



# Investigation on the long-term storage and fate of arsenic obtained as a treatment residual: A case study

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## HIGHLIGHTS

- A simple method for containment of arsenic in the treatment residual was developed.
- Leaching of arsenic from sludge was not significant under aerobic storage condition.
- The containment of arsenic laden waste was effective under field conditions.

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## ABSTRACT

In several places in India, activated alumina is used for effective removal of arsenic from contaminated ground water used for drinking purposes. Once exhausted, activated alumina is regenerated and reused for number of cycles. Regeneration of activated alumina generates treatment residuals containing arsenic, disposal of which needs care so as to avoid further pollution of the neighbouring environment. In the present study, a suitable stabilization and disposal method for the treatment residuals inside a well aerated coarse sand filter bed has been developed. Standard leaching tests carried out with the stabilized treatment residual indicated that the leaching of arsenic from the stabilized treatment residual was minimum, and was within the regulatory limit. Water quality data of all the wells located within 100 m from the sand filter were monitored for nearly four years and no adverse impact of disposal of arsenic-laden treatment residuals in the sand filter was observed.

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## 1. Introduction

Natural arsenic contamination in groundwater in South and South-East Asian countries including India and Bangladesh is considered to be one of the most serious public health problems in the recent past. The use of groundwater for drinking purposes in these regions is favoured by its easy availability and microbial safety as opposed to unsafe nature of surface water which is often contaminated due to prevalent poor hygiene and sanitation practices. The occurrence of dangerous level of arsenic in groundwater used for drinking puts upwards of 100 million people at risk of developing arsenic-related health hazards in the Gangetic Delta regions

alone. The consequence of drinking of arsenic-contaminated water over a long period of time causes severe damages to the human body and often becomes fatal [1]. Many argue that switching over to surface water-based water treatment and supply system provides a long-term and stable solution to the problem. However, in India, due to unregulated agricultural and industrial wastewater discharges surface water is likely to get contaminated also by pesticides and fertilizer residues and other toxic metals and chemicals. This may delay the wide-scale implementation of surface water-based water supply systems as the water treatment in such a case becomes rather complex and expensive. Thus, in order to save lives before a changeover to surface water based treatment and distribution system is made possible, it is imperative to build arsenic removal systems on an urgent basis. Several arsenic removal technologies have been developed over the last two decades; some of them have gained wide-scale application in the field. A significant proportion of the technologies use adsorption

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onto metal hydroxide or hybrid materials using metal hydroxides, the metals being iron, aluminum, titanium, etc. Whether it is adsorption or co-precipitation, all the treatment techniques produce treatment residuals, at varying amounts, containing arsenic in various concentrations. Treatment of water for drinking is important; of equal importance is the ecologically safe management of the treatment residuals which, for a sustainable future, should not leach dangerous proportion of arsenic back in the environment. Central Pollution Control Board of India [2] restricted random disposal of hazardous waste and commented that care should be taken during the disposal of hazardous wastes so that it does not further pollute air, water and soil and does not cause any harm to human beings and habitat in the surroundings. United States Environmental Protection Agency (USEPA) found that bulk liquids and semisolid wastes could be stored in a landfill under certain controlled conditions with a secure liner and a system for the collection and removal of leachate [2–4]. It is further mentioned that a solid waste is considered to be hazardous and toxic if it leaches arsenic at concentrations beyond 1 mg/L, when subjected to toxicity characteristics leaching procedure (TCLP) test method proposed by USEPA as per SW 846, Method 1311. A variety of reactions may take place during the storage of a treatment residual which influence the speciation and mobility of inorganic contaminant(s); such reactions include acid/base interactions, precipitation/dissolution, oxidation/reduction, sorption or ion exchange.

Since 1997, more than 150 community-scale arsenic removal units have been installed in the villages of West Bengal, a state of India neighbouring Bangladesh. The treatment units along with ancillaries and protocols were developed jointly by Bengal Engineering and Science University (BESU), India in collaboration with Lehigh University, USA. The project has been implemented by BESU with the financial help mostly supported by Water For People, Denver, USA. The treatment units mostly used activated alumina (AA), and in a few cases used either hybrid anion exchange (HAIX) resin [5] or a combination of both as adsorbents for arsenic removal. The technology is unique in its characteristics because of its ecologically sustainable practices that include regeneration and reuse of the adsorbent media over multiple cycles.

### 1.1. The treatment unit and its performance

Fig. 1A is a schematic of the treatment unit along with the important reactions taking place inside the unit whereas Fig. 1B shows a photograph of the treatment unit. The units do not require any electricity, addition of chemicals or pH adjustment for their daily operation. The community scale arsenic removal unit essentially is a gravity-type flow-through stainless steel column consisting about 100 L of adsorbent. Groundwater in this area (West Bengal) predominately contains dissolved iron in ferrous form [Fe(II)] in concentrations ranging from 1 to 3200 µg/L [6]. The top part of the column is so designed with a spray head, splash plate and vent pipe that it promotes the oxidation of dissolved ferrous iron by atmospheric oxygen resulting in the formation of precipitates of hydrated Fe(III) oxide particles. Freshly precipitated hydrated Fe(III) oxide (HFO) particle surfaces have surface functional groups of  $\text{FeOH}_2^+$  and  $\text{FeOH}$  at circum-neutral pH. They can selectively bind both arsenites or As(III) and arsenates or As(V) through formation of bidentate and/or monodentate inner-sphere complexes where Fe(III), a transition metal, serves as electron-pair acceptor or Lewis acid [7–9]. The arsenic-rich ferric hydroxide particles get trapped on the adsorbent bed at the bottom portion of the column. Arsenic remaining in the partially-treated water is removed by the adsorbent bed, which comprises of either activated alumina or HAIX resins as adsorbent. The mechanism of arsenic removal in the treatment units has been detailed elsewhere [10].

