

Family filter with iron-coated sand: solution for arsenic removal in rural areas

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Abstract The presence of arsenic in groundwater is recognised as a threat to public health world-wide and specifically in rural areas of several developing countries due to variety of health-related problems observed in populations ingesting arsenic-containing water. Several arsenic removal technologies suitable mainly for centralised treatment are available or under investigation. However, point-of-use arsenic removal systems, suitable for application at household level appear to be the only feasible solution under conditions prevailing in rural areas of developing countries characterised in general by the absence of centralised water supply systems. Several household level arsenic removal units are commercially available and some of them are currently under testing in Bangladesh. Nevertheless there is still need to develop a more efficient and sustainable point-of-use arsenic removal unit. Very promising results were recently obtained in laboratory experiments with a simple "family filter" with iron-coated sand (ICS) or iron-impregnated granular activated carbon. The objective of this study was to establish methodology for assessment and selection of appropriate ICS for arsenic removal with "family filter". An additional objective was to optimise and test further "family filter" with selected ICS. Batch and filtration laboratory adsorption experiments were conducted with five types of ICS originating from Dutch groundwater treatment plants and model and natural groundwater with high arsenic concentration. All ICSs tested demonstrated arsenic removal potential with removal efficiencies ranging from 50 to 100%. Short adsorption experiments can be applied to screen the suitability of different ICSs. Adsorption isotherm and filter runs are, however, needed to establish arsenic adsorption capacity of a particular ICS. Contact time was found to be the critical parameter for "family filter" design and performance. The "family filter", very simple point-of-use treatment unit, equipped with an appropriate ICS demonstrated high arsenic removal potential and could be very attractive for arsenic removal in rural areas of developing countries.

Keywords Arsenic removal; iron-coated sand; point-of-use

Introduction

Acute arsenic toxicity has been known for centuries. There is nowadays also sufficient evidence that long-term exposure to very low arsenic concentrations causes cancer of skin, lungs, urinary tract, bladder and kidney in addition to skin pigmentation changes and skin thickening known as hyperkeratosis (WHO, 2001; Smith *et al.*, 1999). Arsenic present in drinking water is the main source of human intake of inorganic arsenic, known to be much more toxic than organic arsenic found in food (Donohue and Abernathy 1999).

Arsenic contamination of groundwater has been found in Bangladesh, India, Taiwan, Ghana, Mongolia, several countries in South, Central and North America and New Zealand. New cases are emerging in several other countries like Hungary, Greece, Baltic States, Nepal, Sri Lanka, Nicaragua, etc. Arsenic presence in groundwater is consequently recognised as a threat to public health worldwide and specifically in rural areas of several developing countries. The situation is most serious in Bangladesh where millions of people in 50,000 out of 80,000 villages are exposed to arsenic poisoning of drinking water. In total 3.5 million out of 8 million tubewells have arsenic concentration above the Bangladeshi standard of 50 µg/l; that is five times higher than the WHO and EU standards (WHO, 1996;

EC, 1998). More than 20 million people are consequently exposed to arsenic-containing drinking water in Bangladesh alone.

Different treatment technologies like coagulation–sedimentation–filtration, nanofiltration, reverse osmosis, fluidised-bed sand reactor, sub-surface groundwater treatment, etc. are available or under investigation, which when properly operated can reduce arsenic in drinking water. These technologies are, however, inappropriate for application in rural communities of developing countries and specifically Bangladesh where arsenic-related problems are most pronounced. Recent studies suggest that arsenic removal by adsorption onto iron- and/or manganese oxides is very promising (Bajpai and Chauduri, 1999; Petrusovski *et al.*, 2002; Driehaus 2002).

Health hazards are associated only with the use of arsenic-containing water for drinking and food-preparation which accounts for only a few percent of the total domestic water consumption. This strongly suggests that it is economically very attractive to remove arsenic only from the water used for drinking and cooking. Arsenic removal should consequently be done at household level and the applied point-of-use system(s) should be appropriate for conditions prevailing in rural communities of developing countries. In rural areas of developing countries, where centralised water supply systems are absent, this is the only feasible approach.

