

INTRODUCTION

An alarmingly large population of India and Bangladesh (66 million in the Gangetic belt of India¹ and 79.9 million in Bangladesh²) is exposed to arsenic poisoning due to continuous usage of arsenic-contaminated ground water. Arsenic concentration in the water of these regions ranges from 50 ppb to even 5 ppm³ whereas drinking water limit for arsenic as per World health organization (WHO) and United States Environmental Protection Agency (US EPA) is only 10ppb⁴. The number of reported arsenic-poisoning cases is increasing exponentially with each passing day.

Arsenic contamination of groundwater in these areas has mainly occurred due to natural reasons². As per the most plausible theory⁵⁻⁸, in the Late Pleistocene – Recent times, iron and arsenic-bearing sulphidic minerals in upper reaches of the Ganges river belt may have undergone oxidation due to exposure to atmosphere during erosion, resulting in subsequent mobilization of arsenic and iron downstream. The mobilized iron got precipitated as iron oxy-hydroxide and arsenic got either adsorbed onto or co-precipitated with iron oxy-hydroxide. These arsenic containing precipitates then got deposited in the Gangetic delta region in the form of iron oxy-hydroxide coating on aquifer soil particles. In the present day situation, reducing conditions prevailing in the sub-surface environment is causing dissolution of this coating and mobilization of adsorbed/co-precipitated arsenic thereof.

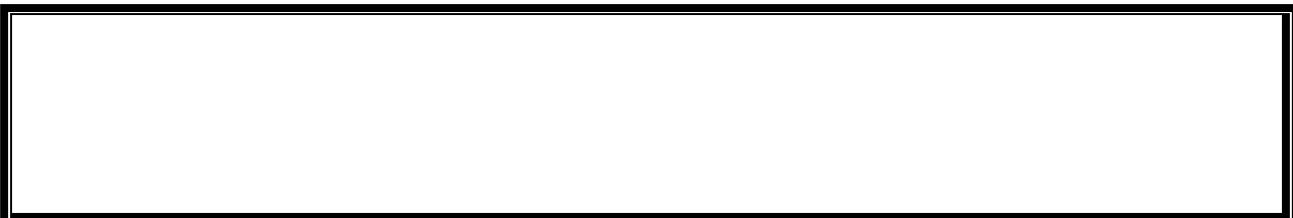
Besides, the same problem, but to a lesser extent, has been observed in other parts of the world (Fig.1) as well, such as China, Taiwan, Inner Mangolia, Obuasi Ghana, Corodoba Argentina, Antofagasta, Chile Lagunera Mexico, Cornwall Britain and more recently in Northern Vietnam⁹. Most of the affected people are poor villagers who can't afford expensive technologies that have now started entering the market. More so, the delicacy of these technologies and the subsequent care and maintenance¹⁰⁻¹² add to their expenses, apart from being inconvenient to be

used by villagers. Considering the rate at which this poison is spreading its web to the most interior parts all over the world, there is an urgent need to develop ways to mitigate this problem by reducing the level of arsenic in drinking water to tolerable limits through easy and inexpensive means.

Though various water treatment technologies and kits for the removal of arsenic are available worldwide, their high cost, problems of waste disposal and effect on environment have proved to be major limitations in implementation and the problem remains unresolved. The successful development of present water filter for arsenic remediation has been demonstrated to be an effective solution to this burning problem.

Objective

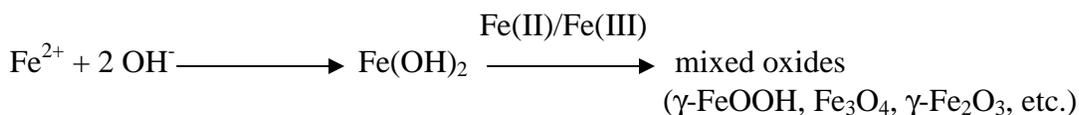
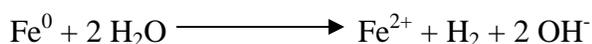
To develop a cost-effective and environment-friendly water filter to provide arsenic-free drinking water in arsenic-contaminated areas.



