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APPRAISAL OF A SIMPLE ARSENIC REMOVAL METHOD FOR GROUNDWATER OF BANGLADESH

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ABSTRACT

A simple three-pitcher (locally known as '3-kalshi') filtration assembly made entirely from readily available local materials is tested for its efficacy in removing arsenic from the groundwater of Bangladesh. In a 3- kalshi assembly, the first kalshi has iron chips and coarse sand, the second kalshi has wood charcoal and fine sand, and the third kalshi is the collector for filtered water. About 240 L of arsenic contaminated groundwater and groundwater spiked with high concentrations of both As(III) and As(V) were filtered. Analytical measurements were performed by using anodic stripping voltammetry (ASV) for trace level As(III) and As(total) and redox potential. Atomic absorption spectrometry with graphite furnace and Zeeman background correction (AASGF-Z) and inductively coupled plasma atomic emission spectrometry (ICPAES) were used to validate measurements of arsenic and measure 24 other metals before and after filtration. Total Fe, ionic conductivity, E_h , pH, temperature and flow rates were measured at various stages of the filtration process. It has been shown that more toxic As(III) can be removed from 800 ppb to below the detection limit of 2 ppb. The As(total) can be removed to a concentration below 10 ppb for most samples even at the highest input concentration of 1100 ppb As(total). The dissolved iron concentration decreased from an average 6000 ppb to 200 ppb. Calculations based on compound formation and arsenic adsorption on hydrous ferric oxide show that, with a constant input of dissolved iron the arsenic removal capacity increases linearly with each filtration. Although the role of metallic iron was difficult to quantitate, it provided excess soluble iron in the filtering media of the second kalshi. The wood charcoal was used to remove any organic impurities that may be present in groundwater. The redox potential change shows speciation of iron in agreement with literature data. The decrease in conductivity by 35% of the original value indicates substantial removal of dissolved ions. This is also supported by ICPAES measurement. The filtered water remained crystal clear for months and free from most toxic metal ions. The daily capacity of the 3-kalshi system varies from 42 -148 L/day. The final water quality meets and exceeds the guideline values suggested by USEPA, World Health Organization and Bangladesh. We suggest the use of this simple setup to make potable water.

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INTRODUCTION

Recently, a high concentration of arsenic was found in the groundwater of Bangladesh and neighboring India (Chatterjee, et. al., 1995; Das et. al., 1995; Samanta, et. al., 1999). The geochemical nature of arsenic contamination of the aquifers of Bengal deltaic region is of serious concern because groundwater is the primary source of drinking water. Hyperkeratosis on the palms and feet is the common symptoms of arsenic poisoning. Long-term exposure to low concentrations of arsenic has been reported to cause cancer of bladder, skin and other internal organs (Tseng, et. al., 1968; International Agency for Research on Cancer, 1980; Smith, 1992). Also, arsenic in its various ionic forms is known to be very toxic to most microorganisms (Cervantes, et. al., 1994). World Health Organization (WHO, 1999) reports that there are about 2.5 million tubewells in Bangladesh and more than 95% of the Bangladesh population of 120 million drinks well water. The present crisis may have affected more than 50 million of people in Bangladesh and the neighboring India. According to WHO, the maximum contamination level (MCL) of arsenic in drinking water is 50 $\mu\text{g/L}$ (or ppb: part-per-billion) and 10 $\mu\text{g/L}$ as a provisional guideline value. Total arsenic measurement shows that more than 60% of water from shallow and deep tubewells (wells with a metal casing) has above 10 ppb guideline value (International Conference, 1998).

The primary concern now is the measurement and purification of drinking water from arsenic. Because arsenic is found only in the well water, the obvious choice would be to drink surface water (river, pond etc.). However, this is limited by the extensive contamination of surface water by fecal matters. Although Bangladesh has one of the world's largest freshwater resources, the lack of appropriate water treatment facilities prevents majority of the population from clean drinking water. An array of methods and technologies are available for the purification of water from arsenic and other trace metal contaminants (EPA, 1999). These are coagulation- filtration, lime softening, activated alumina, ion exchange, reverse osmosis, electro dialysis, nanofiltration and in-situ treatment of well water (Rott, et. al., 1993). The USEPA (United States Environmental Protection Agency) has identified three prospective methods: ion exchange with brine recycles, iron addition-coagulation with direct filtration, and attenuation by naturally occurring iron in water. Although, USEPA technologies are generally developed for large-scale treatment facilities, the basic chemistry for the later method can be utilized in a small scale.

This work was motivated by the need to develop a simple, low cost technique for the removal of arsenic from the groundwater of Bangladesh by using locally available materials. Instead of using methods mentioned above, it was decided to test one of the oldest water purification methods known as the three pitcher (locally known as '3-kalshi') for its efficacy in removing arsenic and other impurities. This work is a scientific appraisal of the 3-kalshi method for the purification of water and its viability in Bangladesh. An evaluation of the method was conducted by measuring water chemistry parameters such as As(III), As(total), Fe(total), ionic conductivity, E_h , pH, temperature and flow rates at various stages of the filtration process. The water quality was further tested by measuring concentrations of 23 other major, minor and trace metals by ICPAES.

