Electrogeneration of H$_2$ for Pd-catalytic hydrodechlorination of 2,4-dichlorophenol in groundwater

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**Abstract**

A novel electrolytic groundwater remediation process, which used the H$_2$ continuously generated at cathode to achieve in situ catalytic hydrodechlorination, was developed for the treatment of 2,4-dichlorophenol (2,4-DCP) in groundwater. Catalytic hydrodechlorination using Pd supported on bamboo charcoal and external H$_2$ showed that 2,4-DCP was completely dechlorinated to phenol within 30 min at pH < 5.5. In a divided electrolytic system, the catalytic hydrodechlorination of 2,4-DCP in cathodic compartment by H$_2$ generated at the cathode under 20 and 50 mA reached 100% at 120 and 60 min, respectively. Two column experiments with influent pHs of 5.5 (unconditioned) and 2 were conducted to evaluate the feasibility of this process. The 2,4-DCP removal efficiencies were about 63% and nearly 100% at influent pHs of 5.5 and 2, respectively. Phenol was solely produced by 2,4-DCP hydrodechlorination, and was subsequently degraded at the anode. A low pH could enhance the hydrodechlorination, but was not necessarily required.

This study provides the preliminary results of a novel effective electrolytic process for the remediation of groundwater contaminated by chlorinated aromatics.

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**1. Introduction**

Chlorinated organic compounds (COCs) have been the focus of intensive concern due to their highly refractory nature, bio-accumulation and toxicity (Moran et al., 2007). Various activities such as chemical, pesticide, metal processing and electronic manufacturing industries can release COCs into the subsurface environment (Gavrilescu, 2005; Moran et al., 2007), where they may pose a threat to drinking water safety and public health. The toxicity of individual COC is closely related to the extent of chlorination. Generally, higher chlorine contents are associated with higher toxicity and poor oxidizability. The release of chlorine atoms leads to a decrease in toxicity and an increase in oxidizability. Therefore, reductive dechlorination is considered to be an effective method for the remediation of COC contaminated groundwater (McNab et al., 2000; Nutter et al., 2005; Henderson and Demond, 2007; Hildebrand et al., 2009; Mitoma et al., 2009; Chu et al., 2010; Phillips et al., 2010).

Biological processes have been widely used for COC dechlorination in groundwater, but they require well controlled growth conditions for the microorganisms (Schreier and Reinhard, 1995). In contrast, dechlorination by zero-valent iron (Fe$^0$) and catalytic hydrodechlorination is suitable under many circumstances. Fe$^0$ (including bimetallic iron) is commonly placed in permeable reactive barriers (PRBs) for the in situ remediation of COC contaminated groundwater (Henderson and Demond, 2007; Phillips et al., 2010). The main mechanisms for COC dechlorination by bimetallic iron include hydrodechlorination (Chun et al., 2010) and sequestration by iron corrosion products (Noubactep, 2009; Ghauch et al., 2010). However, the continuous corrosion of the iron during decades of field operation results in the surface coverage by iron hydrates and oxides, thereby decreasing the long-term performance (Henderson and Demand, 2007; Phillips et al., 2010). Also, it is difficult to determine the remediation efficiency of a built PRB. Catalytic hydrodechlorination by H$_2$ and noble metals is another process for the ex situ treatment of COCs in groundwater (Nutt et al., 2005; Hildebrand et al., 2009; Mitoma et al., 2009). Contaminated groundwater is pumped above ground, mixed with H$_2$, sent through a catalyst bed (mainly Pd) and then released back underground (Davie et al., 2008). For example, Reinhard's group reported the effective hydrodechlorination of a variety of chlorinated organics in the presence of Pd catalyst (McNab and Ruiz, 1998; Lowry and Reinhard, 2000; McNab et al., 2000; Davie et al., 2008). This method is generally effective but is not economic for field application because of the "pump and treat" process. As a result, it may be effective and economical if catalytic hydrodechlorination could be applied in situ for groundwater remediation with the continuous supply of H$_2$ in groundwater.
It is well known that water electrolysis can generate O₂ and H⁺ at the anode as well as H₂ and OH⁻ at cathode. However, during the electrochemical remediation of subsurfaces, both O₂ and H₂ were considered to reduce the efficiency and were wasted (Yuan et al., 2006; Reddy and Cameselle, 2009). Very recently, several researchers have utilized these products for contaminant treatment. Gent et al. (2009) used the alkaline conditions produced near the cathode to hydrolyze organic compounds in groundwater. Others (Lohner and Tihm, 2009; Lohner et al., 2011) used the H₂ and O₂ generated at the cathode and anode, respectively, to stimulate the sequential anaerobic and aerobic degradation of contaminants in the subsurface. Yuan et al. (2011) synthesized H₂O₂ from the H₂ and O₂ produced at the electrodes for the electro-Fenton degradation of contaminants. Besides, Alshawabkeh (2009) pointed out that constructing electrochemical redox barriers by utilizing the electrogenerated H₂ and O₂ for groundwater remediation was one of the two promising opportunities for the development of electrochemical remediation.

