ELSEVIER

Water Research 39 (2005) 3863–3872

WATER RESEARCH

www.elsevier.com/locate/watres

Pilot-scale demonstration of phytofiltration for treatment of arsenic in New Mexico drinking water ☆

Mark P. Elless[a,*], Charissa Y. Poynton[a], Cari A. Willms[a], Mike P. Doyle[b], Alisa C. Lopez[b], Dale A. Sokkary[b], Bruce W. Ferguson[a], Michael J. Blaylock[a]

[a]*Edenspace Systems Corporation, 15100 Enterprise Court, Suite 100, Dulles, VA 20151, USA*
[b]*City of Albuquerque, Parks & Recreation Department, P.O Box 21037, Albuquerque, NM 87154, USA*

Received 26 October 2004; received in revised form 15 July 2005; accepted 21 July 2005
Available online 30 August 2005

Abstract

Arsenic contamination of drinking water poses serious health risks to millions of people worldwide. To reduce such risks, the United States Environmental Protection Agency recently lowered the Maximum Contaminant Level for arsenic in drinking water from 50 to $10\,\mu g\,L^{-1}$. The majority of water systems requiring compliance are small systems that serve less than 10,000 people. Current technologies used to clean arsenic-contaminated water have significant drawbacks, particularly for small treatment systems. In this pilot-scale demonstration, we investigated the use of arsenic-hyperaccumulating ferns to remove arsenic from drinking water using a continuous flow phytofiltration system. Over the course of a 3-month demonstration period, the system consistently produced water having an arsenic concentration less than the detection limit of $2\,\mu g\,L^{-1}$, at flow rates as high as $1900\,L\,day^{-1}$ for a total treated water volume of approximately 60,000 L. Our results demonstrate that phytofiltration provides the basis for a solar-powered hydroponic technique to enable small-scale cleanup of arsenic-contaminated drinking water.

Keywords: Ferns; Hydroponics; Phytoremediation

1. Introduction

Arsenic contamination of drinking water supplies poses significant risks to human health (NRC, 1977, 1999, 2001). Arsenic is a known carcinogen and mutagen and is detrimental to the immune system. Chronic exposure to arsenic in drinking water at concentrations of $50\,\mu g\,L^{-1}$ may result in human cancer risks as high as 13 in 1000 (Pontius et al., 1994) or cause noncancer effects (e.g., thickening of the skin, hearing impairment, birth defects, and gastrointestinal system and liver effects). Reducing exposure to arsenic in drinking water is one option for reducing the incidence of these severe health effects.

To address these risks, the United States Environmental Protection Agency (USEPA) recently lowered the maximum contaminant level (MCL) for arsenic in drinking water from 50 to $10\,\mu g\,L^{-1}$, with a compliance deadline of January 2006 (USEPA, 2001). Although this

☆The use of *Pteris* genus ferns for arsenic phytoremediation has been patented by the University of Florida (US Patent. Nos. 6,280,500 and 6,302,942). The ferns are sold under the brand name "edenfern™," by Edenspace Systems Corporation, under exclusive license from the University of Florida.

*Corresponding author. Tel.: +1 703 961 8700; fax: +1 703 961 8939.
E-mail address: elless@edenspace.com (M.P. Elless).

0043-1354/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.watres.2005.07.029

new MCL applies to all 74,000 community water systems in the US, the USEPA estimates that approximately 4000 of these systems, which serve 12 million people, must take corrective action to attain compliance. Of these 4000 systems, 97% serve fewer than 10,000 people, indicating that small drinking water systems will bear the brunt of complying with the new standard.

Current technologies used to clean arsenic-contaminated water have significant limitations in terms of cost and residual handling, particularly for small treatment systems (USEPA, 2000). Most of the best available technologies for arsenic removal from drinking water require chemicals for pre- and post-pH adjustment for maximal effectiveness and/or generate large volumes of backwash water and spent media or sludge that must be managed. In addition, as most of these technologies rely on sorption of charged species for removal from water, chemicals for pre-oxidation are often required to convert arsenite (that occurs predominantly as the neutral species $H_3AsO_3^0$) to arsenate (that typically exists as an anionic species $H_2AsO_4^-$ or $HAsO_4^{2-}$, depending on pH). The associated operator skill requirements for most of these technologies were rated as moderate or high, requiring advanced operator training (USEPA, 2000).

Phytofiltration, the use of plants to remove contaminants from water, is an emerging water treatment technology. Chandra et al. (1997) demonstrated promising results of Cr removal from water using vascular aquatic plants such as *Scirpus lacustris* and *Phragmites karka*. Earlier, Dushenkov et al. (1995) designed a hydroponic system using sunflower (*Helianthus annus*) plants and Indian mustard (*Brassica juncea*) seedlings to remove uranium, lead and cesium from contaminated waters (Dushenkov and Kapulnik, 2000; Dushenkov and Vasudev, 1997).