Backwashing of the column on every other day helps to maintain the necessary flow rate through the column by driving out the precipitated HFO particles that tend to clog the bed. The arsenic-laden HFO particles in the waste backwash water are trapped on top of a coarse sand filter provided in the same premises [11].

Depending on the arsenic and iron concentration in the raw water, on an average the arsenic removal units produce about 1,000,000 L or 10,000 bed volumes of treated water before the concentration of arsenic in the treated water exceeds the maximum contaminant level (MCL). Once the arsenic concentration in the treated water exceeds the MCL, the adsorbent media is

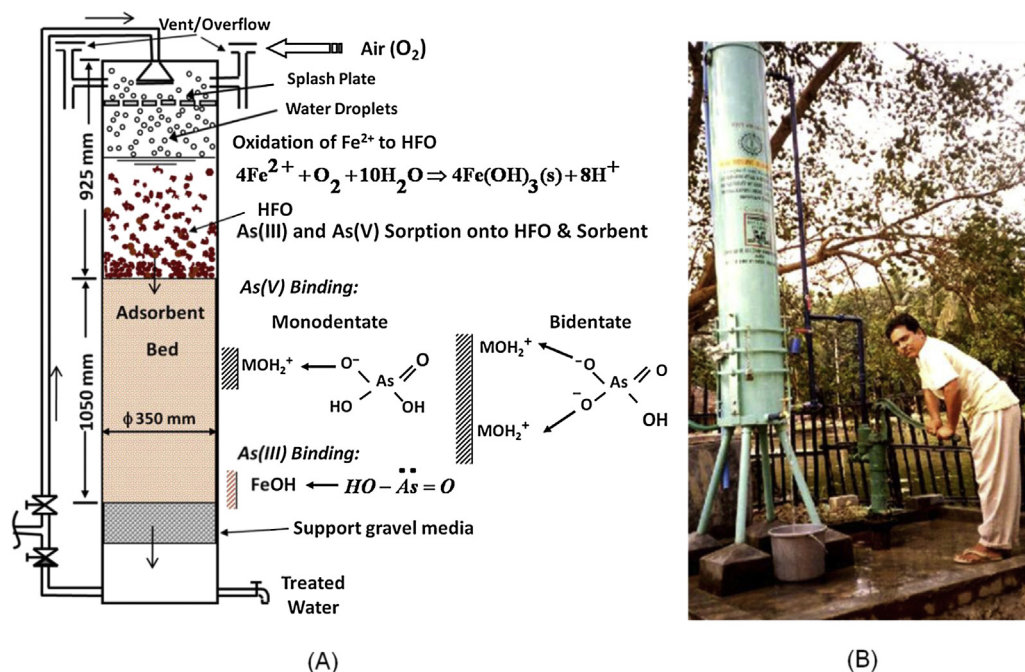


Fig. 1. (A) Schematic of an arsenic removal unit alongwith major reactions taking place during water treatment and (B) photograph of an arsenic removal unit in West Bengal, India.

**Table 1**  
Different steps followed during regeneration of a 50 L batch of exhausted media.

Steps	Solutions used/obtained	Volume (L)	Time of contact/ agitation (min)	Approximate equilibrium pH
I. Water rinse	Well water	70	10	
II. Rinse with alkali	2% sodium hydroxide	140	30	11.5–12.5
III. Rinse with alkali	2% sodium hydroxide	140	60	11.5–12.5
IV. Water rinse	Well water	100	10	10
V. Acid rinse	0.5 N HCl	140	15	5–6
VI. Detoxification of spent regenerant	Treated spent regenerant <sup>a</sup>	≈520	45	6–7

<sup>a</sup> The spent regenerant and rinse solutions were collected and mixed together. Acid/alkali was added to mixed spent wastes and was adjusted to near neutral pH. Details of the process and discussion on the results are described under Section 3.1

replaced with another batch of adsorbent media which is already regenerated. The performance of the units for arsenic removal remains almost the same over many cycles of operation. Examples of such superior performance of the treatment units for arsenic over many cycles are available in open literature [12]. Some of the 150 existing arsenic removal units are performing equally well even after five regenerations [13].

### 1.2. Regeneration of exhausted media and containment of arsenic in spent regenerant

Upon exhaustion of the adsorption column, media from the unit is replaced by fresh or already regenerated media. About 100 L of exhausted media from each unit is taken to a central regeneration facility where regenerations are performed in a stainless steel batch reactor which has a capacity of regeneration of 50 L of adsorbent in a single cycle. The individual steps involved in each regeneration are established and they are indicated in Table 1 along with the other operating conditions.