A variety of household-level arsenic removal technologies like activated alumina filters, different coagulation–sedimentation–filtration based-bucket treatment units, ion exchange adsorption filters, etc. are commercially available and currently under test in Bangladesh (Water Aid, 2001). Nevertheless, there is still a need to develop a more efficient and sustainable point-of-use arsenic removal unit. Very promising preliminary results were obtained in laboratory experiments with a simple “family filter” with iron-coated sand or iron-impregnated granular activated carbon (Petrusovski *et al.*, 2000). Use of iron-coated sand, essentially a waste product from groundwater treatment plants, as an arsenic adsorbent, was particularly attractive given the wide availability of this material.

The aim of this study was to optimise further performance of the “family filter” with iron-coated sand (ICS) as an adsorbent for arsenic. The study was specifically designed to establish methodology for assessment and selection of appropriate ICS for arsenic removal. In addition, the effect of contact time and filtration rate on the family filter performance was examined. Finally, filter runs with optimised “family filter” were performed under laboratory conditions.

Methods and materials

Laboratory-scale adsorption (equilibrium) experiments were conducted to assess arsenic removal potential of different iron-coated sands. In these experiments fixed amounts of adsorbent were put into 0.56 litre polyethylene bottles. The bottles were filled with arsenic-containing water, capped and mixed continuously with a mechanical shaker at room temperature of 25°C. Samples were taken at pre-selected time intervals and filtered through 0.2 µm pore size cellulose acetate membrane filter to separate finely dispersed adsorbent particles.

Batch adsorption experiments were followed-up by filter runs with “family filter”. 950 ml of selected ICS was placed in the “family filter”, comprising a PVC filter column 69 mm in diameter and 500 mm high with flow control valves, sampling points at different bed depths, containers for feed water and collection of filtrate. The family filter was operated at filtration rates ranging from 0.25 to 0.50 m/h resulting in a capacity sufficient to cover daily water consumption for drinking and cooking of a typical family in rural Bangladesh.

Model water mirroring the typical groundwater composition in Bangladesh and Hungarian arsenic-containing groundwater were used in experiments. Model water was

prepared from Delft tap water by increasing HCO_3^- concentration to 275 mg/l, decreasing pH to 6.8 and by spiking 500–1,500 $\mu\text{g/l}$ arsenic in the form of As(III) or As(V). Hungarian groundwater was characterised by high buffering capacity, pH of 7.8 and 275 $\mu\text{g As/l}$.

Iron-coated sands from five groundwater treatment plants in The Netherlands were used in experiments. Main characteristics of ICS used are given in the Table 1.

An atomic adsorption spectrometer (Perkin Elmer 1100B) equipped with the graphite furnace (GF) and HGA 300 programmer was used for arsenic analysis. The analysis was done according to Dutch Standard Method NEN 6457 with arsenic detection limit of $\sim 3 \mu\text{g/l}$ with an accuracy of $\pm 1 \mu\text{g/l}$.

Results and discussion

Arsenic removal potential of five ICS originating from Dutch groundwater treatment plants was examined in a series of short batch adsorption experiments. All ICSs tested demonstrated, under conditions applied, high to very high arsenic removal potential (55–100% removal after 24 h contact time), irrespective of arsenic speciation and initial concentration (Figure 1). In all short batch adsorption experiments conducted ICS-4 demonstrated the highest and ICS-2 the lowest arsenic removal potential among the ICSs tested.

Analysis of the coating composition and specifically iron content suggested that thick iron-based coating is favourable for high arsenic removal potential of the media. Most of the arsenic removal technologies have considerably lower removal efficiency for arsenic present in the As(III) form. Several types of ICS tested demonstrated potential to remove arsenic efficiently irrespective of its speciation (Petrusevski *et al.*, 2000). Results obtained

Table 1 Characteristics of the iron-coated sands tested

	ICS-1	ICS-2	ICS-3	ICS-4	ICS-5
Size of virgin sand (mm)	0.6–1.5	0.6–1.5	1.0–2.0	0.8–2.0	1.5–4.0
Size of ICS (mm)	0.6–1.5	0.6–1.5	1.0–2.0	1.0–4.0	1.5–4.0
Time in use (years)	2	9	1.5	11	3
Fe content (mg Fe/g ICS)	34.5	45.5	35.0	353.8	116.8
Mn content mg Mn/g ICS)	8.5	3.6	1.4	17.2	0.4