Recently, an arsenic-hyperaccumulating fern species (*Pteris vittata*) was discovered that rapidly accumulates arsenic from contaminated soil into its fronds at concentrations as high as 22,000 mg kg^{-1} (DW) within a 6-week period (Ma et al., 2001a). Subsequent research has demonstrated that other species in the *Pteris* genus also hyperaccumulate arsenic (Meharg, 2003; Zhao et al., 2002; Ma et al., 2001b, c). In greenhouse studies, *P. vittata* hyperaccumulated arsenic from soil in its above ground plant tissue at concentrations more than 200-fold higher than other plant species tested (Huang and Chen, 2003). Because of its unique arsenic-accumulating abilities coupled with its rapid growth and generation of high biomass yields (Ma et al., 2001a–c), ferns in the *Pteris* genus have been used in the phytoremediation of soils contaminated via arsenical pesticides or leaching from arsenic bearing, pressure-treated lumber (Edenspace, 2003a, b).

In hydroponic batch studies, *Pteris* ferns have been shown to rapidly reduce arsenic concentrations from spiked drinking water from as high as 500 μg L^{-1} to less than 2 μg L^{-1} even in the presence of sulfate, nitrate and phosphate at concentrations typically observed for US groundwaters (Huang et al., 2004; Poynton et al., 2004). Based on these encouraging results, this novel technology was assessed for performance in a pilot-scale, continuous flow phytofiltration system to remove arsenic from drinking water. The objective of this study was to evaluate the performance of this system according to the following requirements: (a) the technology must be reliable, reproducible and effective in removing arsenic from water to levels that meet the new MCL for arsenic in drinking water; (b) the technology must be cost-effective compared to the best available technologies; (c) the technology must be user friendly without requiring high operator skills and be easy to replicate to meet the needs of different communities; and (d) the technology must generate very little or no secondary waste compared to the best available technologies.

2. Methods

2.1. Bench-scale studies

2.1.1. Phytofiltration performance factors

Several environmental and water quality factors not investigated in previous studies (Huang et al., 2004; Poynton et al., 2004) but believed to potentially impact phytofiltration performance were examined during bench-scale studies prior to the demonstration. Ferns of the *Pteris* genus were prepared in a bare root system as described in Poynton et al. (2004) and placed in drinking water spiked with arsenic to an initial concentration of 50 μg L^{-1}. The performance of the ferns was then evaluated as a function of day length (12, 16, and 20 h light periods), light intensity (full light at 200 μmol m^{-2} s^{-1} vs. 80% shade at 40 μmol m^{-2} s^{-1}), humidity (ambient at 55–65% relative humidity vs. humid at 85–95% relative humidity), and arsenic oxidation state (arsenate as sodium arsenate vs. arsenite as sodium arsenite; speciation confirmed before and after using arsenic speciation cartridges, with cartridges provided by Dr. X. Meng, Stevens Institute of Technology, NJ). All experiments were conducted in triplicate in a growth chamber. All water samples were analyzed using graphite furnace atomic absorption spectroscopy (GFAAS) at Edenspace.

2.2. Pilot-scale demonstration

2.2.1. Design of pilot-scale system

Individual *P. vittata* (L.) ferns grown in potting mix were wrapped in 0.6 cm thick foam sheet and suspended in slotted plastic cups over containers of

Fig. 1. Photographs of the principal components of the phytofiltration system, (a) plant in potting mix, foam wrap, and cup, (b) plant suspension tray showing location of eight plants per tray, (c) an entire wrapped fern plant, (d) tray of eight fern plants, and (e) bank of ferns in phytofiltration nursery system used to develop the root system of the ferns.

aerated solutions as shown in Fig. 1. The ferns were allowed to grow until roots emerged from the cups and developed a mature root system, having a root volume displacement of approximately 2 L. Total dry mass of fronds and roots from one tray of eight mature ferns at the end of the demonstration was 219 and 204 g, respectively.

A modular, continuous flow phytofiltration system, consisting of 10 treatment tanks linked in series was used for the demonstration. Individual treatment tanks, plastic containers with 45 L of water (~22:1 water:root volume), were aerated with an aquarium pump. An inlet reservoir of feed water was maintained at a constant level by means of a float valve. A variable speed peristaltic pump pumped water from the inlet reservoir into the first treatment tank to control the flow rate through this stair step, gravity-flow system. Flow rates were measured several times each day, including at the time of sampling. The outflow was collected in a reservoir and pumped to a storage tank. The system had a footprint of approximately 100 square feet, including inlet and outlet reservoirs and access space. Five additional trays of ferns were maintained in an adjacent batch nursery system containing nutrient solution, allowing trays to be alternated between treatment and nursery during the course of the study.

2.2.2. Site conditions

The City of Albuquerque, New Mexico provided greenhouse space, personnel and tap water for the demonstration. Historical records from quarterly analyses of City of Albuquerque drinking water showed an average water pH of 7.9 and an arsenic concentration of $12\,\mu g\,L^{-1}$ (http://www.cabq.gov/waterquality/datatables/zone3.html). All other water parameters identified in the historical record (e.g., other metals, minerals, and nutrients) were below the MCL or secondary MCL (SMCL).