EXPERIMENTAL SECTION

The basic 3-pitcher (hereafter referred as '3-kalshi', the local name) water purification setup is shown in Figure 1. It consists of three kalshis made of fired unglazed clay used as reservoir for drinking water by 80% of the people in Bangladesh. Local artisans make a variety of shapes of these kalshis. We have used the ones with narrow mouth, round bottom, and have a volume of about 18-L. The three kalshis are stacked on top of each other. The bottom of top two kalshis has a small hole plugged with 100% polyester cloth or similar materials. The first kalshi contains 3 kg (approx. 1/6 kalshi volume) of iron chips (filings) and 2 kg of coarse sand. The low carbon iron chips were obtained from a local foundry (Renwick Ironworks, Kushtia). Small iron nails or rods cut into small pieces may also be used. Care should be taken not to use either galvanized (containing Zn) iron or alloy materials. Both coarse and fine sand was obtained from the local Garai River. The river sand has about 0.05% iron oxide. The second kalshi consists of 1-kg wood charcoal and 2 kg of fine sand. The wood charcoal was collected from burned wood for cooking. All precautions were taken to avoid the fine wood ash, which may dissolve in water and produce a basic solution. The function of the wood charcoal is to adsorb organic impurities that may be present in groundwater. If the wood charcoal is lighter than water, it can be placed in between two layers of fine sand. The fine sand is the final filter. The third kalshi was the collector. To prevent bacterial contamination from sand and iron chips, they may be boiled and washed. All data obtained in this work were obtained after discarding first two kalshi volumes of water.

The concentrations of As(III), and As(total) were measured by a Model HQ-2040 (Advanced Analytics, Virginia, USA) personal computer controlled electrochemical analyzer. This multifunctional computer controlled potentiostat is capable of performing a variety of electrochemical experiments and has a magnetic stirrer controlled by the computer (Hussam, 1988; Hussam et. al. 1988). For arsenic analysis the instrument uses a staircase anodic stripping voltammetry (ASV) which has been shown to be more sensitive than differential pulse anodic stripping voltammetry (Christie, et. al., 1976; Eisner, et. al. 1976). Glass electrochemical cells with Teflon top and Teflon magnetic stir bar were used throughout the experiment. The cell-top has provisions to insert Teflon purging tube and micropipet tips for standard additions.

A thin gold film coated glassy carbon (3.0-mm diameter) was used as a working electrode. A platinum wire directly immersed in test solution (53 mm long) was used as the counter electrode. The reference electrode was an Ag/AgCl in saturated KCl isolated from the test solution by a porous Vycor[®] junction. The working electrode preparation and other analytical protocols are based on published methods (Davis et. al., 1978; Sun, et. al., 1997; Burguera et. al., 1997; Huiliang, et. al., 1988) and that of a modified EPA method 7063: Arsenic in Aqueous Samples and Extracts by Anodic Stripping Voltammetry (ASV) (Pyles, et. al., 1999). Briefly, As(III) is deposited from a 6M HCl acidic solution on a preplated gold coated glassy carbon electrode at -150 mV vs. Ag/AgCl, saturated KCl reference electrode for 60 s. The deposited arsenic is stripped off the electrode by a linear potential ramp from -150 to 500 mV in the same solution while the oxidation current is recorded as a function of potential. The resulting linear scan anodic stripping voltammogram (LSASV) was used to measure the concentration of arsenic. The method of standard addition was employed to eliminate matrix effect of solution. The electrochemical method can be used to measure As(III) in presence of

As(V) at all concentrations. Total arsenic concentration was measured after reduction of As(V) to As(III) by Na_2SO_3 . The analytical performance of the method can be summarized as follows: precision 1-10% relative standard deviation (rsd) of three replicate runs, accuracy 10% rsd (maximum) for 10 ppb quality control sample, three standard deviation of the signal detection limit 1.2 ppb at 95% confidence level at 120 s deposition time, dilution and aliquot addition errors 10% max, and sample carry over 0-4 ppb max. Details of the speciation analysis procedure are described elsewhere (Rasul, et. al. 1999; Rasul, et. al. 1999). The same instrument was used to obtain the redox potential, E_h , of water samples by measuring the rest potential of a polished platinum button electrode against the Ag/AgCl(s), satd. KCl reference electrode (197 mV vs. standard hydrogen electrode, SHE) and corrected for SHE.

A Perkin-Elmer model 5100 Zeeman-effect atomic absorption spectrometer with a graphite furnace (AASGF-Z) and model A-60 autosampler were used for low level arsenic measurement. A 24-trace metal profile of water samples before and after filtration was measured by a direct reading Echelle inductively coupled plasma atomic emission spectrometer (ICPAES) with radial and axial view (Leeman Labs, NH, USA). The ICPAES method detection limits are shown with less than (<) symbol preceding the value. Both AASGF-Z and ICPAES were used with samples from the second series and to validate electrochemical ASV measurement of arsenic Total soluble iron (Fe(II) and Fe(III)) was measured by visible spectrophotometric procedure based on 1,10-phenanthroline colored complex of Fe(II). The estimated detection limit for soluble iron was 50 ppb (assuming, molar absorptivity $\epsilon = 12000$, $b = 1.0$ cm, and $A = 0.01$ au). Total ionic conductivity, pH, and temperature were measured by standard digital meters. Cl^- was measured with an ion selective electrode on a serum electrolyte analyzer (Model-EasyLite Plus, M.I.T Services Inc., USA). The effluent flow rate was measured by collecting water in a measuring cylinder for a fixed time.