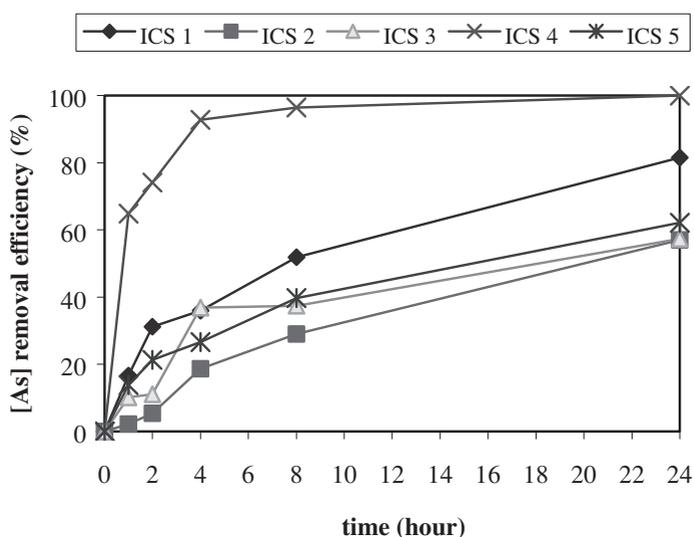


Figure 1 Arsenic removal efficiencies of 5 ICSs as a function of adsorption time; Hungary groundwater with $[\text{As}] = 270 \pm 10 \mu\text{g/L}$; $\text{pH} = 7.80 \pm 0.10$; ICS Dosage = 8 g/L

in this study suggested, however, that presence of manganese in the coating was essential for efficient and fast removal of arsenic present in the As(III) form. ICSs characterised by low to very low manganese content (e.g. ICS-5, ICS-3 and ICS-2) demonstrated considerably lower As(III) removal efficiency specifically during the initial few hours. At the same time ICS-1 and ICS-4, both characterised by relatively high manganese content in the coating, demonstrated much smaller sensitivity to the effect of arsenic speciation on their arsenic removal properties (Figure 2). With prolonged adsorption time (≥ 8 hours) the effect of manganese content in the coating on As(III) removal efficiency was found to be less pronounced. These results are in agreement with earlier findings that demonstrated the potential of manganese oxide, in contrast to ferric hydroxides, to readily oxidise As(III) to As(V) within a time scale of minutes (Bajpai and Chauduri, 1999).

To validate the suitability of short batch experiments to assess different ICSs for arsenic removal adsorption isotherms were established for ICS-4 and ICS-2. These two specific ICSs were based on short adsorption experiments representative of very good and poor arsenic adsorbent. Results obtained demonstrated that As(III) and As(V) adsorption on ICS could be well characterised by Freundlich isotherms. A relatively long period (± 10 days) was, however, needed to achieve equilibrium conditions (Figure 3). The coating of ICS has a high percentage of micro-pores (Sharma *et al.*, 2002) suggesting that pore diffusion controls the overall adsorption kinetics.

Freundlich adsorption isotherms for ICS-2 and ICS-4 demonstrated approximately 1-log unit higher As(III) and As(V) removal capacity of ICS-4 (Figure 4), confirming results obtained in the short batch adsorption experiments.

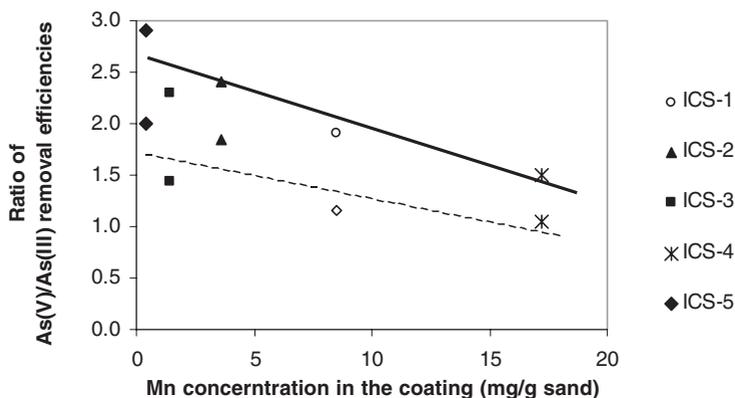


Figure 2 Effect of manganese content in the ICS coating on ratio of As(V) and As(III) removal efficiency in batch adsorption experiments: (a) after 1 h – solid line and (b) after 4 hours – broken line; As concentration in model water $500 \pm 50 \mu\text{g/l}$, $\text{pH} = 6.8 \pm 0.1$; ICS dosage 8 g/l