The pilot demonstration was operated continuously for 84 days from January through March. Over this period, the daily high temperature ranged from 21 to 36 °C (average 29 °C) and low temperature ranged from −3 to 29 °C (average 16 °C). Humidity was fairly constant at approximately 20% and white shade cloth (50% grade) covered the greenhouse throughout the demonstration period.

2.2.3. System setup and operation

The modular system was assembled on site in Albuquerque. After an initial system test, the ferns were

given 4 weeks to acclimatize to the greenhouse conditions. Following acclimatization, the flow through system was operated continuously, with the average ($\pm$1 SE) flow rate increased as follows throughout the demonstration period to test the treatment capacity of the system: 255 ± 5.6 L day^{-1} (Lpd) for $t = 0$–28 days, 392 ± 6.0 Lpd for $t = 29$–56 days, 1044 ± 11.4 Lpd for $t = 56$–63 days, and 1619 ± 16.4 Lpd for $t = 63$–84 days. The minimum and maximum daily flow rates, as measured at the time of sampling, were 212 and 1944 Lpd.

Each set of five trays of ferns was rotated weekly such that those in treatment tank locations 1–5 (with location 1 nearest the inflow reservoir) were moved to tank locations 6–10 (with 10 nearest the outflow reservoir), those in locations 6–10 were moved into the nursery with hydroponic nutrient solution, and fern trays in the nursery were moved to locations 1–5. The sequence of ferns in each set of five trays was never compromised, so that ferns in position 1 were also located in positions 6 and 11 when rotated and never placed in any other position. With this rotation, ferns received nutrients every third week.

At the end of the demonstration period, as a control all fern trays were removed from the treatment tanks and the system was operated as before, at an average rate of 310 ± 11.6 (1 SE) Lpd for 1 week to verify the role of the fern plants in arsenic removal.

2.2.4. Sample collection and analysis

Daily outflow and weekly inflow samples were collected, filtered to 0.45 μm, and acidified with nitric acid prior to analysis for determination of soluble arsenic. Two inflow and outflow water samples, which were neither filtered nor acidified, were also analyzed during the study for total water quality (e.g., turbidity, water chemistry, biological activity, etc.). At three different daily flow rates (379, 1533, and 1650 Lpd), samples were taken and analyzed for soluble arsenic concentration from individual treatment tanks to examine the step-wise rate of arsenic removal by system components. Daily water balance measurements were also calculated as the ratio of the daily inlet to outlet volume. All water samples were analyzed using GFAAS by the Albuquerque Water Quality Laboratory, which is accredited for arsenic analysis by the American Association for Laboratory Accreditation.

Samples of fern fronds were collected midway ($t = 42$ days) and at the end of the study to determine uptake and translocation of arsenic by the plants. The samples were oven dried at 70 °C and ground to pass a 20-mesh sieve. The ground material was then digested using hydrogen peroxide and nitric acid following EPA Method 3050 (USEPA, 1986) and analyzed for total arsenic by inductively coupled plasma spectroscopy following EPA Method 6010 (USEPA, 1986).

3. Results

3.1. Bench-scale studies

Results from the bench-scale studies show that arsenic uptake by *Pteris* ferns is a continuous process and is efficient during daylight or dark hours and is not affected by day length (Fig. 2a). In addition, no significant effect on arsenic uptake was observed from variations in humidity or light intensity, within broad limits (Fig. 2b, c). Our studies also found that the phytofiltration system is capable of removing arsenite as well as arsenate (Fig. 2d), unlike most other treatment technologies.

3.2. Pilot-scale demonstration

3.2.1. Effectiveness of phytofiltration

The inflow As concentration varied during the treatment period between 6.6 and 14 μg L^{-1}, with a mean value of 10.2 ± 0.4 (1 SE) μg L^{-1}. For each of the four periods having distinct average flow rates, the mean As concentration was 8.4, 10.5, 12.2, and 10.3 μg L^{-1}. Regardless of the inflow As concentration or the flow rate at the time of sampling, the outflow As concentration was consistently less than 2 μg L^{-1} (the detection limit of analysis) throughout the 84 days demonstration period (Fig. 3a), with a total volume of approximately 60,000 L of water treated to these low residual As levels. These results confirm the performance observed in the earlier batch studies and demonstrate the capability of this technology in meeting the new MCL for arsenic in a flow through system. As recent research has discovered measurable health effects (e.g., endocrine disruption) from exposure to arsenic at or near the new MCL (Bodwell et al., 2004), the results indicate that this technology would be capable of meeting an even lower MCL.