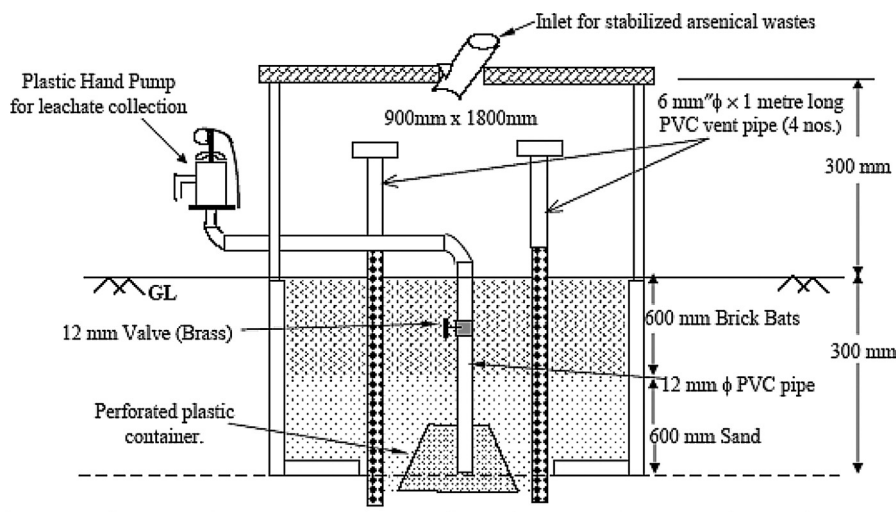
The spent regenerant and rinse solutions obviously contain dangerous levels of arsenic, as indicated later in this article. The large volume of liquid wastes is difficult to handle and also to dispose of, especially in the setting of rural India where all-weather roads are not universally available. The waste solutions are combined together and the pH is adjusted following a protocol discussed later in this article, as a result of which a thick brown precipitate of insoluble ferric hydroxide is formed. Almost all the dissolved arsenic in the spent solution gets absorbed on ferric hydroxide precipitate and thus, separated out from the solution. The arsenic-rich precipitate is the ultimate treatment residue that needs proper disposal.

### 1.3. Disposal of treatment residuals

In a community based well-head arsenic removal system, arsenic-laden wastes evolve from two separate locations. First, arsenic-laden HFO particulates that are formed inside the column are backwashed out every other day and are collected on the top of a coarse sand filter located in the same premise. Second, treatment residuals in the form of sludge are produced at the central regeneration facility after the regeneration followed by stabilization [10]. Chemically, these two wastes are similar; both are rich in iron and arsenic. Both types of arsenic-laden waste are disposed of on top of a coarse sand filter. Fig. 2 shows cross-sectional detail of the coarse sand filter. The coarse sand filter is designed with provision of air vent pipes such a way that its inside is well-ventilated. The super-structure is adequately covered and raised above the ground so to reduce chances of inundation with flood water.

The solids in the sludge get trapped inside the sand filter while the aqueous phase percolates through the sand bed to soil beneath. The dimensions of the coarse sand filters are such that at individual installation sites the sand bed provides adequate space for storage of backwash sludge for about 10 years. The size of the sand filters at the central regeneration facility is kept large so that each of them can store sludge generated from about 100 regenerations.

In this study the principal objective was to verify the environmental performance of the post-regeneration handling and treatment procedures of arsenic-laden liquid and solid wastes. The other objective was to study the long-term storage and fate of arsenic in the treated residuals. Environmental variables play important role towards the mobilization of arsenic from the treatment-residuals and thus conventional leaching tests were used for assessing the leaching potential of such a treatment residual under different environmental conditions. In this study, the quality of groundwater residing in the water table near a coarse



**Fig. 2.** Schematic diagram of sand filter for containment of arsenic-bearing sludge.

sand filter, on top of which arsenic-laden treatment residuals were continuously stored over four years, was monitored. The results of such study are also discussed in this article.

## 2. Materials and methods

### 2.1. Leachate sample collection and analysis

Leachate samples were collected using a hand pump fitted at the bottom of the sand filter as depicted in Fig. 2. A part of the leachate sample was filtered through 0.45  $\mu\text{m}$  membrane filter paper. One part of the filtered leachate sample was adjusted to pH 4.0 by addition of few drops of HCl and was immediately passed through a small column containing a strong base anion exchange resin with polystyrene-divinylbenzene matrix and quaternary ammonium functional group (Bio-Rad, AG 1-X8). The effluent of this anion exchange column should contain only As(III) species because at this pH As(III) remains as non-ionized species while As(V), remaining as anion, gets arrested in the anion exchange column [14]. The extraction rate was maintained at 1–2 drops per second and sample volume was limited within 10 mL. All the leachate samples collected in this way were acidified with a few drops of 8 M  $\text{HNO}_3$  to lower the pH below 2.0 and were preserved for analysis of total arsenic and iron. As(V) in the leachate samples were calculated from difference between total arsenic and the As(III). Total arsenic bound with particulate iron was found out from the difference between the arsenic concentrations measured in the acidified samples of the collected leachate before and after filtration through 0.45  $\mu\text{m}$  membrane filter. Arsenic concentration was analyzed at the Environmental Engineering Laboratory, Bengal Engineering and Science University, Shibpur using an automatic flow injection atomic absorption spectrophotometer (AAS) (Model AA202, Chemito, India) with hydride vapour generation assembly. Iron concentration was measured using the AAS in the flame mode.