RESULTS AND DISCUSSION

The present experiment was performed with groundwater obtained from a tubewell in Kushtia Sadar, which has been continuously monitored for As(III) and As(total). About 40% of groundwater in Kushtia were contaminated with more than 50 ppb As(total). The water quality of the tubewell is representative of the groundwater used by about 400 thousand people of Kushtia Sadar (area 316 sq. km) and may have been used by many for years.

The filtered water was crystal clear and remained so for months while the groundwater turned cloudy and brownish in 2-6 hours. In this work water was filtered through the 3-kalshi setup immediately after collection and spiking. Two series of experiments were performed to evaluate the efficacy of the filtration system. In the first series, arsenic contaminated tubewell water and the same water spiked with higher concentrations of As(III) and As(V) were filtered. No attempts were made to optimize the flow rate in the first series. In the second series the cloth plug in B-kalshi was renewed in order to increase the flow rate. Also, the spiking level of As(III) and As(V) was increased. Table 1 shows the compilation of physicochemical data for first and second series of experiments. The data comprising temperature, pH, ionic conductivity, ppb of As(III), ppb of As(total), ppb of total soluble iron, and flow rate at various stages of the

filtration process. Redox potential, concentrations of 23 metal cations and Cl^- were measured in the second series of experiments.

Table 1 shows both series of experiments with numbers corresponds to about 12 L of water passed through A and B and collected in C. In series 1, the first five experiments were done with tubewell water containing arsenic at indicated levels. Experiments 6-10 in the first series were performed by spiking the tubewell water with sodium salts of arsenite (As(III)) and arsenate (As(V)) as indicated by concentrations of As(III) and As(total) in A kalshi. In the second series of experiments, the first two entries correspond to original tubewell water and the remaining entries (#3-10) are due to spiked tubewell water. Based on the data in Table 1, we make the following observations regarding the efficiency of the present filtration system.

Efficiency of Arsenic Removal

Table 1 shows that in both series of experiments As(III) is nearly completely removed from a maximum value of 800 ppb to below the detection limit of the instrument (ca. 2 ppb) for all influx. It appears that most of the As(III) is oxidized into more stable As(V) and precipitated in A and B kalshis. It has been recognized that As(III) is more prevalent in groundwater than was previously believed which is a concern because As(III) is more toxic than As(V) (Korte, et. al., 1991; Knowles, et. al., 1983). In Bangladesh, the groundwater contains 43-98% of arsenic in the form of As(III) (Rasul et. al. 1999). For direct consumption, this is possibly one of the most toxic groundwater known today. Therefore, the removal of As(III) by any filtration procedure is crucial. In contrast, negligible removal of As(III) from drinking water was achieved by coagulation with alum (Wilkie, et. al., 1996). The overall arsenic removal capability is shown in Figure 2. In the first series of experiments the concentration of total As in the filtered water is reduced to 13.6 ± 3 ppb for all cases. This is much below 50 ppb and nearly 10 ppb within sample spread. In the second series, the first two experiments were performed with the original tubewell water which show removal of As(total) below 10 ppb. To further test the integrity and stability of the system, groundwater spiked with As(III) and As(V) were filtered. Table 1 shows As(total) in the filtered water has decreased from 1005 ppb to 7 ppb with an average value of 6 ± 3 ppb for all samples. The concentrations of total arsenic in the filtered water are nearly independent of the initial concentrations (79 - 1000 ppb) and flow rates indicate an efficient filtration mechanism. In series 1 and series 2, the As(total) removed were 44.0 mg and 72.5 mg respectively, for 120 L water filtered in each series.

The ASV measurements were further validated by GFAAS-Z and ICPAES. The average of the three techniques for samples 2, 5, and 9 for the second series show 129 ± 24 , 600 ± 46 , and 970 ± 190 ppb of arsenic, respectively, in the unfiltered groundwater. Because the method detection limit for ICP was 16 ppb, arsenic concentrations in the filtered water were only measured by ASV and GFAAS-Z. The accuracy within three methods was generally better than 20% over a concentration range of 20 - 1000 ppb.

Role of Soluble Iron in Arsenic Removal

Dissolved iron is a natural component of most groundwater. The dissolved iron concentration in the well water is 5700 - 7100 ppbs. The maximum desirable concentration of iron in water is 300 ppb and the maximum permissible concentration is

1000 ppb (see Table 4). Besides causing pots and pans to become brown, at high concentration dissolved iron can be toxic to small infants (Miah, 1996). Table 1 clearly shows that the concentration of soluble iron originally present in the well water decreased significantly, from an average of 6000 ppb to an average of 200 ppb, which is below the permissible level for most cases.