LABORATORY TRIALS

Working Principle

The arsenic removal filter, developed at NMRL, works on the simple principle of co-precipitation of arsenic with iron and adsorption of this precipitate on iron oxyhydroxides¹³⁻¹⁶, followed by further retention of this precipitate in treated sand. The probable reactions involved in the process are given below:



Sodium salts of arsenite and arsenate get ionized in water medium. The arsenite and arsenate ions are removed further by co-precipitation as FeAsO_4 and FeAsO_3 and by adsorption of these oxides onto ferric oxyhydroxide solids. The same has been reported by a number of workers earlier also.

Experimental

Materials and Methods

The active material, a processed waste from Steel industry, has been obtained from M/s Tata wires Ltd., Mumbai. Sand used has been obtained from the riverbank of River Yamuna in Delhi, India, and from the riverbank of River Ganga in Kolkata, India. Fine cloth filter has been procured locally. AR quality reagents and Milli-Q grade water have been used for solution preparation. Solutions of As^{+3} and As^{+5} have been prepared using corresponding salts, NaAsO_2

and $\text{Na}_2\text{HAsO}_4 \cdot 7\text{H}_2\text{O}$, respectively. Mixture of As^{+3} and As^{+5} (in the ratio of 1:1) has been prepared by dissolving equimolar amount of corresponding salt in Milli-Q grade water. The reactant material is soaked overnight in water before using in the filter. The sand used is subjected to physical treatment (washing and heat treatment) prior to using it in the arsenic removal filter.

Characterization

The reactant material and sand have been characterized for their surface area and composition using Micromeritics ASAP 2010 Surface Area Analyzer at Centre for Fire, Environment and Explosives Safety (CFEES), Delhi, and by Phillips X-ray fluorescence (XRF) at Durgapur Steel Plant, Durgapur respectively.

Characteristics of the reactant material and sand, as given in Table 1, clearly indicate that the reactant material is nothing but 99% iron and acts as zero valent iron. Surface area value of sand indicates that its adsorption capacity is low and is basically functioning as a fine filter in this process.

Table 1. Characteristics of Sand and Reactant Material

Adsorbent	pH (in water)	pH (in As solution)	Fe (%)	Al (%)	Mn (%)	Si (%)	Surface area (BET) m²/g
Sand (Yamuna)	10.2 - 0.5	10.2 - 10.5	8.9 - 10.5	10.5 - 11.0	Not detected	79.2 - 80.0	1
Sand (Ganga)	8.3-8.5	7.5-8.0	4.7- 5.0	11.5- 12.0	Not detected	79.8- 80.0	4
Reactant Material	8.5 - 9.0	8.8 - 9.0	99.2 -99.5	Not detected	0.42 - 0.45	Trace amount	0.5

The variation in the pH of pure water and of arsenic solution when allowed to percolate down through the reactant material and through sand has been determined using a pH meter (Model: Elico LI-120)

Scanning electron micrograph (Fig. 2) of the material as taken on Scanning Electron microscope (Model: Leo 1455) at 500 magnification confirms the fibrous elongated morphology.

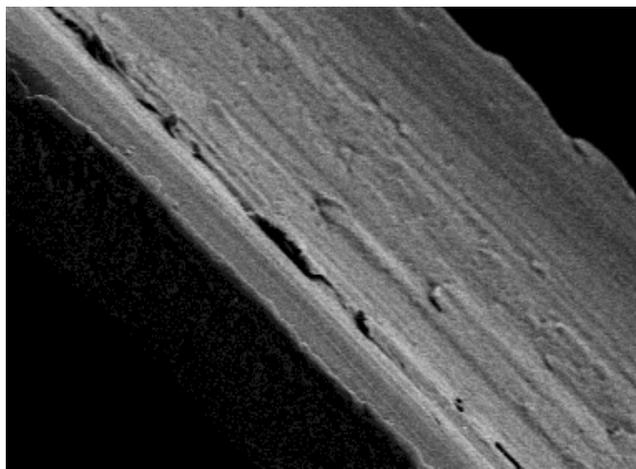


Figure 2. SEM Micrograph of reactant material

Metal analysis

Arsenic concentration in water, prior to and after treatment, has been measured as per ASTM method¹⁷ using Hydride Generator (Model: HG-3000) attached to AAS (Model: GBC 904AA) at Centre for Fire, Environment and Explosives Safety (CFEES), Delhi, India. Iron concentration was determined using AAS. The results were also verified at Department of Environmental Sciences, Jadavpur University, Kolkata.