### 2.2. Leaching test

Leaching potential of the treatment residuals were assessed using TCLP method [15] and also using the method prescribed by American Society for Testing and Materials (ASTM) [16]. Treatment residuals in the form of particles were collected from the top of the coarse sand filters where they were kept for long-term storage. The samples were dried before they are subjected to ASTM and TCLP tests. The grab samples collected from the coarse sand filters were co-mingled with sand as its main constituent.

The TCLP test involved extracting the contaminants from a 10 g size-reduced sample (less than 10 mm) of waste material with an appropriate extraction fluid. pH of the treatment residuals was checked as per method 9045d (USEPA, 2004). Since pH of waste material falls in the low alkaline range (<10), it was leached with glacial acetic acid buffered at pH  $4.93 \pm 0.05$  with 1 N sodium hydroxide. A specific L/S ratio (20:1) on wt/wt basis was employed, and the mixture was rotated in end-over-end tumbler for  $18 \pm 2$  h at 30 rpm. Minimal headspace of ambient air was kept within the bottles. Agitated samples were centrifuged, settled for 5 min. The

solution was filtered through 0.45  $\mu\text{m}$  filter paper, and the filtrate was analyzed for arsenic and iron.

The ASTM test is a deionized water extraction test to simulate a condition in which the waste material is a dominant factor in determining the pH of the extract. The test was carried out with a 10 g sample of size-reduced waste material (less than 10 mm) with reagent water using L/S ratio of 20:1 on wt/wt basis for  $18 \pm 0.25$  h at 30 rpm. After agitation on a shaker table for 18 h and settlement for 5 min, the liquid phase was removed with decantation, filtered through 0.45  $\mu\text{m}$  filter paper. The filtrate was then analyzed for arsenic and iron.

## 3. Results and discussion

### 3.1. Efficiency of the containment process

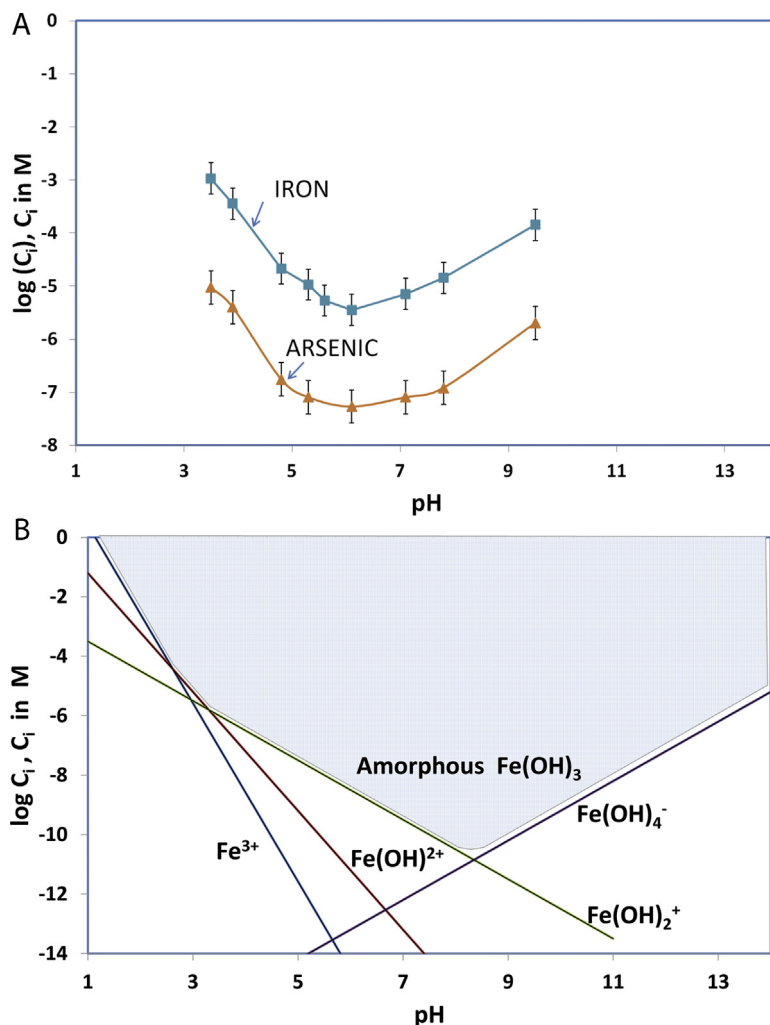
Table 2 shows the quantity as well as the quality of the spent regenerants and rinse solutions in terms of arsenic and iron concentrations. The spent regenerant and rinsed water solutions from regeneration activity are voluminous and contain arsenic at concentrations three orders of magnitude higher than the drinking water standard prevailing in India. Obviously, further handling and disposal of such large volume of toxic liquid poses safety-related concerns. Chemically, the spent solutions have two distinct characteristics; one group of solutions is alkaline and another is acidic. The spent solutions are mixed together in a large vessel so that the mixed solution attains a near-neutral pH. Because of the larger volume and higher pH of the spent alkali solution compared to the acidic waste solution, mixing of all the spent solutions together produces a solution that is still alkaline in nature. In order to find out the optimum pH at which arsenic concentration in the treated spent solution is the minimum, we performed laboratory studies where the pHs of the mixed solution of spent regenerants were varied by the addition of further acid or alkali. Dissolved arsenic and iron concentrations in the mixed solution were recorded at different equilibrium pH. Fig. 3A shows dissolved arsenic and iron concentrations in the supernatant of mixed solution at different pH values. Iron and arsenic concentrations diminished as the pH is lowered, and reached a minimum around near-neutral pH with simultaneous formation of a thick brown precipitate of ferric hydroxide. The curve for dissolved iron concentration in the treated wastewater is similar to a curve shown in Fig. 3B which depicts the solubility of ferric hydroxide at different pH for a dilute solution. The mixture of spent regenerants has a high total dissolved solids (TDS) concentration and is mainly composed of sodium and chloride ions contributed due to the caustic and hydrochloric acid solutions used in the regeneration process. The diagonal shift observed in the wastewater curve is due to the non-ideality effect resulting from the high salt concentration in the treated wastewater.