Dissolved iron, primarily present as Fe(II) in groundwater plays a very significant role in removing arsenic and other trace cations and anions. In contact with air Fe(II) is oxidized to Fe(III) and precipitates as Fe(OH)₃, hydrous ferric oxide (HFO: Fe₂O₃, 2-3 H₂O), Fe(HCO₃)₂ etc. Also, arsenite in the presence of zero valent iron, Mn²⁺ in ground water, and MnO₂ in the sand is catalytically oxidized to arsenate in the heterogeneous media at indicated pH range (Scott, et. al., 1995; Oscarson, et. al., 1980). It is well known that HFO binds arsenate formed during the slow percolation process (Sullivan, et. al., 1996; Seyler, et. al., 1989). In addition to As(V), recent data also shows As(III) is strongly sorbed by iron(III) oxides such as amorphous Fe(OH)₃, HFO and Goethite (Manning et. al., 1998; Pierce, et. al., 1980). Arsenate anion bound to HFO can form common naturally occurring arsenate minerals FeAsO₄, 2H₂O (Scorodite) and FeHAsO₄, 8H₂O (Symplectite) as the dominant solid phase (Azcue, et. al., 1994). Recently, it has been shown that 0.267 mols of arsenic per kg of HFO are removed by sorption on HFO below pH 7.5 (Raven, et. al., 1998). Therefore, arsenic is removed by iron species either by compound formation or by adsorption or both. We also note that phyllosilicate, an abundant mineral component of sand has an affinity for arsenic at 9.62 µg As(III)/g phyllosilicate (Frost et. al., 1977). If phyllosilicate plays a significant role in removing As(III), then it may have removed a significant portion of As(III) in the first kalshi. However, saturation of phyllosilicate by iron and other ions in solution may limit its role as a sole agent for arsenic removal.

Table 1 shows that there is excess Fe present in the groundwater than is required by stoichiometry of FeAsO₄(s), other insoluble arsenic species or adsorption. The excess iron is accumulating in the filtering media (sand) after each kalshi of water is filtered. Figure 3 shows the excess arsenic removal capacity due to the excess iron accumulating in the kalshi after filtration of each liter of water. Figure 3 clearly shows that compound formation and precipitation are the most effective means of arsenic removal compared to adsorption. The compound formation (solid circle) is calculated on the basis of As/Fe mole ratio of unity and represents the maximum limit. The adsorption calculation is based on the literature data (Pierce, et. al., 1982; Raven, et. al., 1998) and represents the lower limit for arsenic removal by excess iron. The excess capacity due to compound formation or adsorption can diminish with decreasing soluble iron in the water. But with a constant input of soluble iron either naturally present or deliberately added (e.g., as FeCl₃), the capacity for arsenic removal increases linearly with each extraction for both cases. These calculations show that this simple process can remove large quantities of arsenic.

To understand the role of iron further, the concentration of iron in B-kalshi was measured in the beginning and at the end of the series. The concentration had increased from 13270 ppb to 16240 ppb. These high values are attributed to the leaching of metallic iron from the first kalshi and the sampling of fine colloidal HFO particles during measurement. The colloidal particles helped to reduce all trace anions and cations and did not filter through the fine sand. This is evident from ICPAES measurement of 24 metals

including soluble iron in the filtered water discussed later. The filtered water remained clear for months while the unfiltered water showed brownish precipitate in few hours.

Even with such increased capacity arsenic cannot be completely removed from water. Table 1 shows that the lower limit range is 3 - 18 ppb. Factors such as leakage, mechanical bed failure, and bed clogging by hydrous ferric oxide may, however, limit the efficiency of the process in the long run.

Role of Metallic Iron

Elemental iron (or zero valent iron) is one of the most effective agents for environmental remediation of inorganic (Wilson, 1995) and organic (chlorinated solvents, nitroaromatics etc.) (Powel, et. al., 1995) species because it is a strong reducer. The use of metallic iron to remediate metal contaminated sites has increased because it is non-toxic and inexpensive. Literature data clearly demonstrate that zero valent iron can be useful for arsenic remediation at low pH and high sulfide containing water (Nikolaidis, et. al. 1998). The reducing property of metallic iron is most effective at low pH and slows down significantly at neutral pH. However, the hydroxide species formed on the metallic iron function as active adsorption sites for anions of arsenate and arsenite at neutral and basic pH. Although the exact role of zero valent iron in the present work cannot be quantitated, it is used to provide a constant input of iron (soluble or surface precipitate) for groundwater low in soluble iron.

Redox Potential Change

Table 2 shows the pH and redox potentials, E_h , for inflow and outflow water for the second series of experiments. To compare the redox quality of water produced by the filtration process electron activities are calculated and expressed by a nondimensional scale, pe using the relation (Morel, 1983; Degueudre, et. al., 1999): $pe = (F/2.303RT) E_h$.

Table 2 clearly shows the outflow E_h is more oxidizing than the inflow water by 100 mV. The inflow water does not, however, represent the true groundwater condition because of its collection, spiking, and residence in the first kalshi where some oxygenation occurred. Water in contact with air will have an E_h in the range of 350 - 500 mV and a pe between 5-8 are in agreement with the reported values (Cullen, et. al., 1989). Due to large excess of soluble iron present in the inflow water, the average inflow $E_h = 351 \pm 39$ and $pH = 6.8 \pm 0.12$ represents iron species $Fe^{2+}/Fe(OH)_2^+$ in equilibrium. The 100 mV shift in the E_h and a pH shift to 7.7 for the filtered water shifts the equilibrium towards oxidizing condition where $Fe(OH)_3(aq)/Fe(OH)_2^+$ is the predominant equilibrium.