Design of Arsenic Removal Filter

Arsenic removal filter as shown in Figure 3 has been designed and fabricated both in plastic and in stainless steel.

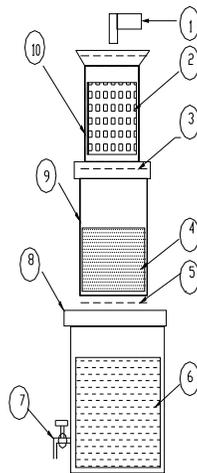


Figure 3. Schematic Diagram of Arsenic Removal Filter

1. Inlet for Arsenic-Contaminated Water
2. Reactant Material
3. Fine Cloth Filter
4. Treated Sand
5. Fine Cloth Filter
6. Arsenic-Free Water
7. Outlet for Arsenic- Free Water
8. Container for Arsenic-Free Water
9. Container for Treated Sand
10. Container for Reactant Material

As shown in the above figure, the filter comprises of three chambers. The first chamber contains the reactant material enclosed in a fine cloth bag. In the second chamber is placed a fine cloth bag containing treated sand. The third chamber simply acts as a collector chamber for treated water. Arsenic-contaminated water is allowed to enter the first chamber of the filter at a predetermined flow rate from where it passes down to the second chamber and finally gets collected in the third chamber. The time it takes for water to flow down from the first chamber to the third chamber is about 2 minutes.

Using the above stated design, optimization studies w.r.t. inlet water flow rate, amount of reactant material and amount of treated sand were carried out.

Optimization of Flow Rate

Keeping the amount of reactant material and treated sand constant at 500 g and 1500 g, respectively (the capacities of first, second and third chambers designed to be 7 L, 7 L and 16 L, respectively, for this purpose), experiments were carried out to study the effect of flow rate of arsenic (As^{+3} or As^{+5} or 1:1 mixture of As^{+3} and As^{+5}) contaminated water on the arsenic removal efficiency of the filter. The results of these experiments showed that irrespective of the arsenic species present in water, 15 Lph was the maximum allowable flow rate for the inlet water stream (contaminated with arsenic) because the arsenic concentration in filtered water raised beyond prescribed limits once this flow rate value was exceeded. It was also established that if the amount of reactant material and treated sand was raised to 1000 g and 3000 g, respectively (the capacities of first, second and third chambers designed to be 16 L, 25 L and 50 L, respectively, for this purpose), maximum allowable flow rate that could be achieved was 30 Lph. The results are depicted in Figure 4.