3.2.2. Arsenic removal by ferns

The arsenic mass balance was calculated to confirm that arsenic removed from the water was due to uptake in the ferns. Verification of the arsenic removal by the fern plants can be shown by comparing the arsenic content of the fronds following the demonstration with the decrease in arsenic in the outflow water. Arsenic concentrations in harvested fronds prior to treatment were <20 mg kg^{-1} whereas those following treatment ranged from 66 to 407 mg kg^{-1} (ferns located nearer the inflow, such as the fern tray located in positions 1, 6, and 11 upon rotation, contained the greatest arsenic concentrations) and averaged 161 ± 26 (1 SE) mg kg^{-1}. Arsenic was not detected in the roots of the ferns (<30 mg kg^{-1}), indicating a rapid translocation of the arsenic from roots to the fronds for storage. Using a frond biomass value of 219 g per tray and an average

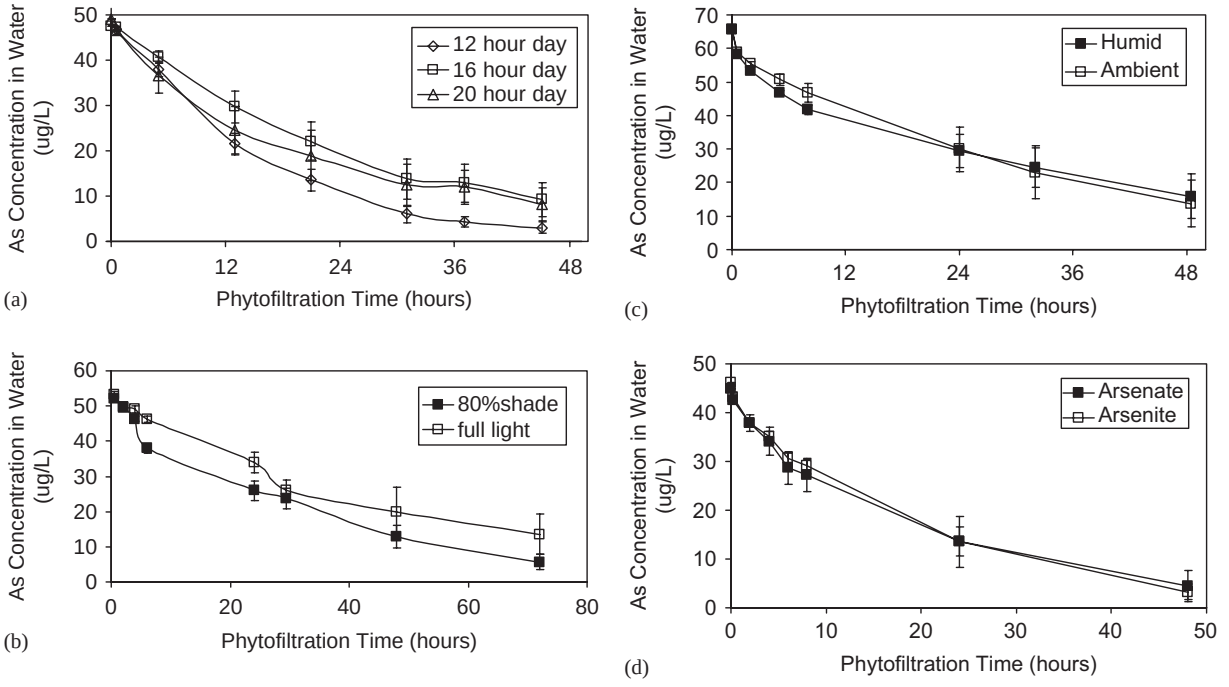

Fig. 2. Effect of (a) day length and (b) light intensity on phytofiltration performance. Light intensity under full and 80% shade was 200 and 40 μmol $m^{-2} s^{-1}$, respectively. Effect of (c) humidity (ambient = 50–60% RH; humid = 85–95% RH) and (d) arsenic speciation on phytofiltration performance.

final As concentration in the fronds of 161 mg kg^{-1}, the total amount of arsenic removed via plant uptake throughout the demonstration period was 528 mg, representing between 86% and 106% of the measured change in the arsenic concentration of the treated water (615–496 mg of As removed from water, assuming a final concentration of either 0 or 2 μg L^{-1}, respectively). In the absence of ferns in the system, there was no difference in As concentration between inflow and outflow water samples (Fig. 3b). These results demonstrate that the ferns were responsible for arsenic removal from the system.

The ability of the ferns to remove arsenic from low solution concentrations (averaging approximately 10 μg L^{-1} throughout the demonstration) coupled with its ability to store arsenic in its fronds at high concentrations (averaging 161 mg kg^{-1}) results in an average bioaccumulation factor exceeding 16,000, illustrating the efficiency of the ferns in removing arsenic from drinking water.

3.2.3. System capacity and efficiency

The maximum capacity of the system for removing arsenic was not reached during the demonstration period. Arsenic concentrations in the treated water were consistently below the detection limit of 2 μg L^{-1} by the eighth treatment tank, even at the fastest flow rate (Fig. 4). The average quantity of arsenic removed per plant per day increased with time (187, 306, and 456 μg day^{-1}), with an average value of 316 μg day^{-1}. When normalized to frond weight or root volume, this value corresponds to 1.44 μg $day^{-1} g^{-1}$ (d.w.) or 0.158 μg $day^{-1} mL^{-1}$. This increase in arsenic removal per plant with time may be due to the ferns having become established in this system and/or the increased flow rate with time, which exposed the ferns to greater quantities of arsenic. These data also illustrate that the As removal efficiency of the system did not decrease with time, even though arsenic accumulation in the ferns continually increased. Because the final arsenic concentrations in the ferns were still much lower than the highest reported (22,000 mg kg^{-1}), the ferns are expected to have much more capacity before a saturation effect on arsenic removal efficiency becomes noticeable.