Effect on pH of Water

Table 1 shows that the pH of the filtered water increased from 6.8 ± 0.1 to 7.8 ± 0.1 . This is caused by two factors (i) the 95% decrease in soluble iron concentration as a Lewis acid, and (ii) the relative increase in carbonate -bicarbonate concentration due to exchange of dissolved CO_2 (16-26 mg/L) from the ambient atmosphere for a prolonged contact time. The pH of the filtered water is almost the same as many bottled or spring water.

Removal of Other Ionic Species

To understand the process of filtration through an inorganic media a complete measurement of inorganic cations and anions is required. Table 3 shows the ICPAES measurement of average concentrations of 24 elements in samples 2, 5, and 9 (of second series) before and after filtration through the 3 -kalshi system. The arsenic concentration is shown as the range. It shows reduction of As concentration from 1160 ppb to below the method detection limit for ICPAES and below 10 ppb as discussed earlier. Table 3 shows almost complete removal of Fe and Mn to 84, and <1 ppb, respectively. These two metals forms hydrous oxide precipitates and removes other trace metals by coprecipitation, AsO_3^{3-} and AsO_4^{3-} in particular. Also, about 50% each of Ca, Ba, and Sr were removed by the filtration system. We note that among 25 elements the concentration of Ca is the highest (113-mg/L). In presence of high iron concentration, a high concentration of Ca^{2+} is beneficial to the removal of arsenic. Because, the adsorption of Ca^{2+} on HFO increases the positive charge density of the HFO colloids and thus enhances adsorption of AsO_4^{3-} (Wilkie et. al. 1996). A small increase in alkali metal ions (Na + K) concentration is indicative of a low-level ion exchange of these ions in silicate sand minerals with that of alkaline earth cations. All other trace metals are present at extremely low concentrations of no significance. The filtered water is crystal-clear and free form most toxic metals. The Cl^- concentration in the unfiltered and filtered water was 171 and 112 mg/L, respectively. The highest Cl^- concentration found in the unfiltered water was 400 mg/L. Work is in progress to understand the role of anions in the filtration process.

Measurement of ionic conductivity is also essential to understand the overall filtration process in terms of soluble ionic components passing through the filtering media. Table 1 shows that the ionic conductivity of the solution decreased consistently from A to B to C. On average a 25% decrease in conductivity occurred from A to B. This is indicative of a process where majority of metal ions are sorbed or precipitated in the first kalshi. The decrease in conductivity from B to C was about 12%. The decrease in conductivity in the final filtered water is consistent with the finding that filtering media itself (sand in particular) did not dissolve or contribute to any significant excess in solution.

Flow Rate and Hourly Capacity

The flow rate of effluent during filtration is shown in the last column. The average outflow rate for the first series of experiments is 29 ± 6 mL/min and did not decrease throughout the experiment in either A or B kalshi. This flow rate amounts to 1.6 L/hour is the minimum available for an unoptimized system. The flow rate for the second series was increased three times to 103 ± 5 mL/min after renewal of cloth plug in B-kalshi. The final flow rate 6.2 L/hour is adequate for the supply of drinking and cooking water for a middle size family of 4-5.

CONCLUSION

This work shows that arsenic in groundwater can be removed by a simple filtration procedure using locally available material and without adding chemicals. The overall water quality obtained from the 3-kalshi setup is compared with that of standards in Table 4. Clearly, the water quality obtained from 3-kalshi setup meets and exceeds the WHO and Bangladesh standard and made potable water from contaminated water of near

wastewater quality. The present system can be further optimized to increase the flow rate, the efficiency, and the aesthetics for a wider acceptance and use. In this respect local innovation and local participation are essential. Because groundwater is assumed to be free from pathogenic bacteria, the water quality parameters shown do not include such information. To further this work and to understand the speciation of groundwater by chemical equilibrium models require complete analysis of cations, anions, organic humic materials, and mineral precipitates. We continue to work in these areas, but we urge immediate use of the 3-kalshi method to mitigate part of the present arsenic crisis.

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TABLE 1
Analytical Data from 3-Kalshi Experiment*