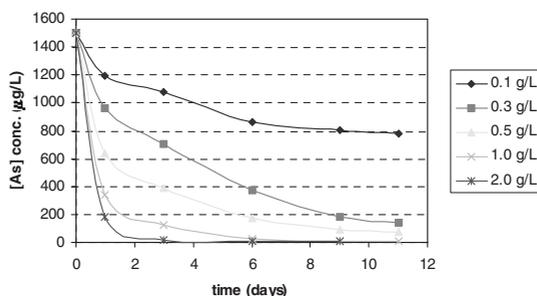


Figure 3 Effect of adsorption time and ICS dosage on arsenic removal ($\text{pH} = 6.8$, initial As(III) concentration = $1,500 \mu\text{g/l}$)

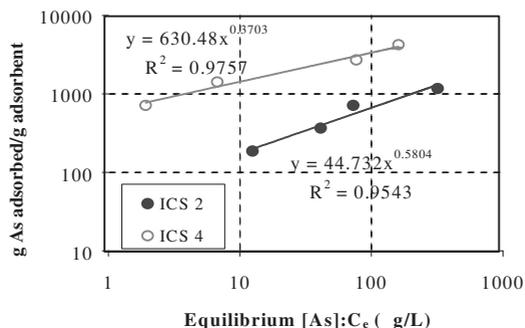


Figure 4 Freundlich adsorption isotherm for ICS 2 and ICS 4; model water with $[\text{As}(\text{V})] = 1,490 \pm 10 \mu\text{g/L}$ and $\text{pH} = 6.80 \pm 0.10$; contact time = 11 days

Considerably higher arsenic removal potential of ICS-4 in comparison to ICS-2, observed in short adsorption experiments, was also confirmed in filter runs with the family filters equipped with ICS-2 and ICS-4 (Figure 5). A rapid increase in arsenic concentration in the family filter with ICS-2 was observed after approximately 100 bed volumes filtered. In contrast, the family filter with ICS-4 produced filtrate with very low or no arsenic throughout the filter run (approximately 1,000 bed volumes filtered).

Arsenic adsorption isotherms together with results from conducted filter runs confirmed that short batch adsorption experiments can be used to screen the suitability of different ICSs as adsorbent in the family filter.

Given its superiority demonstrated in batch and preliminary filtration experiments, ICS-4 was selected and used in further experiments with the “family filter”.

Filtration rate and contact time are two essential “family filter” process design parameters. Consequently a separate set of filtration experiments was conducted to study the effect of these parameters on arsenic removal efficiency. In these experiments filtration rates ranged from 0.25 to 0.5 m/h. Sampling points available at different bed depths allowed assessment of the effect of contact time up to 35 minutes. Results obtained (Figure 6) demonstrated that under conditions applied a contact time of approximately 15 minutes was required to achieve complete arsenic removal. The results obtained also show that contact time, rather than filtration rate, is the critical parameter for design of family filter with ICS. Within the range tested higher filtration rates applied can, consequently, be compensated for by the higher filter bed depth.

The “family filter”, consisting of short PVC pipe (69 mm in diameter) equipped with 1

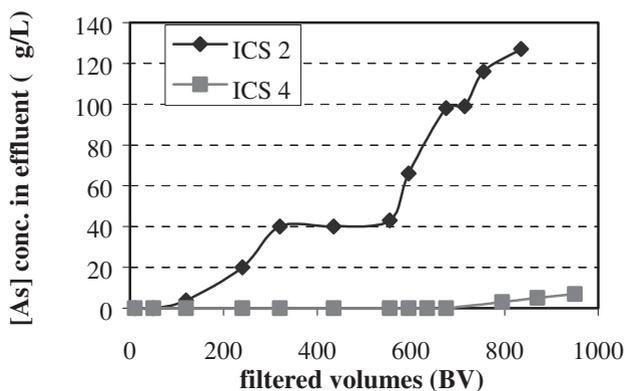


Figure 5 Arsenic concentration of “family filter” filtrate with ICS 2 and ICS 4 as a function of filtered volume; filtration rate = 0.50 m/h; feed water: $[\text{As}(\text{V})] = 500 \pm 50 \mu\text{g/L}$ and $\text{pH} = 6.80 \pm 0.10$; bed depth = 30 cm