Given expected water losses from evaporation and plant transpiration, the difference between input water volume and output water volume as a function of flow rate was measured as another index of phytofiltration efficiency. In the demonstration, this index of water treatment efficiency increased as the flow rate increased, with average water recoveries of 85.3%, 90.8%, 97.6%, and 95.4% for flow rates of 255, 392, 1044, and 1619 Lpd, respectively, representing water losses of 37.5, 36.1, 25.1, and 74.5 Lpd. These results suggest

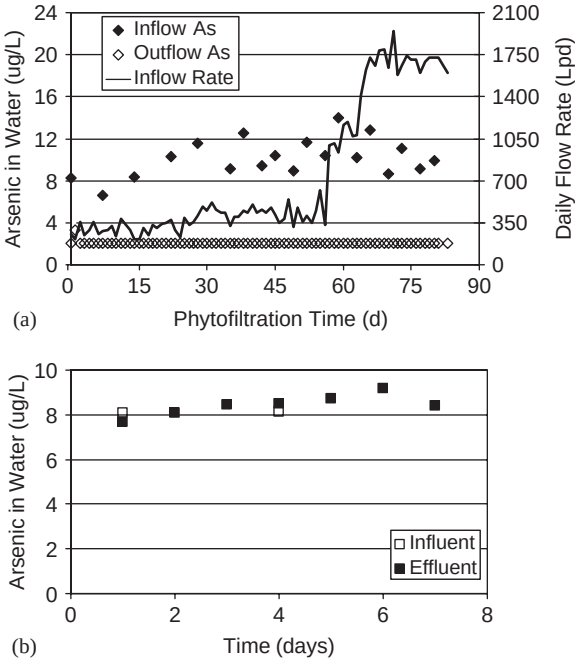

Fig. 3. Performance of the phytofiltration system for removing soluble arsenic from water in the (a) presence and (b) absence of the ferns. The daily flow rate plotted is the rate measured at the time of sampling only.

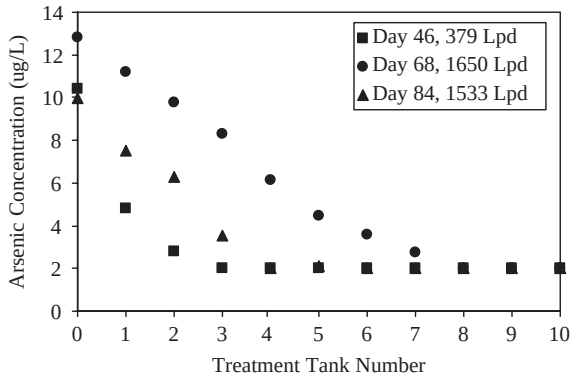

Fig. 4. Soluble arsenic concentrations in each tank at three different flow rates (detection limit = $2\,\mu g\,L^{-1}$).

that the water efficiency of the technique will be greatest when the starting arsenic concentration is close to the target concentration, allowing faster flow rates to be implemented. Because average water recovery measured for the no plant control (average flow rate of 310 Lpd) was 95.3%, representing an evaporative water loss of 14.6 Lpd, the majority of the water lost appears to be due mainly to plant transpiration, with rates ranging from 0.11 to 0.76 Lpd plant^{-1}. Plant transpiration for these mature ferns should be independent of flow rate, with the observed variations due to variations in the water requirements of individual sets of fern trays. Because transpiration should remain constant with respect to flow rate, water loss due to transpiration as a percentage of the total volume of water treated should decrease as the volume treated per unit time increases.

3.2.4. *Effect on water quality*

The total water quality of the outflow water was very similar to that of the inflow water (Table 1). The turbidity of the outflow water was slightly lower than for the inflow water at both sampling times. The pH and mineral content (determined as electrical conductivity) were approximately the same in inflow and outflow samples. The dissolved oxygen content was slightly greater in the outflow water, presumably as a result of aeration through the system. The heterotrophic plate count (HPC), which is a measure of microorganisms that require organic carbon for growth, including bacteria, yeasts and moulds, was higher in the outflow samples than the inflow samples. The increase in HPC in the outflow was more pronounced at the daily flow rate of 367 Lpd on day 44, than at the higher flow rate of 1575 Lpd on day 72, most likely because of the longer residence time. There was no detection of other organisms (e.g., protozoa, nematodes, amoeba, ciliates, etc.) in the treated water on either sampling date. Although HPC has no known health effects and therefore has no promulgated MCL (www.epa.gov/safewater/mcl.html), disinfection and/or filtration is required for drinking water systems relying principally on surface waters that have HPC > 500 bacterial colonies mL^{-1}. It is expected that fern-based phytofiltration of drinking water for removal of arsenic would occur upstream of disinfection and filtration processes already in place at the drinking water system.