Expt. No.	Tem °C	pH			Conductivity μS/cm			As(III) ppb		As(Tot) ppb		Fe(Tot), ppb		Flow rate, mL/min		
Series 1 data																
Kalshi	→	A	B	C	A	B	C	A	C	A	C	A	C	A	B	
1	27.5	6.7	8.1	8	559	258	358	75	bdl	101	18	7100	480	25	18	
2	29	6.9	7.6	8.2	489	369	362	73	bdl	79	16	6020	200	25	25	
3	30	6.8	7.7	8.2	472	360	333	116	bdl	120	13	6600	370	25	25	
4	30	6.8	7.8	8	587	418	318	89	2.2	111	11	6160	170	33	35	
5	30	6.7	7.8	7.9	531	411	273	109	2	115	17	6650	150	32	32	
6	30.4	6.8	7.8	7.9	550	271	229	309	2	711	10	6570	70	27	27	
7	33.3	6.8	7.8	7.8	519	475	284	457	2	639	15	6680	70	38	40	
8	31	6.9	7.6	7.8	502	426	353	470	bdl	525	11	6790	50	34	34	
9	31	6.8	7.6	7.8	580	423	346	282	bdl	710	10	6130	bdl	25	25	
10	31	6.9	7.9	8.1	554	338	297	480	bdl	723	13	5720	70	30	30	
Series 1 summary																
Avg.	30.3	6.8	7.8	8	534	375	315		2.05			13.4	6442		29	29
±range	1.5	0.1	0.2	0.2	38.5	70.1	43.8		0.1			2.95	417.9		4.7	6.4
Series 2 data																
1	30	6.8	7.1	7.8	608	367	354	129	bdl	132	7.4	6290	460		110	
2	29	6.7	7.2	7.8	608	496	456	108	bdl	116	4	6440	490		95	
3	29.5	6.9	7.1	7.6	580	393	379	332	bdl	492	4.8	5998	147		105	
4	29.5	6.8	7.2	7.6	618	464	424	303	bdl	410	4.5	6035	147		110	
5	29	6.7	7.3	7.7	592	469	397	463	bdl	644	9	5886	203		105	
6	29.8	7.1	7.3	7.8	645	483	465	441	bdl	595	3	6221	110		100	
7	29.3	6.8	7.3	7.9	595	418	371	641	bdl	873	6	5905	147		107	
8	28.7	6.9	7.2	7.8	596	498	457	663	bdl	864	13	6127	92		103	
9	29	6.9	7.3	7.7	596	467	411	712	bdl	973	3	5849	110		95	
10	29.4	6.9	7.2	7.7	600	514	444	808	bdl	1005	7	5849	73		103	
Series 2 summary																
Avg.	29.3	6.9	7.2	7.7	604	457	416					6	6060	198		103
±range	0.4	0.1	0.1	0.1	18	48	40					3	204			5

*A = First kalshi with tubewell water, coarse sand and iron chips; B = Second kalshi with wood charcoal and fine sand; C = Third kalshi i.e., collector for filtered water; bdl = below the detection limit of ASV technique (2 ppb).

TABLE 2
Redox Behavior of Water in Series-2 Experiments. Measurement of E_h and pH for Inflow and Outflow Water

Expt # Series 2	pH-in inflow	pH-out outflow	pe-in inflow	pe-out outflow	E_h-in inflow (mV)	E_h-out Outflow (mV)
1	6.8	7.8	4.9	7.5	290	441
2	6.7	7.8	5.0	6.8	295	402
3	6.9	7.6	6.6	7.5	387	441
4	6.8	7.6	5.6	7.5	334	441
5	6.7	7.7	5.6	7.3	334	432
6	7.1	7.8	7.0	7.7	412	456
7	6.8	7.9	6.0	9.7	353	573
8	6.9	7.8	6.6	7.7	392	456
9	6.9	7.7	6.1	7.5	358	446
10	6.9	7.7	6.0	7.6	353	451
Avg.	6.8	7.7	5.9	7.7	351	454
±range	0.12	0.1	0.67	0.75	39	45

TABLE 3
ICPAES Measurement of Metal Concentrations Before and After Filtration by 3-Kalshi Method

Element	Before (mg/L)	After (mg/L)
Aluminum, Al	0.031 ± 0.022	0.023 ± 0.011
Antimony, Sb	<0.013	<0.013
Arsenic, As *	0.130 - 1.16	<0.016
Barium, Ba	0.166 ± 0.006	0.063 ± 0.01
Beryllium, Be	<0.001	<0.001
Cadmium, Cd	<0.001	<0.001
Calcium, Ca	113 ± 2.5	59.1 ± 7.5
Chromium, Cr	<0.002	<0.002
Cobalt, Co	<0.002	<0.002
Copper, Cu	0.008 ± 0.001	0.005 ± 0.002
Iron, Fe	6.897 ± 0.110	0.084 ± 0.002
Lead, Pb	0.005	0.006 ± 0.002
Magnesium, Mg	21.67 ± 0.55	23.17 ± 3.29
Manganese, Mn	0.723 ± 0.017	<0.001
Molybdenum, Mo	0.002 ± 0.001	0.003 ± 0.001
Nickel, Ni	<0.002	<0.002
Potassium, K	2.23 ± 0.23	6.71 ± 1.31
Selenium, Se	<0.012	<0.012
Silver, Ag	<0.002	<0.002
Sodium, Na	19.5 ± 1.14	26.7 ± 3.15
Strontium, Sr	0.287 ± 0.01	0.164 ± 0.02
Thallium, Tl	<0.067	<0.067
Tin, Sn	0.006 ± 0.004	0.011 ± 0.008
Vanadium, V	<0.001	0.006 ± 0.003
Zinc, Zn	0.08 ± 0.11	0.009 ± 0.002

TABLE 4
Drinking water Inorganic Quality Parameters: Comparison of 3-Kalshi Water with those of USEPA, World Health Organization (WHO) and Bangladesh Standards ^a

