points and critical pressure points. The collected liquid is referred to as condensate or gas derived liquids and requires treatment before discharge to a POTW or the environment.

LFG condensate is composed principally of an aqueous phase and a floating hydrocarbon organic phase. Pollutant compounds found in most condensate samples in either the aqueous or organic phase are benzene, toluene, 2-butanol (MEK), phenol, ethyl benzene, benzyl alcohol, bis (2-chloroisopropyl) ether, bis (2-ethylhexyl) phthalate, naphthalene, n-nitrosodimethylamine, 2,4-dimethylphenol, and 4-methylphenol (Briggs, 1988). The organics partition between the aqueous phase and organic phase depending on the temperature and the organic phase/water partition coefficients (Briggs, 1988). LFG condensate production can amount up to 5000 L/day in a municipal landfill (Briggs, 1988). The management of LFG condensate is problematic since there is little information available concerning condensate treatment and therefore, disposal options are not clear.

In this study, a LFG condensate sample was collected from a landfill located in Pennsylvania, USA. In a preliminary test, BOD (18,000 mg/L) and arsenic (7–40 mg/L) concentrations were found to be unacceptable for discharging this waste stream to the existing landfill waste water treatment plant. In particular, attention was paid to the high level arsenic because of its well-known toxicity and strict regulation. The arsenic was reported to be in the form of organic arsenic based on arsenic speciation.

The natural input of arsenic in the environment may be due to weathering processes of As-bearing minerals in soils and sediments. Anthropogenic activities include mining and smelting, and commercial use of wood preservatives, biocides, pesticides, alloying agents and others (Huang et al., 2009; Lafferty and Loeppert, 2005).

Arsenic has been a human health concern since it is carcinogenic to several organs in the human body (Parks et al., 2003; Smith et al., 1992). The maximum contamination level of arsenic in the drinking water in the US was changed from 50 μg/L to 10 μg/L in 2001 (USEPA, 2001). The date by which systems must comply with the new 10 ppb standard was January 23, 2006.
to 250 mg/L of As was found in landfill leachate samples (unpublished data). In environmental systems, inorganic arsenic typically exists in two oxidation states: iAs^{III} and iAs^{V}; organic arsenic occurs as methylated and more complex compounds: Methylarsonous acid (MMAs^{III}), Methylarsonic acid (MMAs^{V}), Dimethylarsinous acid (DMAs^{III}), Dimethylarsinic acid (DMAs^{V}), Trimethylalumin oxide (TMAsO^{V}), and Trimethylalene oxide (TMAs^{III}) (Lafferty and Loeppert, 2005) as listed in Table 1. In landfills, anaerobic bio-decomposition combines with complex chemical–physical processes, providing a condition for inorganic arsenic transformation through bio-alkylation and hydrde generation (Pinel-Raffaitin et al., 2007; Michalke et al., 2000). Extensive mechanistic studies have been conducted to explore the organic transformations of arsenic. Bio-methylation leads to the formation of methylated arsenic by combining reduction and methylation (Challenger, 1945; Cullen and Reimer, 1989). Volatile methyl derivatives of arsenic can potentially be transported from waste to biogases and ultimately reside in the landfill biogas condensate.

Inorganic arsenic treatment has been extensively studied to meet the stricter regulation. Coagulation and Fe–Mn treatment showed some success to immobilize soluble inorganic arsenic (Edward, 1994), for removal from aqueous solution by sedimentation, filtration and membrane separation. Enhanced coagulation can be employed either to meet stricter regulations for arsenic in treated water (Bocelli et al., 2005) or to treat the water with high arsenic concentration (Song et al., 2006). Polymeric coagulants also showed better performance than conventional coagulants for arsenic (Fan et al., 2003). However, there is limited information for organic arsenic treatment, although some research is reported for organic arsenic removal for drinking water treatment (Thirunavukkarasu et al., 2002).

2. Materials and methods

2.1. Sample collection

The landfill gas condensate sample was collected from a pilot scale chiller system which removed liquids from the gas stream in a landfill located at Pennsylvania (PA), USA. The gas condensate sample was shipped in polyethylene containers directly from the landfill to our lab, and stored at 4°C in the dark immediately after being received to reduce microbial activity. Before sampling for treatment and analysis, containers were shaken well to resuspend settled particles.