The laboratory observation that the minimum dissolved iron and arsenic concentrations occur in the treated wastewater around a pH 7 was directly applied in the field to finalize a protocol for containment of the arsenic from the spent regenerants. The spent regenerants are mixed and the pH was adjusted to pH 7 and the solution is allowed to stand for about 60 min for the formation and precipitation of the ferric hydroxide sludge. Table 3 shows, for different regeneration activities, the iron and arsenic concentration in

**Table 2**  
Characteristics of the spent regenerant produced from a regeneration activity.

Description	Volume (L)	pH	Total arsenic ( $\mu\text{g/L}$ )	Total iron ( $\text{mg/L}$ )
Spent caustic 1st batch	140	12.5	39600	2500
Spent caustic 2nd batch	140	12.5	11200	245
Water rinse	100	10	3700	10.5
Acid rinse	140	5.5	320	2.86





**Fig. 3.** A. Dissolved arsenic and iron concentrations in the supernatant of the wastewater generated after regeneration of exhausted activated alumina. B. Solubility of ferric hydroxide as a function of pH. Drawn using values available in Ref. [23].

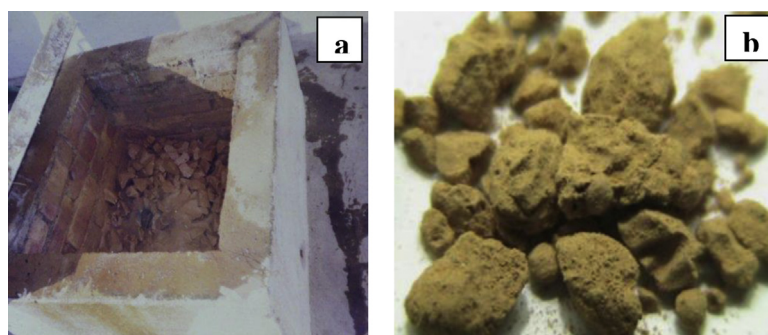
the mixed solution of spent regenerants before and 60 min after the pH adjustment around 7. The supernatant of the solution after pH adjustments did not show arsenic concentration beyond 0.12 mg/L and therefore, is considered to be safe as per Indian Standards, for open discharge to surface water streams.

The following points are noteworthy: (a) As a result of the pH adjustment, the dissolved iron concentrations diminished by more than three orders of magnitude. The dissolved ferric ions gets transformed into solid phase ferric hydroxide or HFO particles that separate out from the bulk solution and settle down; (b) Simultaneously, there is also more than two orders of magnitude drop in the dissolved arsenic concentration. It is clear from the results in Table 3 that the freshly formed precipitates of HFO particles were effective in significant removal of dissolved arsenic from the wastewater.

As the formation of HFO precipitates is primarily responsible for the removal of dissolved arsenic from the spent solutions, presence of enough ferric iron in the spent regenerants is necessary for sufficient removal of arsenic. In almost all arsenic contaminated wells in the Indian Subcontinent, arsenic co-exists with iron in the groundwater [17]. Also, the arsenic removal units are capable of simultaneous removal of iron in the form of ferric hydroxide precipitates which gets dissolved at the extreme pH situations during regeneration. Thus, the presence of large excess of ferric ion in the spent regenerant solutions is almost a certainty. However, in the rare cases where the presence of iron is low, a viable alternative is to add an inexpensive ferric salt to the mixed regenerant before the pH is adjusted. The sludge formed after the pH adjustment is disposed on top of coarse sand filters. The arsenic-laden HFO

**Table 3**  
Concentration of arsenic and iron in mixed supernatant before and 60 min after pH adjustment.

Description	Regenerations of exhausted adsorbents received from community arsenic removal units							
	Regeneration #1 (September 6, 2006)		Regeneration#2 (Mar. 24, 2007)		Regeneration#3 (March 25, 2007)		Regeneration#4 (Aug.10, 2007)	
	As mg/L	Fe mg/L	As mg/L	Fe mg/L	As mg/L	Fe mg/L	As mg/L	Fe mg/L
Mixed solution before pH adjustment	4.9	324	7.8	482	5.31	411.5	5.25	578
Supernatant of the solution after pH adjustment	0.12	2.79	0.11	2.51	0.107	2.61	0.092	3.85



**Fig. 4.** Photograph of (a) inside view of the coarse-sand filter used for storage of stabilized spent regenerant; (b) 20× magnified view of dried treatment residual of stabilized regeneration waste.