Constituent	USEPA (MCL)	WHO, Guideline	Bangladesh	3-Kalshi water
Arsenic (total)- mg/L	0.05	0.01	0.05	0.003-0.018
Iron (total) - mg/L	0.3	0.3	0.3 (1.0)	0.08 - 0.49
pH	6.5-8.5	6.5-8.5	6.5-8.5	7.74 ± 0.1
Sodium - mg/L		200		26.7 ± 3.1
Calcium - mg/L			75 (200)	59.1 ± 7.5
Copper - mg/L	1.3	1.0 - 2.0	1.5	0.005
Manganese - mg/L	0.05	0.1 - 0.5	0.1 (0.5)	<0.001
Zinc - mg/L	5	3.0	5 (15)	0.01
Aluminum -mg/L	0.05-0.2	0.2	0.1(0.2)	0.03
Lead -mg/L	0.015	0.01	0.10	0.006
Chromium, mg/L	0.1	0.05	0.05	<0.002
Cadmium, mg/L	0.005	0.003	0.01	<0.001
Barium, mg/L	2.0	0.7	1.0	0.063 ± 0.01
Antimony, mg/L	0.006	0.005		<0.013
Molybdenum, mg/L		0.07		0.003
Nickel, mg/L	0.1	0.02		<0.002
Selenium, mg/L	0.05	0.01		<0.012
Silver, mg/L	0.1			<0.002
Chloride, mg/L	250	250	200 (600)	110 - 400
Total dissolved solids (TDS), mg/L	500	1000	500 (1500)	208

- a. Bangladesh standard values are given as maximum desirable concentration with maximum permissible concentration in parentheses. TDS for 3-kalshi was calculated from the conductivity data excluding silica present in the filtered water.

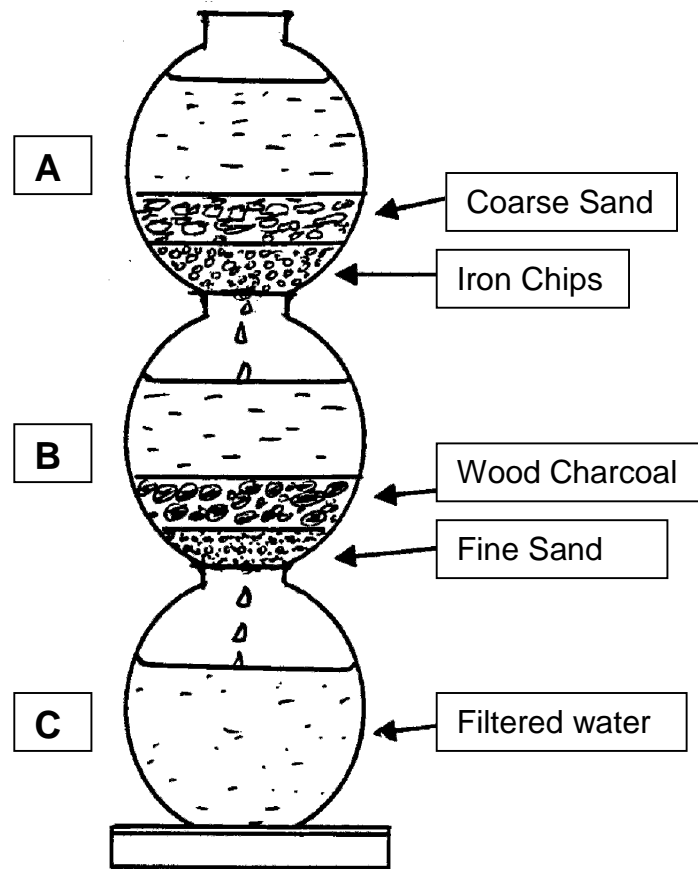
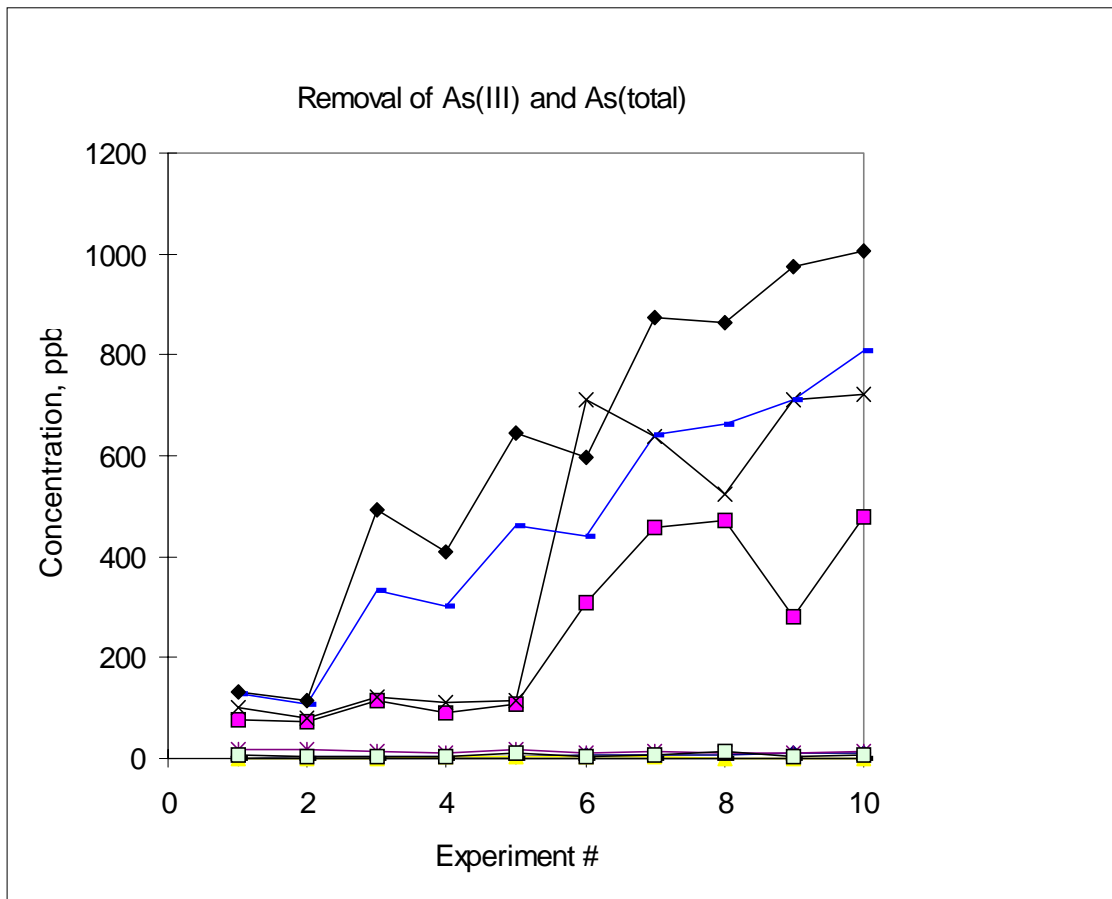