In this study, most of the arsenic in the LFG condensate was identified as organic arsenic.

2.2. Treatment methods

2.2.1. Sequencing Batch Reactor (SBR)

Biological treatment of landfill biogas condensate was operated in a lab-scale SBR system using a 10 L reactor. The initial biomass was taken from an operating biological reactor treating condensate at a landfill. The solids retention time and hydraulic retention time were 25 days and 10 days, respectively. To simulate the dilution achieved by the treated effluent from the biological leachate treatment plant, the gas condensate was diluted to 15% with water containing the sufficient nutrients (180 mg/L of nitrogen as urea and 38 mg/L of phosphorus as K_{2}HPO_{4}). The feed TOC and arsenic concentrations were 930 mg/L and 10.6 mg/L respectively. The MLSS of the reactor averaged 3300 mg/L ± 400 mg/L at steady state and the pH value was maintained at 8.2–8.3.

2.2.2. Coagulation

Coagulation was conducted with a six paddle stirrer (Model 300, Phipps & Bird, Inc., Richmond, VA). Ferric chloride (FeCl_{3}) was used as coagulant with various concentrations (25, 50, 100, 200, 500, and 1000 mg/L). 600 mL beakers were used to fit paddles of the stirrer. The sample size was limited to 200 mL in each beaker because of the limited amount of condensate available for testing. The coagulation procedure was as follows: flash stirring for 1 min at 150 rpm; slow stirring for 25 min at 35 rpm; settling for 25 min.

2.2.3. Permanganate oxidation

Potassium permanganate (KMnO_{4}) was used as a conventional oxidant with various concentrations (100, 500, 1000 and 1500 mg/L). Sample size was 100 mL each. Samples were stirred for 15 min with KMnO_{4} then settled overnight in a 250 mL beaker.

2.2.4. Fenton’s reagent oxidation

Advanced oxidation processes generate and use hydroxyl radical (·OH) which can breakdown compounds that cannot be destroyed by conventional oxidation methods. The electrochemical oxidizing potential of hydroxyl radical is 2.8 V, which is much higher than other conventional oxidants, such as ozone, hydrogen peroxide and chlorine and only second to fluorine (Al-Kdasi et al., 2004). Fenton’s reagent was used in this study as an advanced oxidation technology because of its operational simplicity and effectiveness (Lopez et al., 2004). The reaction for Fenton’s reagent is shown as follows:

\[
\text{Fe}^{2+} + \text{H}_{2}\text{O}_{2} \rightarrow \text{Fe}^{3+} + \cdot\text{OH} + \text{OH}^{-}
\]

As shown in Eq. (1), the hydroxyl radical (·OH) is generated as the oxidant and Fe^{3+} can be used as the coagulant, because OH· generated in the Fenton’s reaction at a low pH value is preferred thermodynamically.

In this study, the Fenton’s reaction was conducted in an acid environment. Before the reaction, pH was adjusted to 3.49 to make the reaction thermodynamically favorable. The Fenton’s reaction took place in a 250 mL beaker with magnetic stirrer and the sample size was 100 mL.

2.2.5. Carbon absorption

In the granular activated carbon (GAC) absorption test, 500 mL of SBR effluent was mixed with various amounts of GAC (0, 4, 10 and 20 g/L). Then the mixture of sample and GAC was shaken for 4 h in a 1-l capped plastic bottle to achieve saturated absorption. The GAC (Calgon Carbon Corporation, F-300, Pittsburgh, PA) used in this study is coal based, 8 × 30 mesh.

2.2.6. Membrane separation

Reverse osmosis (RO) was used as a membrane separation method in this study. The RO system (Model WHER25, Whirlpool, Ecodyne Water Systems Inc., Woodbury, MN) was driven by a peristaltic pump with pressure measured as 14.5 psig. The recovery ratio was 9.83%. The total dissolved solids (TDS) rejection rate is 90–95% at 50 psi, 77 °F and 750 TDS.