**Table 4**

Arsenic and iron content in dried treatment residuals collected as grab samples from coarse-sand filters.

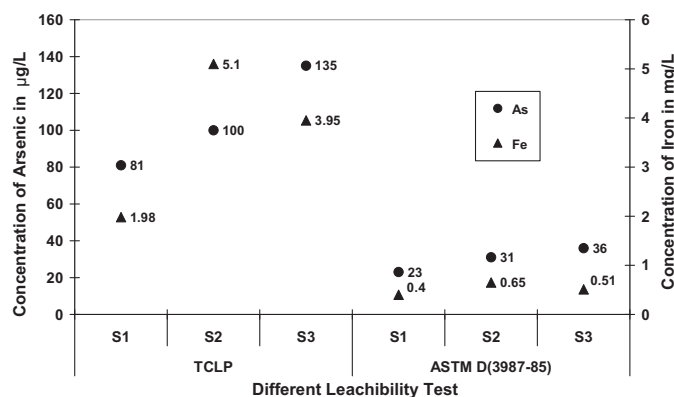
Grab sample number	Moisture content (% wt)	As (mg/kg of dry sludge)	Fe (mg/kg of dry sludge)
Sample#1	68.2	4.93	95.27
Sample#2	82.7	5.46	173.3
Sample#3	85.1	7.75	135.6

particles in the sludge are trapped inside the filter, while the innocuous aqueous phase percolates down to the ground. The amount of arsenic present in the spent regenerant is thus essentially transferred into a solid phase primarily consisting of ferric hydroxide precipitate which forms a sludge weighing around 2 kg depending upon iron concentration of the raw water. The arsenic-laden solid waste contained in the coarse sand filter is thus considered to be the treatment residual.

### 3.2. Leachability of treatment residuals

Treatment residuals in the form of arsenic-laden HFO particles were collected from the top of the coarse sand filters and were dried before they are subjected to ASTM and TCLP tests in order to find out their leaching potential. The grab samples collected from the coarse sand filters were co-mingled with sand as its main constituent. Arsenic and iron content in the dried mass were analyzed after digesting solid samples as per USEPA Method 3050B [18]. Fig. 4 shows a 20× magnified photograph of a dried mass of arsenic-laden treatment residual. The photograph shows that within the coarse-sand filter the particulates agglomerated to form larger sized granules of size ranging between 0.5 and 2.5 cm. Protocols for ASTM and TCLP leaching tests are briefly indicated in the materials and methods section of this article. The physical and chemical nature of the sludge samples are indicated in Table 4.

Fig. 5 shows the results of the TCLP and ASTM leachability tests performed on the grab samples collected from the coarse-sand filters. After each regeneration activity performed for the exhausted adsorbents received from arsenic removal units installed in different locations, the resultant semi-solid stabilized treatment residuals are stored inside the coarse-sand filter located at the central regeneration facility. Over a period of time there have been numerous regeneration activities performed, which generated treatment residuals of different amounts of arsenic and iron content. As the grab samples were collected from different depths of the coarse-sand filter, the leaching study results showed diverse data points. Irrespective of the diverse nature of the data, it may be noted that there was no significant leaching of arsenic from the treatment residuals. The fact that it passes the TCLP test, makes the waste suitable for disposal in well-developed and scientific landfills suggesting that the solid waste would not leach significant amount of arsenic. However, combined redox and pH chemistry plays a bigger role in the mobility of arsenic ions. Recent investigations reported that landfill leachates contained high concentrations of arsenic [19–21] and in fact, they have pointed out to the inability of TCLP tests to correctly predict the leachability of arsenic-laden ferric hydroxide sludge under a landfill-like situation which is anoxic as well as acidic [20]. There is no scientific and well-maintained landfill near the project-site. Thus it is imperative that wherever the stabilized sludge is stored, the redox and pH conditions shall be



**Fig. 5.** Characteristics of leachate from arsenic-laden treatment residual subjected to TCLP and ASTM leaching tests. S1, S2 and S3 represent three different grab samples collected from the coarse-sand filter.

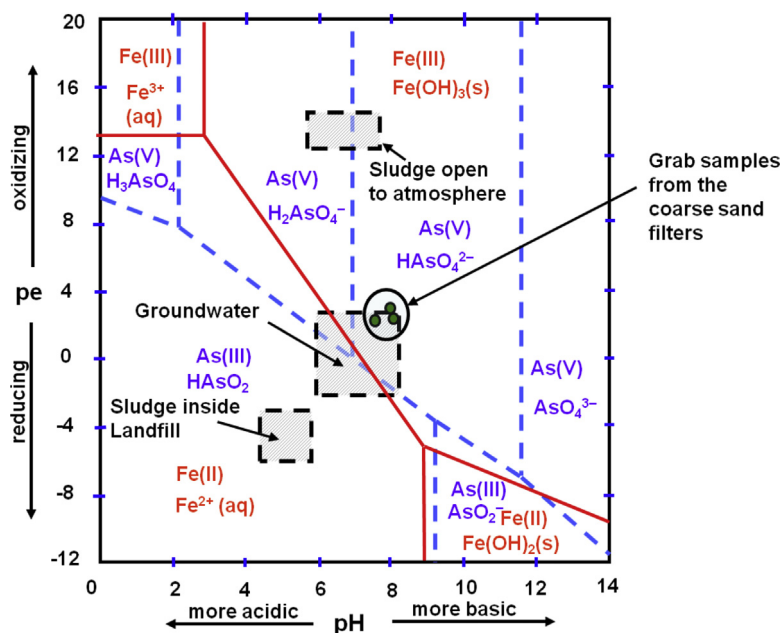


Fig. 6. Predominance diagram of different species of arsenic and iron. Grab samples are the leachate samples collected from the bottom of the filters.

so maintained that there is minimum leaching of arsenic from the solid treatment residues. Therefore, the coarse sand filter where the arsenic-laden sludge is stored was specially designed to store the treatment residual for an extended period of time without causing any unacceptable leaching from such storage.