FIGURE 1
Schematic diagram of a 3-kalshi (pitcher) setup for water purification

**FIGURE 2***

Efficiency of arsenic removal by 3-kalshi method. Series 1 experiment: X - As(total), ■ - As(III). Series 2: ◆: As(total), - - As(III) for input water. The filtered water concentrations for both series of experiments are shown near zero, parallel to abscissa.

(*Figure 2 in the original publication is misplaced at page 1056 of the same issue. An errata is in press)

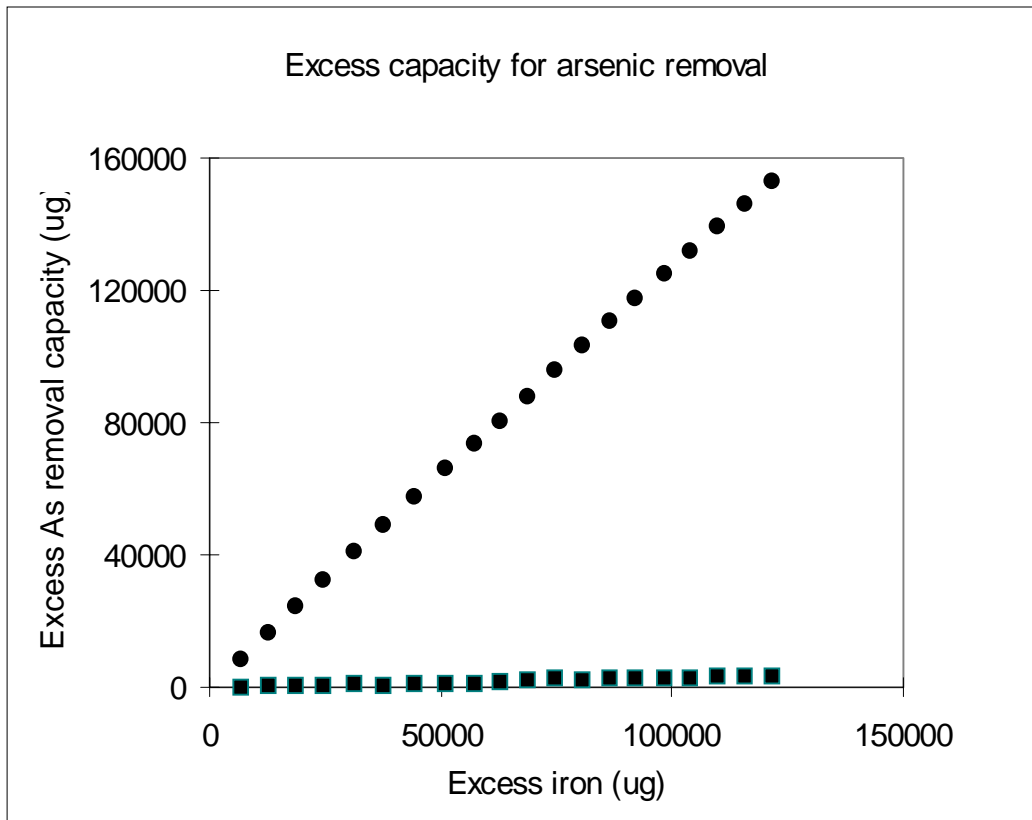


FIGURE 3

Plot showing excess capacity for arsenic removal by the 3-kalshi method. Capacity calculation is based on formation of (●) - $\text{Fe}(\text{AsO}_4)$, (■) - adsorption data.