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Table 1: Oxidation state III: Abbreviation Oxidation state V: Abbreviation

<table>
<thead>
<tr>
<th>Species</th>
<th>Abbreviation</th>
<th>Oxidation state III</th>
<th>Abbreviation</th>
<th>Oxidation state V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>iAs</td>
<td>iAs^{III}</td>
<td>iAs^{V}</td>
<td></td>
</tr>
<tr>
<td>Methylarsonous</td>
<td>MMAs</td>
<td>MMAs^{III}</td>
<td>MMAs^{V}</td>
<td></td>
</tr>
<tr>
<td>Methylarsenic</td>
<td>DMAs</td>
<td>DMAs^{III}</td>
<td>DMAs^{V}</td>
<td></td>
</tr>
<tr>
<td>Trimethylalase</td>
<td>TMAs</td>
<td>TMAs^{III}</td>
<td>TMAs^{V}</td>
<td></td>
</tr>
<tr>
<td>Trimethylamine</td>
<td>TMA</td>
<td>TMA^{III}</td>
<td>TMA^{V}</td>
<td></td>
</tr>
</tbody>
</table>
2.3. Analyses

All chemicals used in this study were analytical grade. All the glassware was washed with soapy water, water rinsed, soaked in 10% nitric acid, rinsed with deionized water and baked for 4 h at 450 °C. Total organic carbon (TOC) was analyzed using high temperature combustion with a TOC analyzer (Shimadzu TOC-5000A, Japan), the method detection limit (MDL) is 0.426 mg/L. Arsenic analysis was conducted by using a Thermo Electron X-Series inductively coupled plasma with mass spectrometer (ICP-MS) per Standard Method 3125-B (APHA, 1998), detection limit is 1 ppb. ICP-MS Samples and calibration standards were prepared in a matrix of 2% nitric acid by volume. Mixed liquid suspended solid (MLSS) was measured as per standard method (APHA, 1998).

Arsenic speciation was done at Exova (Santa Fe Spring, CA). Different species of arsenic was differentiated into AsIII, AsV, DMA and MMA by with liquid chromatography (LC), arsenic species was quantified by inductively coupled plasma-mass spectroscopy (ICP-MS). 1.0 mL of sample was diluted to 5 mL with de-ionized water to meet the detection limit before analysis for arsenic species.

2.4. Cost evaluation

Cost analysis of chemicals used in this study was based on the optimum dosage and the unit price in the U.S. market. No other factors, such as chemical sludge disposal, and reject solution treatment were included in cost consideration. Price of chemicals may vary for different time and locations. The cost evaluation was used to provide a reference for price comparison of different technologies.

3. Results and discussion

3.1. Biological treatment

Biological treatment was conducted in a SBR system to treat the diluted landfill gas condensate, since this process is widely used at landfills for leachate treatment. The biomass in the SBR system was taken from another activated sludge system treating undiluted landfill gas condensate, which resulted in the high initial MLSS. The performance of the SBR system on TOC and total arsenic removal are shown in Figs. 1 and 2, respectively. As shown in Fig. 1, there were three phases regarding the organic matter removal in the SBR system. In phase I, from day 1 to day 9, the TOC concentration in the SBR effluent dropped sharply from 143 mg/L (day 1) to 64 mg/L (day 9). Over this same time period, the biomass concentration in the biological reactor was reduced from 8728 mg/L (day 2) to 3590 mg/L (day 9) in terms of MLSS.

In phase II, from day 10 to day 25, the MLSS did not change little, but the effluent organic matter continued to decline from 57 mg/L (day 10) to 22 mg/L (day 25). In phase III, the effluent organic matter remained relatively constant and averaged 25 mg/L. Effluent TOC from day 26 to the end of operation. The biomass concentration also remained constant. The overall TOC removal in the SBR was around 85%.

Concerning the toxicity of arsenic, the biological system performed well under the high arsenic environment. This result indicated that arsenic in organic form did not hinder the biological activity in the biological system. The low toxicity of organic arsenic has reported from toxicology studies of arsenic species (Hughes, 2002; Cullen and Bentley, 2005); the toxicity of inorganic As was reported to be hundreds to thousands higher than organic species of arsenic.