4. Discussion

During the demonstration, the fern-based phytofiltration system was shown to be an effective and reliable technology for removing arsenic from drinking water. Treated water consistently had an arsenic concentration of less than $2\,\mu g\,L^{-1}$, regardless of the inflow arsenic concentration or flow rate, while in the absence of plants no decrease in the arsenic concentration was observed. Therefore, the ferns can be considered the 'active ingredient' in this system.

The ferns can be thought of as having a separate uptake (the roots) and storage (the fronds) system. Therefore, as arsenic accumulates in the fronds and is depleted in the roots, there is no capacity effect on the roots, so the rate of uptake remains constant at arsenic levels tested in this study. The rapid translocation of arsenic from the roots to the fronds observed in *P. vittata* during this study confirms the similar result

Table 1
Chemical and biological characteristics of inflow & outflow water at two sampling points

Parameter	Unit	Sample 1 (day 44)		Sample 2 (day 72)	
		Inflow	Outflow	Inflow	Outflow
Flow rate	Lpd	386	367	1707	1574
Chemical					
COD	$mg\,L^{-1}$	11	69	NA	NA
DO	$mg\,L^{-1}$	5.02	69	5.41	7.14
EC	$\mu mhos\,cm^{-1}$	382	420	418	443
pH		7.97	8.35	8.35	8.04
Turbidity	NTU	0.38	0.11	0.04	0
TOC	$mg\,L^{-1}$	NA	1.124	1.823	1.34
Biological					
HPC	$Ct\,mL^{-1}$	0	3575	19	902
Amoeba	Count	0	0	0	0
Ciliophora	Count	0	0	0	0
Flagellata	Count	0	0	0	0
Nematoda	Count	0	0	0	0
Rotifera	Count	0	0	0	0
Stalked Ciliates	Count	0	0	0	0
Tardigrada	Count	0	0	0	0
Filamentous organisms	Relative density	0	0	0	0

Abbreviations: COD, chemical oxygen demand; HPC, heterotrophic plate count; TOC, total organic carbon; DO, dissolved oxygen; EC, electrical conductivity; NTU, nephelometric turbidity unit; NA, not available.

observed by Poynton et al. (2004). This result is in contrast to many other technologies, for example ion exchange resins, where the processes of uptake and storage are dependent on the same mechanism and the efficiency of the resin drops unless regenerated (USEPA, 2003).

In the demonstration test system, maximum capacity was limited by system design (tubing size and water flow capacity) rather than fern capacity to remove arsenic. As such, the maximum flow rate of the system was not reached during this demonstration, but a maximum treatment capacity may be estimated from the measurements of arsenic concentration in each treatment tank along the system. Using the data from Fig. 4, an average arsenic removal rate of approximately 2400 μg As per tray per day results when the flow rate was 1,650 Lpd. If it is assumed that the starting concentration in the source water for the city of Albuquerque is $14\,\mu g\,L^{-1}$, the highest concentration recorded, then a phytofiltration system of 10 trays of ferns, or 80 plants, could treat approximately 3785 Lpd to $8\,\mu g\,L^{-1}$ to ensure meeting the new MCL. At a more stringent target outflow concentration of $2\,\mu g\,L^{-1}$, the system could treat approximately 2000 Lpd. Operation of the system at maximum capacity is important as greater water recovery ($\geqslant 95\%$) and less residence time improves the efficiency and quality of the treated water, thereby reducing the load on subsequent polishing steps, such as filtration and disinfection.

The high arsenic concentration that can accumulate in the fronds makes *P. vittata* a highly efficient store of the removed arsenic. Because these fern species are perennial, the fronds can be harvested on a periodic basis, and ferns can generate new fronds. Coupled with no decrease in arsenic removal efficiency observed with time (see Fig. 4 and accompanying text), these perennial fern plants can be used repeatedly in a phytofiltration system.

Several options for disposal of the treatment ferns exist. Firstly, the ferns could be allowed to accumulate arsenic to high levels (presumably at least $20{,}000\,mg\,kg^{-1}$) to minimize the total mass for disposal. Alternatively, ferns could be harvested earlier to allow disposal as nonhazardous waste through landfilling or, in the typical case when fern arsenic concentrations are below $73\,mg\,kg^{-1}$ or the applicable technically based local limit (TBLL), through application to land as biosolids (40 CFR 503). In certain areas of the world, harvested biomass might be used as an alternative to straw in making bricks. Edenspace research (data not shown) also indicates that the ferns can be processed to extract most of the recovered arsenic for efficient disposal or recycling.

4.1. Limitations

As a plant-based technology, light is required for fern growth. Natural sunlight could be used in either

an outdoor setting in a warm climate or inside a greenhouse. Small communities seeking compliance with the new MCL might consider adding this technology to existing greenhouses, or a greenhouse to an existing water treatment system. Alternate uses of the greenhouses (e.g., for fresh produce year round) could reduce water treatment costs by sharing overhead expenses. Construction of a greenhouse does increase capital costs associated with this technology (Table 2), and the floor space required to treat large volumes of water may make the technique impractical for large-scale treatment plants.