### 3.3. Performance of the coarse sand filter

Both pH and redox conditions uniquely determine the speciation of arsenic and iron that in turn control the leachability of arsenic from the solid treatment residual. Fig. 6 shows the composite predominance diagram of various arsenic and iron species using equilibrium relationships available in open literature [22,23].

The figure highlights (shaded rectangles) the three separate predominance zones of interest: neutralized HFO sludge open to atmosphere, groundwater and the sludge inside landfill. The reduced species of arsenic (arsenite or As(III)) and iron (Fe(II)) predominates inside a landfill-like condition which is anoxic as well as acidic. On the contrary, under aerated condition, the insoluble Fe(III) species and As(V) predominates in the neutralized arsenic-laden HFO sludge. The above scientific understanding led to the development of the improved design of the coarse sand filter as mentioned in Fig. 2 where vent pipes open to the atmosphere are provided in order to keep the interior of the coarse sand filter well aerated.

Table 5 shows the reports of quality of leachate collected from the bottom of the coarse sand filter. A part of the sample collected was filtered through 0.45 micron filter papers in order to separate any particulate iron remaining in the leachate. The filtered leachate was further analyzed to determine the speciation of arsenic

remaining in the leachate. Along with pH, the redox potentials (Eh) of the samples were also measured.

It may be noted that the coarse sand filter, at the time of collection of the leachate, already was holding treatment residual generated from more than 100 regeneration activities. The result obtained from Table 5 was satisfactory as the overall arsenic concentration in the leachate remained well below the regulatory limit of 1 mg/L. Most of the dissolved arsenic was in As(V) form indicating no reduction of As(V) to As(III) within the coarse sand filter. The redox potential measured in terms of Eh or pe for the leachate also validate that the content inside of the coarse-sand filter remained in the oxic condition. The pH and redox conditions of the leachate samples are plotted on Fig. 6. The location of the grab samples on the predominance diagram indicated in Fig. 6 also shows that iron is present in the ferric state and arsenic in arsenate or As(V) form. It signifies that there should not be any significant leaching of arsenic from the coarse sand filter. It may be noted from Table 5 that the leachate contained fine particulates of arsenic-laden HFO that contributed significantly towards the total arsenic content in the leachate. This suggests that there is scope of further improvement in the design of the coarse sand filters so that its HFO particulate trapping efficiency increases resulting in further minimization of arsenic in the leachate.

### 3.4. Analysis of contaminant transport through groundwater

The central regeneration facility is located within a residential area with water table residing close to the ground. Although the leaching data conclusively pointed out that there is no significant leaching of arsenic from the coarse sand filters, it was however

**Table 5**  
Quality of leachate collected from the coarse sand filter at the central regeneration facility.

Sample number	pH	Eh (V)	pe at 25 °C	Fe (mg/L)			As (mg/L)		
				Total	Dissolved	Particulate	Total	Dissolved	Attached with particulate iron
1	7.5	0.13	2.2	3.2	1.45	1.75	0.174	0.122	0.052
2	7.9	0.17	2.9	4.12	1.72	2.40	0.256	0.115	0.141
3	8.0	0.16	2.7	3.69	1.38	2.31	0.145	0.099	0.046

pe = 16.9\*(Eh), where Eh is in V.

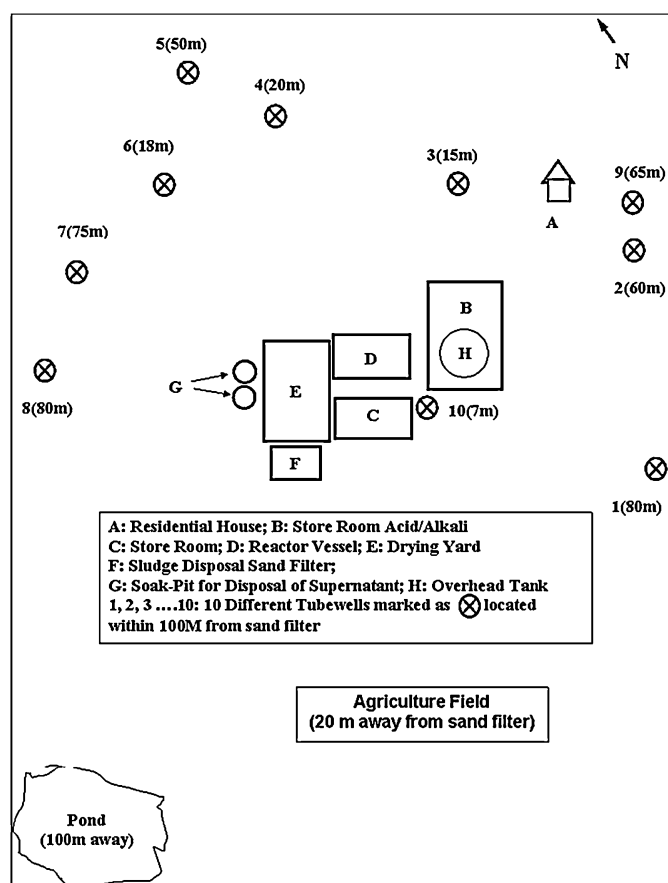


Fig. 7. Site map of centralized regeneration unit (Not to scale).