The arsenic removal performance of the SBR system is shown in Fig. 2. There were two phases regarding the As treatment. During phase I, the effluent total arsenic concentration was reduced from 17 mg/L to 9 mg/L. As mentioned above, the biomass of the SBR system was taken from another activated sludge system treating undiluted landfill gas condensate, which resulted in the As concentration in the reactor being higher than in the feed. From day 10 to the end of the operation, which corresponds to phases II and III of the TOC treatment, the effluent total arsenic concentration fluctuated around 7.8 mg/L. The total arsenic removal efficiency from day 10 to day 37 was 26%.

A comparison of the removals in these phases provided insight into the mechanisms for reduction in arsenic and TOC. During phase I the biomass concentration in the reactor rapidly declined and most of the TOC and As removal was thought to be caused by biomass wastage. After day 9, biomass and arsenic concentrations remained steady but the TOC continued to decline, which is believed to be caused by bio-degradation. The organic compounds found in most landfill gas condensates have been reported to be volatile and readily degradable (Briggs, 1988). It is thought that a small fraction of the organic arsenic is immobilized by biomass absorption then removed from the biological system by sludge wastage. Biosorption of different species of metalloid was reported previously (Çeçen and Gürsoy, 2001), arsenic biosorption by biomass is under investigation.

FeCl3 is known to be an effective coagulant for inorganic arsenic and was therefore used as a coagulant for the SBR daily effluent. Each day, the effluent from the bioreactor was dosed with 400 mg/L of FeCl3. The results are shown in Fig. 2. By comparing the effluent arsenic following coagulation over days 9, 10 and 11 with the uncoagulated effluent, it can be seen that the addition of ferric chloride removed approximately additional 1 mg/L of arsenic (14.0%, 13.3% and 12.6% for days 9, 10 and 11 respectively).

Additional coagulation studies were conducted with a wider range of doses using the SBR effluent collected over day 12 to day 20. As shown in Fig. 3, the removal efficiency of arsenic in the SBR effluent fluctuated between 0.7% and 8.0% at a variety of doses up to 1000 mg/L of FeCl3, leaving 6.7–7.2 mg/L of arsenic in the treated solution. While organic matter was removed up to 65% in terms of TOC with 200 mg/L of FeCl3 (Fig. 3), resulting in an effluent TOC of 11 mg/L, the effect on arsenic, shown in Fig. 3, was minimal. Since inorganic arsenic was reported to be successfully removed by coagulation–flocculation (Edwards, 1994; Boccelli et al., 2005; Song et al., 2006; Fan et al., 2003), these results indicate that most of arsenic in the SBR effluent was in organic form and bio-oxidation did not mineralize the component of the organic As complex in the SBR system thus preventing precipitation.

Hence, regarding the landfill gas condensate treatment, biological system (SBR) showed success for organic matter removal. For arsenic removal, bio-degradation was not the removal mechanism, biosorption followed by biomass wastage removed approximately 25% of the arsenic, but the concentration in the effluent was not low enough to be discharged directly to receiving waters.

3.2. Oxidation followed by coagulation

The failure of bio-oxidation/coagulation to remove arsenic from the condensate led to an attempt to oxidize the organic arsenic using chemical oxidation. Potassium permanganate (KMnO4) was used as an oxidant to treat the SBR effluent using doses of 100, 500, 1000, 1500 mg/L. As shown in Fig. 4, up to 62% of the residual organic matter was removed in terms of TOC with a KMnO4 dose of 1000 mg/L, leaving the effluent TOC at 12 mg/L. The removal efficiency increased with higher amounts of KMnO4 up to 500 mg/L.
Additional KMnO₄ above 500 mg/L did not improve the treatment performance.

FeCl₃ coagulation was applied on the KMnO₄ treated SBR effluent to determine if the arsenic had been oxidized. As shown in Fig. 5, no more than 6% of arsenic could be removed by the combination of chemical oxidation and FeCl₃ coagulation with FeCl₃ dose of 600 mg/L. Even though a slight increase in removal efficiency was observed with more coagulant, no significant removal was found within a practical dose range.

As reported by a previous study (Torrens and Salerno, 1995), KMnO₄ was superior to peroxide and ozone for ground water arsenic treatment as an oxidant the results from this study, combined with the study of Torrens and Salerno indicate that, KMnO₄, and chemical oxidants in general, do not break down the organic structure of organic arsenic, although it could remove other organic matter contained in biologically treated condensate.