Anode : \[2 \text{H}_2\text{O} - 4e^- = \text{O}_2 + 4\text{H}^+\] (1)

Cathode : \[2\text{H}_2\text{O} + 2e^- = \text{H}_2 + 2\text{OH}^-\] (2)

In this study, a novel electrolytic groundwater remediation process, which used the H₂ continuously generated at the cathode for in situ catalytic hydrodechlorination of COCs, was developed. 2,4-Dichlorophenol (2,4-DCP) and Pd supported on bamboo charcoal (Pd/C) were used as the COC and catalyst, respectively. Bamboo charcoal is a new kind of renewable carbon materials, and showed slight adsorption to 2,4-DCP and phenol. The electrodes were graphite, which is inert, cheap and stable. The objectives was to evaluate the feasibility of this novel electrolytic system for the remediation of 2,4-DCP contaminated groundwater.

2. Materials and methods

2.1. Chemicals, synthesis of Pd/C catalyst, adsorption isotherms of 2,4-DCP on Pd/C and silica, and anodic oxidation of phenol

The descriptions of the chemicals, the synthesis and characterization of the Pd/C catalyst, the adsorption of 2,4-DCP on quartz sand and the Pd/C catalyst, and the anodic oxidation of phenol are available in the Supplementary material (SM). Deionized water (18.0 mΩ cm), obtained from a Millipore Milli-Q system, was used.

2.2. Hydrodechlorination of 2,4-DCP by external H₂ in batch mode

The feasibility of 2,4-DCP hydrodechlorination was first evaluated using external H₂ (99.999%). A total of 200 mL of 2,4-DCP solution (0.16 mM) was treated in a three-neck flask. Before the reactions were started, N₂ was bubbled for 15 min to purge any dissolved oxygen from the solution. Then 0.5 g of Pd/C catalyst was added, and H₂ was supplied at a constant flow rate of 50 mL min⁻¹. The solution temperature was maintained at 30 °C in a water bath. The solution pH was adjusted with 0.5 M H₂SO₄ and NaOH. The electrolyte was supplied by Na₂SO₄. Control experiments with H₂ bubbling in the absence of Pd/C and without H₂ bubbling in the presence of Pd/C were also conducted. At regular time intervals, approximately 2 mL of solution was removed for analysis. Each experiment was performed in duplicate.

2.3. Hydrodechlorination of 2,4-DCP by cathodic H₂ in batch mode

The hydrodechlorination by H₂ generated at the cathode was then investigated in the batch mode. Two three-neck flasks were used as the anodic and cathodic compartments, which were connected by a salt bridge consisting of 2% agar solution saturated with KCl. The cathodic compartment was filled with 240 mL of 2,4-DCP solution (0.16 mM) in 10 mM Na₂SO₄. The anodic compartment was filled with 10 mM Na₂SO₄. Graphite sheets (10 × 10 × 50 mm) were used as the anode and cathode. N₂ was first bubbled for 15 min to remove any oxygen in the cathodic compartment. After 1 g of Pd/C was added to the cathodic compartment, the reaction was initiated by switching on the direct current power supply (GPC-3060D, Taiwan Goodwill Instrument). The influence of electric current (10–50 mA) was investigated. Control experiment with electrolysis at 40 mA in the absence of Pd/C was also conducted. The solutions were maintained at 20 °C in a water bath. At regular time intervals, about 2 mL of solution was removed for analysis. Each run was performed in duplicate.