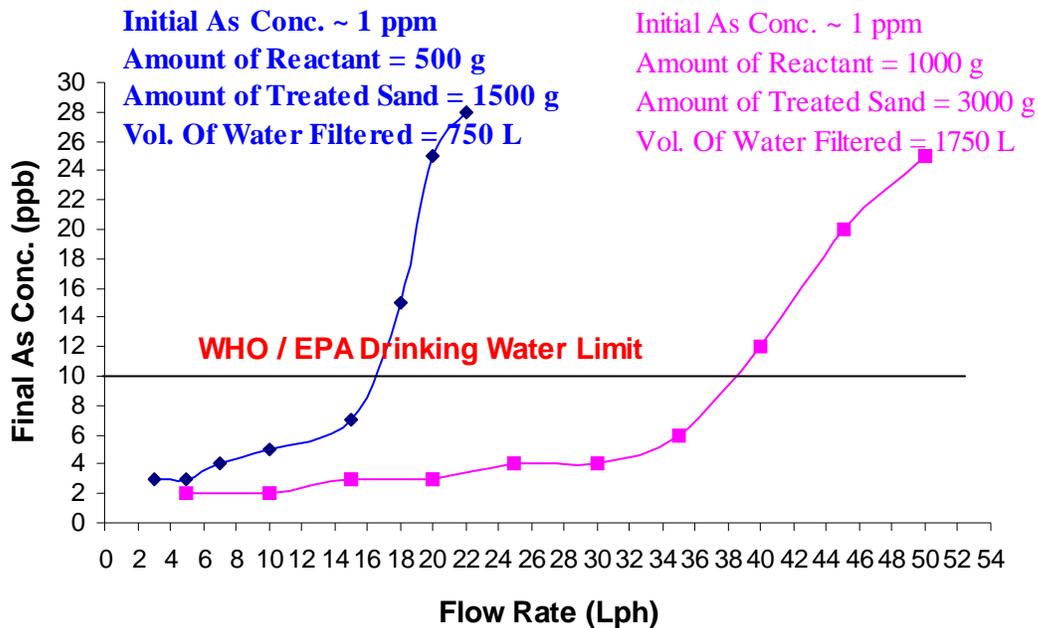


Figure 4. Optimization of Flow Rate

Thus two filter systems were designed based on the above observations. The details of both the systems are given below:

System I

- | | | |
|----------------------------------|---|---|
| 1. Adsorbent (Steel plant waste) | - | 500 gms |
| 2. Treated Sand | - | 1500 gms |
| 3. Flow rate | - | 15 lit / hr (Lph) |
| 4. Initial As conc. range | - | 1- 4 ppm |
| 5. Final As Conc. | - | < 3 ppb (Well below EPA / WHO's drinking water limit of 10 ppb) |
| 6. Volume of water treated | - | 750 lits. |
| 7. Quality of water | - | Suitable for drinking purpose. |
| 8. Leaching of other metals | - | No leaching |

System II

- | | | |
|----------------------------------|---|--|
| 1. Adsorbent (Steel plant waste) | - | 1000 gms |
| 2. Treated Sand | - | 3000 gms |
| 3. Flow rate | - | 30 lit./hr |
| 4. Initial As conc. range | - | 1ppm |
| 5. Final As Conc. | - | < 3 ppb (Well below EPA / WHO's
drinking water limit of 10 ppb) |
| 6. Volume of water treated | - | 1750 lits. |
| 7. Quality of water | - | Suitable for drinking purpose. |
| 8. Leaching of other metals | - | No leaching |

Effect of Initial Arsenic Concentration

The effect of initial arsenic (1:1 mixture of As^{+3} and As^{+5}) concentration (varying from 1.0 ppm to 4 ppm) on the arsenic removal efficiency of the filter, in terms of total volume of water filtered (final arsenic concentration in filtered water < 10 ppb), using optimized amounts of reactant material and treated sand for the two flow rate systems was studied and the observations are illustrated in the form of a bar chart (Fig. 5). As expected, an increase in the arsenic concentration in water leads to a decrease in the total volume of water that can be treated using this filter.