Some advanced oxidation processes are believed to be capable of breaking down the compounds that cannot be destroyed by conventional oxidation methods. Fenton’s reagent is widely used as an advanced oxidation process since it is simple and effective. Fenton’s treatment is believed to be a combination of oxidation and coagulation since both radical hydroxide (OH) and ferric cation exist in the system. So in this study, no additional coagulant was added to the Fenton’s effluent.

Fenton’s reagent with various concentrations of H₂O₂ (2.9, 14.7, 29.4, 58.8, 88.2, and 147.1 mg/L) and a constant amount of Ferrous sulfate (17.9 mg/L) was applied to the SBR effluent, providing H₂O₂ and Ferrous sulfate molar ratio ranges from 0.82 to 36.76. The treated arsenic concentration was plotted with H₂O₂ concentration and is shown in Fig. 6. It can be seen that, arsenic removal efficiency increased with the H₂O₂ dose up to 15 mg/L. The maximum removal efficiency achieved by Fenton’s reagent was 18%, leaving the effluent arsenic as low as 5.9 mg/L. The results showed that, Fenton’s reagent as an advanced oxidation process, performed much better than coagulation alone (8.0% removal) or KMnO₄ followed by coag-
ulation (5.6% removal) for the SBR effluent. However, the Fenton’s treatment effluent arsenic concentration (5.9 mg/L) was still far higher than the acceptable level for discharge.

Chemical oxidation, both conventional and advanced, showed limited capability to break down the methylated arsenic species into inorganic species. The results indicate that methylated arsenic species are fairly stable, which coincides the low toxicity of them.

3.3. Carbon adsorption

Activated carbon has been widely used as an adsorbent on inorganic and organic environmental contaminants removal, such as Cd (Liu et al., 2010), Hg (Kim et al., 2011), bromate in raw water (Liu et al., 2011), dissolved organic carbon in surface water (Yapsakli and Çeçen, 2010), and surfactants, volatile organic compounds (VOCs), pesticides, PCBs, semi volatile organic compounds (SVOCs) (Rosu et al., 2007). Vapor phase activated carbon adsorption is also used for landfill gas treatment (Gaur et al., 2010) aromatics and chlorinated compounds removal. However, it was seldom reported for arsenic removal in landfill gas/landfill gas condensate. In this study, granular activated carbon was applied to the SBR effluent for arsenic removal. As shown in Fig. 7, more arsenic was removed by higher dose of activated carbon. The highest removal efficiency (6.5%) was achieved with 20 g/L of activated carbon, leaving 6.6 mg/L arsenic in the carbon treated liquid. A higher dose of activated carbon was not tried since no obvious improvement could be expected over a practical dose range. Activated carbon tested in this study showed limited treatment capacity for arsenic in LFG condensate. The treated liquid was not acceptable for discharge.

3.4. Membrane separation

Reverse osmosis (RO) is widely used to separate a variety of contaminants from aqueous solution. Arsenic treatment by RO was reported for drinking water (Walker et al., 2008; Kang et al.,

![Fig. 4. TOC of permanganate oxidized SBR effluent.](image)

![Fig. 5. As in SBR effluent treated with permanganate oxidation followed by coagulation.](image)

![Fig. 6. Fenton's treatment results for As in SBR effluent.](image)
Most of these studies focused on inorganic species of arsenic. It was reported (Clifford et al., 1986) that RO systems are typically capable of removing arsenate with high efficiency (98–99% removal), but can be significantly less efficient in treating arsenite (46–75% removal). Organic arsenic species treatment by RO has been seldom reported (Torrens and Salerno, 1995).

In this study, RO was applied to SBR treated LFG condensate. The results are shown in Fig. 8. As shown in Fig. 8, 95.8% of the arsenic was removed by the RO systems, leaving 311.4 µg/L of arsenic in the RO permeate. When the RO feed was diluted to 3:1, the arsenic concentration in RO permeate was reduced to 135 µg/L and the removal efficiency was 93.1%, which can meet the discharge limit of 200 µg/L.

An arsenic speciation study showed (Table 2) that 108 µg/L out of 135 µg/L of arsenic in the RO permeate was arsenite (AsIII). This result coincides with previous study that RO is not highly effective for arsenic removal (Clifford et al., 1986) and also it verifies the feasibility of organic arsenic treatment by RO system. Preoxidation of AsIII before RO may improve performance.