2.4. Hydrodechlorination of 2,4-DCP in groundwater in column experiments

Two column experiments with Pd/C catalyst were performed with the influent pHs of 5.5 and 2.0 to investigate the hydrodechlorination of 2,4-DCP. One control column with the same quantity of bamboo charcoal without Pd loading was also tested to evaluate contaminant degradation at the electrodes and adsorption on bamboo charcoal and silica. As shown in Fig. 1, the experimental setup consisted of a vertical column (50 mm diameter × 100 mm length) containing two perforated graphite electrodes (60 mm diameter × 10 mm length) as the anode and cathode in each end. The column was then fully packed with quartz sand with a porosity of 0.23. The simulated 2,4-DCP contaminated groundwater (0.08 mM) containing 20 mM Na₂SO₄ was fed into the column from the bottom cathode using a peristaltic pump at 20 mL h⁻¹ (1.94 m d⁻¹). During the experiments, N₂ was continuously introduced into the reservoir containing the groundwater.
to avoid the influence of O₂. The column was rinsed with the simulated 2,4-DCP contaminated groundwater before the power was switched on. The voltage was controlled at 20 V (2 V cm⁻¹), which is comparable to the electrokinetic remediation (Yuan et al., 2006; Reddy and Cameselle, 2009). One sample was collected from the outlet to evaluate the overall remediation efficiency, and another sample was collected from a port 40 mm from the inlet to evaluate the hydrodechlorination efficiency. It took 2.31 and 0.92 h for the groundwater to reach the outlet and the port 40 mm from the inlet, respectively.

2.5. Analysis and characterization

The samples were filtered through a 0.45 μm filtration membrane before analysis. 2,4-DCP, 2-chlorophenol (2-CP), 4-chlorophenol (4-CP) and phenol were measured by an Agilent 1200 series high performance liquid chromatograph (HPLC) equipped with an 1200 series variable wavelength detector and an Zorbax Eclipse XDB-C18 chromatographic column (Φ 4.6 × 150 mm, 5 μm). For phenolic compounds analysis, the mobile phase was the mixture of acetate buffer (0.5%) and methanol at 40:60 (v:v) at 1.5 mL min⁻¹, and the detection wavelength was 278 nm. Any Pd that leached into solution after reaction was detected by an ELAN DRC-e inductively coupled plasma mass spectrometer (PerkinElmer, USA).

Prior to characterization, the Pd/C catalyst after the reaction was washed with deionized water to a neutral pH and dried at 70 °C under vacuum overnight. The fresh and reacted Pd/C catalysts were characterized by environmental scanning electron microscopy equipped with energy dispersive X-ray analysis (ESEM/EDX, FEI Quanta 200), field scanning electron microscopy (FSEM, FEI Sirion 200), X-ray diffraction (XRD, PANalytical B. V. X'Pert PRO X-ray diffractometer with Cu K radiation), and X-ray photoelectron spectroscopy (XPS, VG Multilab 200). The Zeta potentials of the quartz sand and Pd/C particles at different pHs were measured on a Malvern Zetasizer (NanoZS).

3. Results and discussion

3.1. Characterization of the synthesized Pd/C catalyst

The ESEM image of the synthesized Pd/C catalyst in Fig. 2a shows the presence of small particles on the bamboo charcoal surface, which were identified as Pd particles by the corresponding EDX result. The Pd content was measured as 10.1% (w/w). The high resolution FSEM images in Fig. 2b reveal that the Pd particles were evenly scattered on the bamboo charcoal surface with a particle size of about 20 nm. The XRD patterns of the fresh Pd/C catalyst (Fig. SM-1) show five peaks at 40.3, 46.8, 68.4, 82.1, and 86.7° which correspond to the (1 1 1), (2 2 0), (2 0 0), (3 1 1), and (2 2 2) planes of a face-centered-cubic (FCC) lattice, respectively, indicating a FCC structure to the Pd particles (Cui et al., 2005; He et al., 2009). The average crystal size of the Pd particles was calculated as 15 nm by the Scherrer equation, which is close to the size identified by FSEM. The chemical states of the surface atoms in the synthesized catalysts were further analyzed by XPS (Fig. SM-2). The Pd peaks (335.3 eV) exhibited tailing at high binding energy (336.9 eV), which is in agreement with literature (Chen et al., 2004). The shoulder peak for Pd(0) was attributed to the presence of Pd(II), which was probably due to the incomplete reduction of the precursor salt or the presence of PD(O) (Wang and Wang, 2008). The dominant component of the Pd3d binding energy was confirmed as Pd(0). Also, the weight fraction of Pd3d measured by XPS was 11.0%, which was approximately equal to that measured by ESEM/EDX.