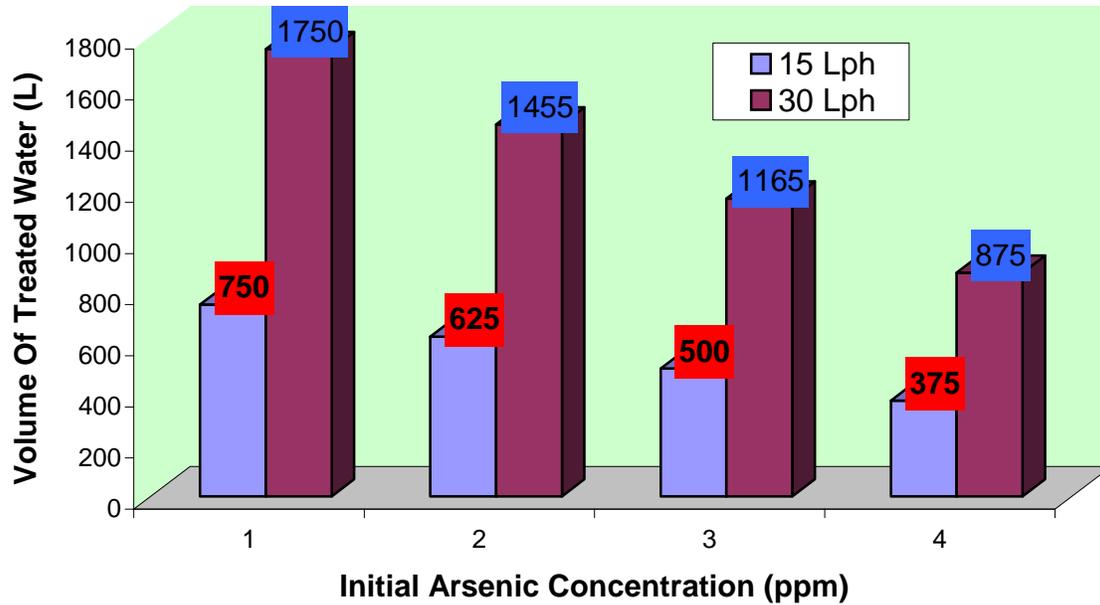


Figure 5. Effect of Initial Arsenic Concentration

Water Quality

The filtered water collected in the third chamber was analyzed for its arsenic concentration, iron (that may leach out from the reactant material during the process) concentration and microbes. The results as enlisted in Table 2 clearly indicate that the quality of the filtered water conforms to the internationally (WHO and US EPA) set drinking water standards¹⁸.

Table 2. Results of Water Analysis

S.No.	Arsenic Species Present	Arsenic conc. (mg/L)		Iron conc. (mg/L)		E.Coli (count /100ml) after 48 hrs.	
		Initial	After Treatment (Final potable water)	Initial	After Treatment (Final potable water)	Initial	After treatment (Final potable water)
1	As(III)	1000	<.03	Not Detected	<0.3	8	0
2	As(V)	1050	<.03	Not Detected	<0.3	8	0
3	Mixture of As (III) and As (V) in the ratio of 1:1	1025	<.03	Not Detected	<0.3	8	0

FIELD TRIALS

After successful laboratory evaluation, six filters (four fabricated from stainless steel and two fabricated from plastic) operating at 15 Lph flow rate were installed in four arsenic-affected villages, namely, Kamdevkati, Raghavpur, Simulpur and Chatra villages; of 24 Paraganas (N) district, Kolkata (West Bengal (India)) (Fig. 6), to test the viability of this technology in field conditions. The reports collected so far indicate excellent performance of the filters. However, it has been observed that stainless steel filters are more durable, as expected, than plastic filters for long-term usage and are recommended for further use (Table 3).



Figure 6. Installation of filters in field

Table3. Field Evaluation Data

Date of Installation	Site of Installation	Total Volume of water filtered till 30th December, 2004	Iron Concentration (ppm)		Arsenic Concentration (ppm)	
			Initial	Final	Initial	Final
23/09/03	Kamdevkati Village (Stainless Steel Kit)	10,050 L	0.040 ± 0.001	0.042 ± 0.001	0.068 ± 0.01	0.004 ± 0.001
07/10/03	Chatra Village (Plastic Kit) (Data of the earlier kit that has now been discontinued)	10,000 L	0.168 ± 0.02	0.063 ± 0.001	0.271 ± 0.02	0.003 ± 0.001
20/11/03	Kamdevkati Village (Stainless Steel Kit)	10,000 L	0.105 ± 0.02	0.210 ± 0.02	0.049 ± 0.001	0.003 ± 0.001
20/11/03	Kamdevkati Village (Plastic Kit)	10,000 L	0.084 ± 0.001	0.126 ± 0.02	0.135 ± 0.02	< 0.003 ± 0.001
20/11/03	Simulpur Village (Stainless Steel Kit)	10,000 L	0.462 ± 0.02	0.168 ± 0.02	0.374 ± 0.02	0.005 ± 0.001
21/11/03	Raghavpur Village (Stainless Steel Kit)	10,000 L	0.168 ± 0.02	0.189 ± 0.02	0.180 ± 0.02	< 0.003 ± 0.001
21/11/03	Chatra Village (Plastic Kit) (Data of the new kit that has replaced the earlier damaged one)	2060 L Damaged and no longer in use	0.168 ± 0.02	0.105 ± 0.02	0.271 ± 0.02	0.004 ± 0.001

Correlation of Laboratory and Field data

A very good correlation between laboratory and field results (Figs. 7 (a) and 7 (b)) has been obtained in terms of the capacity of the reactant material used in the filter for the removal of arsenic from water. The capacity is calculated on the basis of initial arsenic concentration in influent water with respect to the total quantity of water filtered by filter in the laboratory and in field so far.