felt necessary to be sure that there is absolutely no effect of the contamination transport on the aquifer or the private wells situated near the regeneration facility. A not-to-scale map of the central regeneration facility with its adjacent wells is indicated in Fig. 7. The straight-line distances of the wells from the coarse sand filter bed are indicated within parentheses.

The water quality has been checked in the nearby wells since installation and commissioning of the central regeneration facility in November, 2003. Table 6 provides the historical water quality data of some of the near-by wells since January, 2005. In order to provide benchmarks against which arsenic-concentration data can be compared, arsenic-concentration data are compared with IS10500:1991 standard. It may be noted that the area is a part

of active arsenic-contaminated region of the Indian subcontinent and wells producing water with arsenic concentration beyond the  $50 \mu\text{g/L}$  permissible limit [24] is not uncommon.

Arsenic concentration in none of the tubewells showed any upward change. Proximity of the well from sand filter location does not have any significance with raw water arsenic concentration. Wells at location 7 and 8 contained high concentrations of arsenic compared to other wells in the area. Two of the nearest wells at locations 3 (15 m) and 10 (7 m) never showed any indication of an increase in the arsenic concentration. Moreover, the depth of the wells at location 3 and 10 was lowest, about 15 m, making them the most vulnerable to contamination if the groundwater movement were towards the East. This comparative study reveals that

Table 6

Arsenic concentration measured at wells located within a 100 m distance from the coarse sand filter.

Well number as marked in Fig. 7	Distance from sand filter (m)	Arsenic concentration measured in well water (mg/L)					
		10.01.05 (418 days)	20.07.05 (609 days)	19.09.05 (670 days)	20.06.06 (944 days)	03.08.07 (1353 days)	15.05.08 (1639 days)
1	80	0.024	<sup>a</sup>	0.017	0.028	0.02	0.023
2	60	0.014	0.019	0.009	0.017	0.032	0.029
3	15	0.004	0.003	0.006	0.009	0.008	0.01
4	20	0.004	0.004	0.010	0.021	0.011	0.014
5	50	0.029	<sup>a</sup>	0.020	<sup>a</sup>	0.013	0.01
6	18	0.064	<sup>a</sup>	0.059	0.039	0.05	0.046
7	25	0.050	0.048	0.056	0.025	0.04	0.035
8	30	0.041	0.041	0.041	0.037	0.034	0.03
9	65	0.003	0.001	0.004	0.012	0.009	0.011
10	7		<sup>b</sup> 0.021	0.013	0.026	0.019	0.023

<sup>a</sup> Data not available (water sample could not be collected).

<sup>b</sup> Regeneration centre well installed in July, 2005.



is there no sign of any long-term effect of leaching of arsenic from the coarse sand filter in the regeneration facility to the aquifer as well as to the near-by wells.

#### 4. Conclusion

Currently more than 150 well-head arsenic removal units are in use in villages bordering eastern India and Bangladesh and nearly 200,000 villagers routinely drink arsenic-safe water from these units that are run and maintained by a villagers' committee in every location. The arsenic removal technology is simple and user-friendly. This technology is easily scalable and can be managed by rural community with ease. However, a major environmental challenge lies not in removing dissolved arsenic from contaminated groundwater but in attaining safe, long-term disposal of arsenic-laden treatment residuals. A successful technology should also provide responsible and sustainable solution towards closing the arsenic loop and ensuring the future health and safety of people from any leaching of arsenic back in the environment. This article has demonstrated a robust arsenic removal technology with the following most significant features:

1. Use of robust and mechanically strong adsorbent media allows for regeneration and reuse of the media.
2. Exhausted adsorbents were successfully regenerated at a central regeneration facility following simple procedure and using locally available chemicals and trained villagers. The arsenic removed was contained as solid treatment residual having weight less than 50 times compared to exhausted adsorbent.
3. The treatment residuals were stored inside aerated sand filters in an ecologically safe manner.

Any toxic substance, whose stability or sorption affinity significantly diminishes under reducing environments, may appear in landfill leachate at significantly higher concentrations. The underlying chemistry of this mechanism reinforces the scientific premise that any engineered process pertaining to long-term arsenic disposal must take place under relatively oxidizing environments. It was conclusively demonstrated that there was no significant leaching of arsenic from the coarse-sand filters used for the storage of arsenic-laden treatment residual. It was also demonstrated that the small amount of arsenic leached through the filter did not cause any further contamination of nearby wells. Overall, the arsenic removal process demonstrated an ecologically sustainable way of removal of arsenic from contaminated water in a developing country. A similar process can be easily replicated in other places which experiences similar problems with their drinking water. Moreover, these results can be extrapolated in future to the developed world towards the instigation of proper arsenic disposal regulations.

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