Table 2
Cost comparison of activated alumina to phytofiltration for removal of arsenic from drinking water, assuming a design flow of 600,000 LPD

Cost parameter	Activated alumina	Phytofiltration
Capital	$92,700	$119,500
Annual O & M	$34,300	$15,300
Annual waste disposal	$1,200	$100
Year 1 costs	$128,200	$134,900
Years 1–3 costs	$199,200	$165,700
Years 1–5 costs	$270,200	$196,500
Years 1–10 costs	$447,700	$273,500

Data for activated alumina from USEPA (2000).

4.2. Benefits

This phytofiltration technology has five advantages over existing water treatment technologies. First, fern removal of arsenic is not affected by certain anions at concentrations typical of US groundwaters, such as sulfate, nitrate, and phosphate (Huang et al., 2004), which can reduce the efficiency of other methods. This is because the system takes advantage of the specificity of the biological mechanisms that take arsenic into the plants. Secondly, unlike some competing technologies, phytofiltration removes arsenite as well as arsenate (Fig. 1d), particularly important for small-scale systems using ground water as the drinking water source. Chemicals used for pre-oxidation of arsenite to arsenate are not required, thereby lowering treatment costs. Thirdly, phytofiltration does not require hazardous chemicals, such as strong acids or bases used to regenerate alumina beds or exchange resins. The technology is also simple to operate, with minimal requirements for operator training. Fourthly, because the ferns grow well under low light conditions, artificial light sources can be effective alternatives for natural sunlight and may be appropriately used in non-greenhouse applications. Finally, since plant cultivation and harvesting are relatively inexpensive processes, arsenic phytofiltration could have a significant cost saving advantage over time compared to current available technologies, due to lower annual operation and maintenance costs and waste disposal costs (Table 2). A summary of these and other

Table 3
Comparison of best available technologies (USEPA, 2003) to phytofiltration for removal of arsenic from drinking water

Factors	Ion exchange	Activated alumina	Reverse osmosis	Enhanced lime softening	Enhanced (conventional) coagulation filtration	Oxidation filtration	Phytofiltration
Removal efficiency	95%	95%	>95%	90%	95% (w/ $FeCl_3$) <90% (w/ Alum)	50–90%	>95%
Total water loss	1–2%	1–2%	15–75%	0%	0%	1–2%	3–5% at high flow rates
Pre-oxidation required	Yes	Yes	Likely	Yes	Yes	Yes	No
Optimal pH	6.5–9	5.5–8.3	N/A	10.5–11	5.5–8.5	5.5–8.5	4.0–10.0
Operator skill required	High	Low	Medium	High	High	Medium	Low
Waste generated[a]	1, 2, 3	1, 3	4	3, 5	3, 5	3, 5	6
Other considerations[b]	1, 2, 3, 4	1, 2, 3	5	2	1, 2	None	6
Centralized cost	Medium	Medium	High	Low	Low	Medium	Low

[a]Waste Generated Code: 1 = spent media, 2 = spent brine, 3 = backwash water, 4 = reject water, 5 = sludge, 6 = fern biomass.
[b]Other Considerations Code: 1 = possible pre pH adjustment, 2 = possible post pH adjustment, 3 = pre filtration required, 4 = potentially hazardous brine waste, 5 = high water loss, 6 = possible post filtration and disinfection.

comparisons between the BATs and phytofiltration for removal of arsenic is shown in Table 3.

4.3. Operational design and implementation

It is important to emphasize that the phytofiltration system described in this paper is not intended as a replacement for BATs currently used at large drinking water systems in the United States. The niches for this technology are (a) the small drinking water systems in the US that need to meet the newly promulgated drinking water standard by the January 2006 deadline but whose operating budgets cannot afford implementation of any BAT, and (b) poor, primarily rural areas in South Asia and elsewhere whose drinking water supplies greatly exceed the World Health Organization limit of $50\,\mu g\,L^{-1}$. Although the minimal residence time measured during this demonstration was 5.4 h compared to 0.1–0.2 h that is typical for ion exchange, it is anticipated that some users with low flow requirements may be willing to substitute time for cost.

In such locations, the operational design of the phytofiltration system employed will depend on site conditions, such as daily flow requirements and overall cost-effectiveness in altering the prototype design described here. For many areas it is anticipated that low daily flow requirements may be met with minor alterations of the prototype design. To address many small drinking water systems in the US, scaling up the design to handle greater daily flow rates would be necessary. Modifications might include use of floating racks of ferns located in large tanks so that larger volumes of water can be treated, and plumbing the system so that the ferns in any tank can be fertilized by opening/closing valves rather than by transporting the ferns into a separate area. In any location, if desired the treated water from the phytofiltration system can simply enter the existing disinfection system for removal of microbial contaminants.