3.2. Pd/C catalyzed hydrodechlorination of 2,4-DCP by external H₂

External H₂ was firstly used to investigate the profile of 2,4-DCP hydrodechlorination. The control experiments suggest that both H₂ bubbling and Pd/C adsorption removed less than 10% of 2,4-DCP from solution in the pH range from 3.5 to 11. The hydrodechlorination of 2,4-DCP at different pH values are shown in Fig. 3, indicating an efficient hydrodechlorination of 2,4-DCP by external H₂. When the solution pH was maintained at 3.5, much lower than its pKa (7.89), the 2,4-DCP was completely reduced within 20 min (Fig. 3a). The hydrodechlorination profile reveals that phenol was produced in the initial 20 min, but then declined from 20 to 120 min. It has been found that phenol could be hydrogenated to cyclohexanone (Yuan and Keane, 2007). When the pH was raised to 5.5, 96% of the 2,4-DCP was hydrodechlorinated within 20 min, and 100% removal occurred at 40 min (Fig. 3b). The 2,4-DCP was again quantitatively hydrodechlorinated to phenol. However, the decrease in the phenol concentration after 20 min was slight. At pH of 11, much higher than the pKa of 2,4-DCP, the 2,4-DCP was slowly hydrodechlorinated, and only 41% was reduced within 120 min (Fig. 3c).

The aqueous solubility of 2,4-DCP increases from 4.66 g L⁻¹ at pH 4.80 to 110 g L⁻¹ at pH 9.30 (Huang et al., 2000), which indicates the difficult adsorption at high pHs. The dependence of 2,4-DCP adsorption on pH is clearly reflected in Fig. SM-3a. Because the Pd/C is negatively charged (Fig. SM-4), the electrostatic repulsion between the 2,4-dichlorophenolate anions and Pd/C catalyst surface becomes significant at high pHs (Shin and Keane, 1999). Since catalyzed hydrogenation is an electrophilic reaction (Shin and Keane, 1999; Zhu and Lim, 2007), the 2,4-dichlorophenolate anion could have been hydrodechlorinated more quickly than 2,4-DCP. The rapid hydrodechlorination at low pH suggests that adsorption played a more important role on hydrodechlorination than the dissociation of the 2,4-DCP. The influence of pH on 2,4-DCP hydrodechlorination described above is in agreement with the 2,4-DCP hydrodechlorination at high initial concentrations (Yuan and Keane, 2004, 2007) and pentachlorophenol hydrodechlorination at low initial concentrations (Patel and Suresh, 2008).

3.3. Pd/C catalyzed hydrodechlorination of 2,4-DCP by cathodic H₂

Control experiments proves that 2,4-DCP cannot be hydrodechlorinated at graphite cathode within 120 min in the absence of the Pd/C catalyst (data not shown). Fig. 4 shows that 2,4-DCP was effectively hydrodechlorinated to phenol by cathodic H₂ in the presence of the Pd/C catalyst. The pseudo first order decay rate constants (k₁) at 10, 20 and 50 mA were 0.0050 ± 0.0007, 0.033 ± 0.004 and 0.047 ± 0.002 min⁻¹, respectively. In the cathodic compartment, the electro-generated H₂ (clearly observable) dissolved in solution were transported to the Pd/C surface where they were decomposed to form active H. This active H was responsible for the hydrodechlorination of 2,4-DCP. With the increase in current, more H₂ was generated (Skadberg et al., 1999) and more active H was formed on the surface of Pd, causing a higher hydrodechlorination rate. The concentration of Pd leached into solution was 15 μg L⁻¹ (0.01% of total Pd) after 9 h, indicating that the loss of Pd was minimal during treatment. In a similar earlier work where H₂ was produced in an undivided electrolytic system, McNab and Ruiz (1998) found the effective hydrodechlorination of trichloroethene (TCE) by Pd/Al₂O₃.