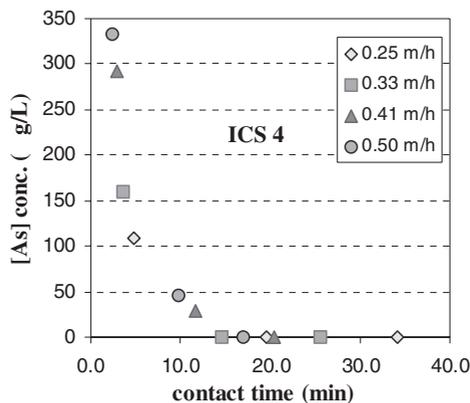


Figure 6 Arsenic concentration in "family filter" filtrate as a function of contact time and filtration rate; feed water with $[\text{As(III)}] = 500 \pm 10 \mu\text{g/L}$ and $\text{pH} = 6.80 \pm 0.10$

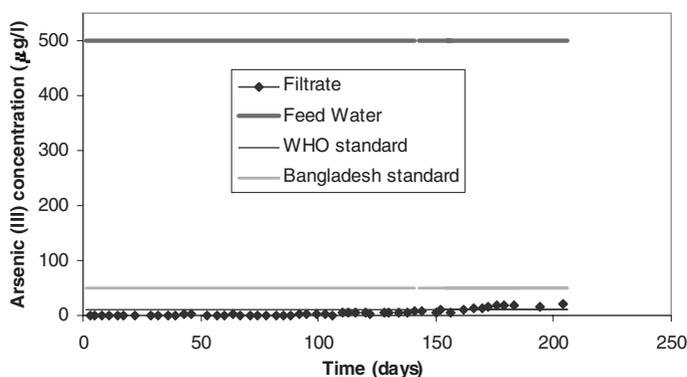


Figure 7 Arsenic removal with "family filter" (Adsorbent = 950 ml of ICS; bed depth = 26 cm; filtration rate = 0.25 m/h)

litre of ICS-4, produced arsenic-free water ($<10 \mu\text{g/l}$) from model water with very high arsenic concentrations for more than six months (Figure 7). The capacity of the "family filter" was sufficient to provide water for drinking and cooking for a typical family in rural Bangladesh.

"Family filter" is very simple, does not require any chemicals, operates under gravity, and consequently does not require a power supply. Extrapolation of results obtained in this study suggest that a family filter equipped with 2 litres of ICS-4 can on average provide a family in rural Bangladesh with arsenic-free water for 18 months without adsorbent replacement. It is consequently expected that the "family filter" capital and operational costs will be very low and affordable for rural communities in developing countries. Results obtained demonstrated that "family filter" with ICS, essentially a by-product from existing groundwater iron removal plants, could be a very efficient and feasible solution for arsenic-related problems in rural areas of Bangladesh and other developing countries. Further "family filter" laboratory and field tests are underway to establish a robust design for the unit and to enhance its arsenic removal potential.

Conclusions

- Iron-coated sands (ICSs) originating from several groundwater treatment plants in The Netherlands demonstrated potential to remove arsenic. However, their arsenic removal efficiency and adsorption capacity varied widely.

- A thick iron coating appeared to be required for a high arsenic removal capacity. Presence of manganese in the coating was found to be essential for fast and efficient removal of arsenic present in As(III) form.
- Relatively short adsorption experiments (≤ 8 hours) can be used to screen arsenic removal potential of different ICSs. Arsenic adsorption isotherm and filter runs are, however, required to provide accurate information on their actual arsenic removal capacity and their performance as adsorbents in the “family filter”.
- Contact time rather than filtration rate is the critical parameter for performance of the family filter. The family filter equipped with ICS-4 requires approximately 15 minutes contact time to achieve complete arsenic removal. Higher filtration rates applied, within the range tested, can consequently be compensated for by a higher adsorbent depth that will allow the required contact time.
- The “family filter” with appropriate ICS has great potential for producing arsenic-free water ($< 10 \mu\text{g As/l}$) from groundwater with high arsenic concentrations, irrespective of arsenic speciation. The “family filter” can be considered as an appropriate and feasible solution for arsenic problems in rural areas of Bangladesh and other developing countries.

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