5. Conclusions

These results demonstrate that this phytofiltration technology may provide the basis for a solar-powered hydroponic technique that enables the efficient cleanup of arsenic-contaminated drinking water in a cost-effective manner.

Acknowledgments

The project described was supported by Grant number 5 R44 ES011065-03 from the National Institute of Environmental Health Sciences (NIEHS), NIH. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIEHS, NIH. The authors wish to acknowledge helpful suggestions concerning this manuscript by Dr. Lena Ma, University of Florida.

References

Bodwell, J.E., Kingsley, L.A., Hamilton, J.W., 2004. Arsenic at very low concentrations alters glucocorticoid receptor (GR)-mediated gene activation but not GR-mediated gene repression: Complex dose-response effects are closely correlated with levels of activated GR and require a functional GR DNA binding domain. Chem. Res. Toxicol. 17 (8), 1064–1076.

Chandra, P., Sinha, S., Rai, U.N., 1997. In: Kruger, E.L., Anderson, T.A., Coats, J.R. (Eds.), Phytoremediation of Soil and Water Contaminants. American Chemical Society, Washington, DC, pp. 274–282.

Dushenkov, S., Kapulnik, Y., 2000. Phytofiltration of metals. In: Raskin, I., Ensley, B.D. (Eds.), Phytoremediation of Toxic Metals, Using Plants to Clean Up the Environment. Willey, New York, pp. 89–106.

Dushenkov, V., Vasudev, D., 1997. Removal of uranium from water using terrestrial plants. Environ. Sci. Technol. 31, 3468–3474.

Dushenkov, V., Kumar, N.P.B.A., Motto, H., Raskin, I., 1995. Rhizofiltration—the use of plants to remove heavy metals from aqueous streams. Environ. Sci. Technol. 29, 1239–1245.

Edenspace Systems Corporation, 2003a. Phytoremediation of Arsenic-Contaminated Soils, Final Report, US Department of Agriculture, Washington, DC.

Edenspace Systems Corporation, 2003b. Phytoremediation of Arsenic from CCA-Contaminated Soils, Final Report, US Environmental Protection Agency, Washington, DC.

Huang, J.W., Chen, J., 2003. Role of pH in phytoremediation of contaminated soils. In: Rengel, Z. (Ed.), Handbook of Soil Acidity. Marcel Dekker, Inc, New York, pp. 449–472.

Huang, J.W., Poynton, C.Y., Kochian, L.V., Elless, M.P., 2004. Phytofiltration of arsenic from drinking water using arsenic-hyperaccumulating ferns. Environ. Sci. Technol. 38 (12), 3412–3417.

Ma, L.Q., Komar, K.M., Tu, C., Zhang, W.H., Cai, Y., Kennelley, E.D., 2001a. A fern that hyperaccumulates arsenic. Nature 409, 579.

Ma, L.Q., Komar, K.M., Kennelley, E.D., 2001b. Methods for removing pollutants from contaminated soil materials with a fern plant. US Patent No. 6,280,500, Issue date 8/28/01,US Government Patent Office, Washington, DC.

Ma, L.Q., Komar, K.M., Kennelley, E.D., 2001c. Methods for removing pollutants from contaminated soil materials with a fern plant. US Patent No. 6,302,942, Issue date 10/16/01, US Government Patent Office, Washington, DC.

Meharg, A., 2003. Variation in arsenic accumulation—hyper-accumulation in ferns and their allies. New Phytol. 157, 25–31.

National Research Council, 1977. Committee of Medical and Biological Effects of Environmental Pollutants: Arsenic. National Academy of Sciences, Washington, DC.

National Research Council, 1999. Arsenic in Drinking Water. National Academy Press, Washington, DC.

National Research Council, 2001. Arsenic in Drinking Water. National Academy Press, Washington, DC.

Pontius, F.W., Brown, K.G., Chen, J.C., 1994. Health implications of arsenic in drinking water. J. Am. Water Works Assoc. 86, 52–63.

Poynton, C.Y., Huang, J.W., Blaylock, M.J., Kochian, L.V., Elless, M.P., 2004. Mechanisms of arsenic hyperaccumulation in *Pteris* species: root As influx and translocation. Planta 219 (6), 1080–1088.

USEPA, 1986. SW-846, Test Methods for Evaluating Solid Wastes. Office of Solid Waste and Emergency Response, Washington, DC.

USEPA, 2000. Arsenic Occurrence in Public Drinking Water Supplies. EPA 815-R-00-023. Office of Ground Water and Drinking Water, Washington, DC.

USEPA, 2001. National primary drinking water regulations; Arsenic and clarifications to compliance and new source contaminants monitoring; Final rule. Federal Register, Part VIII, 40 CFR Parts 9, 141, and 142. US Government Printing Office, Washington, DC.

USEPA, 2003. Arsenic treatment technology evaluation handbook for small systems, EPA 816-R-03-014. Office of Water, Washington, DC.

Zhao, F.J., Dunham, S.J., McGrath, S.P., 2002. Arsenic hyperaccumulation by different fern species. New Phytol. 156, 27–31.