Assuming that the electrical current is corresponded to H₂ production and 2,4-DCP hydrodechlorination, the current efficiency was calculated based on Faraday’s law. As shown in Table 1, the current efficiency at 10 mA slowly increased to 2.4% at 120 min, while at 20 and 50 mA the current efficiency increased during the early stages and then decreased. The maximum current
Efficiencies at 20 and 50 mA were 11.8% at 60 min and 15.2% at 40 min, respectively. The maximum current efficiency occurred when the H$_2$ produced exceeded its saturated solubility in the cathodic compartment (0.19 mmol), implying that the dissolution of H$_2$ was the rate-limited step for hydrodechlorination. In the initial stages, the current efficiency increased with increased amounts of H$_2$ dissolved in solution. When the solution became saturated with H$_2$, some of the H$_2$ was evolved, decreasing the current efficiency. The current efficiency was in the same range as reported for the electrocatalytic reduction of chlorinated compounds on the Pd-loaded cathode (Tsyganok and Otsuka, 1999).

3.4. Treatment of 2,4-DCP in a flow-through electrolytic system

In the column with Pd/C catalyst at an influent pH of 5.5, Fig. 5 shows that the removals of 2,4-DCP at the port 40 mm from inlet...
and in the outlet were about 50% and 63%, respectively, after 48 h, and phenol was measured at both ports. As a comparison, phenol was not measured in the control column with bamboo charcoal instead of Pd/C catalyst (Fig. SM-5). At the sampling port 40 mm from the inlet, Fig. 5a shows that the concentration of 2,4-DCP rapidly increased to 0.23 mM after 6 h, much higher than the influent concentration of 0.08 mM, and then declined to about 0.04 mM after 24 h. A similar but less significant variation occurred at the outlet (Fig. 5b). The sharp rise in the 2,4-DCP concentration is attributed to variations in the adsorption/desorption of 2,4-DCP at different pHs (Fig. SM-3). At the influent pH of 5.5, significant adsorption of 2,4-DCP led to its removal during the initial stage of the experiment. As the electrolytic reaction proceeded, the pH near cathode increased to >10 after 6 h (Fig. 5c). The desorption of the adsorbed 2,4-DCP resulted in the appearance of 2,4-DCP concentrations higher than its influent concentration after 3 h of electrolysis.

Phenol was the sole product measured at the port 40 mm from inlet. The concentration of phenol rose to 0.03 mM at 6 h, and remained almost constant at 0.013 mM during later stages (Fig. 5a). Because phenol was not measured in the control column experiment, the production of phenol confirms the feasibility of the Pd-catalytic hydrodechlorination by the cathodic H₂ in the flow-through electrolytic system. As the oxidation of phenol at graphite anode was significant (Fig. SM-6), and the adsorption onto the quartz sand was slight at high pHs (Fig. SM-3b), the disappearance of phenol in the effluent implied its degradation at the anode.

The results using external H₂ showed that the increases in pH decreased the 2,4-DCP hydrodechlorination efficiency. In particular, at pH 11 the efficiency was very low. However, Fig. 5c presents that the pH at the port 40 mm from inlet rose to 10 at 6 h, to 11 at 10 h, and even above 12 after 12 h. Under these high pH conditions, the great removal of 2,4-DCP and production of phenol was still achieved after 7 h (Fig. 5b). As the Pd/C particles were placed adjacent to cathode, and both bamboo charcoal and Pd are conductive, the Pd/C catalyst particles may act as “micro-conductors” facilitating 2,4-DCP hydrodechlorination (Rohrs et al., 2002). A certain amount of H₂ can be produced on the Pd surface and quickly decomposed to atomic H for 2,4-DCP hydrodechlorination. Consequently, H₂ generated at both the cathode and the Pd/C “micro-conductors” was catalyzed for hydrodechlorination.

Another column experiment was performed to examine hydrodechlorination enhancement at an influent pH of 2.0. The
experiment was run for a much longer duration of 216 h to evaluate the long-term performance of the system. At the port 40 mm from inlet and at the outlet, Fig. 6a and b show that 2,4-DCP and phenol were not measured in the initial 24 and 36 h, respectively, which is mainly attributed to the strong adsorption at low pHs. When the pH increased after 36 h (Fig. 6c), the concentrations of 2,4-DCP and phenol detected at both sampling ports were much lower at the influent pH of 2 than at the influent pH of 5.5, which

Table 1
Current efficiency of catalytic hydrodechlorination by cathode H₂.a

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a Reaction conditions were accorded with Fig. 4 in the manuscript.

b Hydrogen production in theory.

c Hydrogen consumption calculated from phenol and monochlorophenol production.