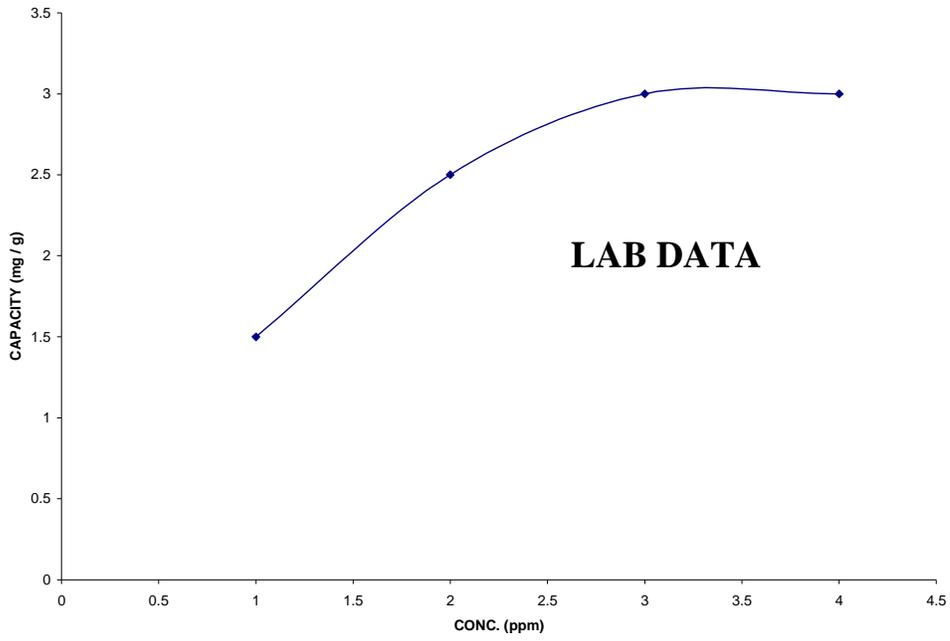


Fig. 7 (a)