### 3.5. Cost analysis and treatment comparison

The treatment methods for arsenic removal tested in this study for SBR effluent are listed in Table 3. Reverse osmosis showed outstanding performance on organic arsenic removal in the LFG condensate SBR effluent, making it a technically feasible method for the direct discharge of treated LFG condensate in terms of arsenic concentration. None of the other methods listed in Table 3 shown more than 20% removal efficiency. Among those methods, Fenton’s reagent performed best with 15.1% removal efficiency, however the arsenic concentration in the treated sample (5.9 mg/L) was much higher than the discharge limit for arsenic (200 µg/L).

![Fig. 7. Carbon Absorption results for As in SBR effluent.](image)

![Fig. 8. Reverse osmosis arsenic removal for diluted and undiluted SBR effluents.](image)

### Table 2

<table>
<thead>
<tr>
<th>As species</th>
<th>AsIII</th>
<th>AsV</th>
<th>MMA</th>
<th>DMA</th>
<th>Other</th>
<th>Total</th>
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<tbody>
<tr>
<td>Concentration (µg/L)</td>
<td>108</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>27</td>
<td>135</td>
</tr>
</tbody>
</table>

* Not detected.
4. Conclusions

1. Biological treatment is effective for removal of TOC in landfill gas condensate. The high removal efficiency (more than 95%) and low effluent TOC concentration (25 mg/L) in the SBR system in this study verified the biodegradability of organic matter in the landfill gas condensate. Biological treatment is not effective for organic arsenic in the landfill gas condensate. A maximum of 26% of total arsenic was removed from the SBR system at steady state. Arsenic removal in the biological system was believed to be through adsorption to biomass and removal with waste activated sludge.

2. Physico-chemical treatment methods, such as FeCl₃ coagulation, KMnO₄ followed by coagulation, Fenton’s reagent and activated carbon, were tested and proved ineffective for organic arsenic treatment. Among those, Fenton’s reagent performed best with 15.1% removal efficiency and 5.9 mg/L arsenic in the treated sample.

3. Though reported not highly effective for As(III), RO system showed success on organic arsenic treatment in this study with up to 95.8% arsenic removed. A speciation analysis indicated that, most arsenic in the RO permeate was As(III).

4. Even not included in this study, iron/ granular ferric oxide co-precipitation and adsorptive resin may show some potential effectiveness for the As removal as a post-treatment for the biologically treated LFG condensate. Also, UV oxidation may have potential treatment effectiveness to break down the methylated arsenic species. In the future study, performance and mechanism will be examined and explored for other potential treatment approaches for the LFG condensate and As species.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2013.01.013.

References


Table 3

<table>
<thead>
<tr>
<th>Treatment method</th>
<th>Maximum removal (%)</th>
<th>Effluent As concentration</th>
<th>Condition</th>
<th>Cost level a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulation/flocculation (FeCl₃)</td>
<td>8.0</td>
<td>6.7 mg/L</td>
<td>500 mg/L FeCl₃</td>
<td>1</td>
</tr>
<tr>
<td>Oxidation + coagulation (K MnO₄ + FeCl₃)</td>
<td>5.6</td>
<td>6.8 mg/L</td>
<td>500 mg/L K MnO₄ + 600 mg/L FeCl₃</td>
<td>4.7</td>
</tr>
<tr>
<td>Advanced oxidation (Fenton’s reagent)</td>
<td>15.1</td>
<td>5.9 mg/L</td>
<td>1000 mg/L Fe²⁺ + 500 mg/L H₂O₂ pH = 3.49</td>
<td>9.4</td>
</tr>
<tr>
<td>Carbon absorption</td>
<td>6.5</td>
<td>6.6 mg/L</td>
<td>20 g/L granulated activated carbon contact time = 4 h</td>
<td>43.2</td>
</tr>
<tr>
<td>Membrane separation (reverse osmosis)</td>
<td>95.8</td>
<td>311 µg/L</td>
<td>Pressure = 14.5 psi recovery = 5.83%</td>
<td>43.6</td>
</tr>
</tbody>
</table>

a Cost of coagulation–flocculation by FeCl₃ was taken as a cost equivalent.