d Current efficiency.
3.5. Characterization of the reacted Pd/C catalyst

After use in the flow-through electrolytic system, the used catalyst was characterized to further assess its stability. Fig. 2e and f shows the Pd particles were partly aggregated after reaction. From the XRD spectra of the reacted Pd/C catalyst (Fig. SM-1 and SM-2), an obvious peak occurred at 26°, which was assigned to the highly structured (graphitic) carbon (Amorim et al., 2005). The FCC structure of the Pd particles was also proved. The average crystal size of the Pd particles was calculated to be about 22 nm, which was larger than the particles in the fresh catalyst (15 nm). The slight increase in particle size is attributed to the removal of small particles during treatment. The intensity of the Pd peaks after reaction was less than the fresh catalyst which is due to the decrease in Pd content and surface coverage.

The XPS results show that the weight fraction of Pd3d in the Pd/C catalyst decreased from 11.0% to 3.7% after reaction. The measurement of Pd in solution indicated that 0.01% was leached after 9 h treatment. The interactions between the Pd and the bamboo charcoal were weak (Yuan and Keane, 2003), which may lead to the shedding of Pd particles after long-term groundwater flow. The pores of the bamboo charcoal can be partly blocked during the reaction, resulting in the coverage of the Pd surface. As the XPS can only detect photoelectrons from 10 nm of the outer surface, the surface coverage mainly contributed to the decrease in Pd3d weight fraction. XPS results (Fig. SM-2) also suggest that Pd(0) was the predominant chemical state despite the increase in Pd(II). Bueres et al. (2010) reported an increase in Pd(II) after hydrodechlorination, and ascribed the increase to the interaction of Pd(0) with neighboring protons and oxidation by the produced chloride ions. Although the catalytic hydrodechlorination efficiency did not decrease during either the external H2 or the flow-through remediation processes tested, the characterization results suggest that the catalytic performance of the Pd/C was declining.

3.6. Comparison with previous work on electrolytic remediation

Using electrolytic PRBs, Gilbert’s group (Gilbert and Sale, 2005; Gilbert et al., 2008) found that direct anodic oxidation and cathodic reduction were mainly responsible for contaminant degradation, with the cost dependent on the catalytic activity of the electrode. Although high removal rates were achieved for energetic compounds and TCE in groundwater (Gilbert and Sale, 2005; Gilbert et al., 2008), this technique may be costly and less efficient for the treatment of contaminants which are difficult to oxidize or reduce, such as chlorophenols, chlorobenzenes and polychlorinated biphenyls. The dependence on the catalytic activity of the electrode was avoided in present study because the electrodes solely functioned as H2 producers. The Pd/C catalyst can effectively catalyze contaminant hydrodechlorination using H2 generated at the cathode. Thus, the process developed in this study has advantages over Gilbert’s process, particularly for the treatment of refractory contaminants.

As H2 can be generated in situ at the cathode in the subsurface by installing an electrolytic system, this process could be potentially applied for in situ groundwater remediation. The decline in Pd/C catalytic activity may reduce the remediation efficiency, but this can be overcome by replacement or regeneration (Davie et al., 2008). The high pH near cathode may lead to mineral precipitation and fouling (i.e. Ca(OH)2, Mg(OH)2, Fe(OH)2), which was determined by the groundwater chemistry. The precipitation and fouling may cover the surface of catalyst, thereby reducing the activity to some extent. In contrast, the low pH near anode may dissolve the minerals (i.e. CaCO3, FeO), which somewhat changes the groundwater chemistry. However, the negative influence of pH variation can be suppressed by decreasing the distance between cathode and anode, using a three-electrode system (Yuan et al., 2011), or polarity reversal with high voltage pulse. Further work is underway to optimize the operation parameters and to evaluate the influence of groundwater chemistry on the remediation performance.

4. Conclusions

In this study, we attempted to undertake Pd-catalytic hydrodechlorination by H2 generated at the cathode for the remediation of 2,4-DCP contaminated groundwater. Pd/C particles were able to effectively catalyze the hydrodechlorination of 2,4-DCP in groundwater by using cathodic H2. The high removal rates for 2,4-DCP and its hydrodechlorination products in the column experiments proved the feasibility of this novel process. Our future work will optimize the operating parameters, investigate the influence of groundwater chemistry on the remediation efficiency, and evaluate the efficiency of the process for remediating real COC contaminated groundwater.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.chemosphere.2012.01.058.

References