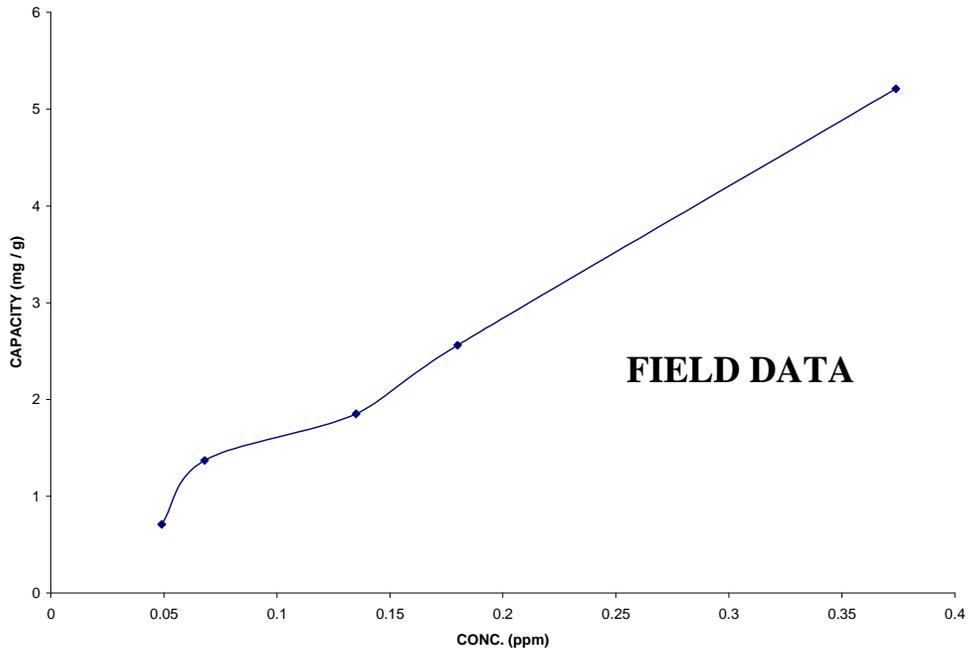


Fig. 7 (b)

WASTE DISPOSAL

Although the waste generated during arsenic removal process is not environmentally harmful as such, as reported by earlier workers, yet disposal of arsenic-laden waste is an important aspect under growing environmental regulations. Therefore, precipitate formed during reaction and the used sand is being disposed off in the form of impermeable concrete blocks of M-25¹⁹ standard grade used in construction industry resulting in no waste generation in the process and making the technology environment-friendly and green.

Leaching tests have been carried out for the waste generated during the process as well as for concrete blocks as per the standard Toxicity Characteristic Leaching Procedure (TCLP) for solid wastes (EPA protocol SW-846-1311)²⁰, and the results are tabulated in Table 4.

Table 4. Results of Leaching Tests

Type of waste	Arsenic Concentration in Filtered Water (ppb)	
	<i>Laboratory Samples</i>	<i>Field Samples</i>
Waste	BDL*	BDL
Concrete Blocks	BDL	BDL

- BDL: Below Detection Limit i.e.<3ppb

TECHNOLOGY STATUS

1. Laboratory and field trials successfully completed.
2. Successful demonstration of Arsenic Removal Filter in Arsenic Task Force, Kolkata, on 22nd September, 2003
3. Successful field trials at Kamdevkati & Chatra villages of 24 Paraganas Distt in Kolkata in association with 'Save the Environment' (NGO) and AIIHPH (All India Institute of Hygiene and Public Health).
4. Filters are in use for last five years and are working satisfactorily with yearly replacement reactant material.
5. Arsenic and iron concentration well below WHO/EPA drinking water standards (< 10 & < 300 ppb respectively).
6. Indian patent granted.
7. International Patent filed.
8. Transfer of technology to 'save The Environment' (NGO), Kolkata, M/s, Shiva Engg. Works, Kolkata and M/s S B Equipments, Delhi..
9. Three hundred filters have already been installed in Lalmath village of Nadia Distt. W.B. under Department of Science and Technology (DST) sponsored project and two thousand one hundred more being installed in another seven villages of W.B., Bihar and U.P.

10. Awards:

- **Silver Medal for innovative Technology in Anveshan Competition at IIM, Ahmedabad - 29th June, 2003**
- **Bhartiya Stree Shakti National Award for innovative Technology - 2005**

- **DRDO Defence Spin-off Technology Award - 2007**

cost

The cost of the stainless steel (SS) filter system designed to operate at 15 Lph is ~ Rs. 1700.00(US \$ 34) only, which is a one-time investment. However, a bulk production of the filters will bring down the cost effectively.

The cost of arsenic-free water, using above filter, works out to be Rs. 0.31 per 1000 litres of filtered water (based on laboratory evaluation). The cost break-up is given below:

Cost of Adsorbent	-	Rs. 46.00 / 1000 gm (1 kg)
Cost for each batch of Adsorbent	-	Rs. 23.00
Cost of River Sand	-	Rs. 0.50 / 1000 gm (1 kg)
Cost of each batch sand (1500gms)	-	Rs. 0.75
Cost of each batch of arsenic-free water	-	Rs. 23. 75
Cost of arsenic free water	-	Rs.0. 31/ 1000 lit

CONCLUSIONS

The water filter for arsenic removal as discussed above can provide a reliable solution to the basic problem of arsenic contamination in ground water because of its following features:

1. Requires no Power (electricity or battery)
2. Easy maintenance
3. Cost-effective
4. Environment-friendly
5. User Friendly
6. Easy waste disposal

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