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REMOVAL OF ARSENIC FROM GROUNDWATER BY FERRIC CHLORIDE

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ABSTRACT: Removal of arsenic from groundwater by coagulation with ferric chloride has been evaluated in batch sorption experiments. Removal of both As(V) and As(III) was found to increase with increasing coagulant (ferric chloride) dose. For higher coagulant doses, removal efficiencies appear to be independent of initial arsenic concentration. Removal efficiency of As(III) was found to be significantly lower than that of As(V). Removal of As(III) pre-oxidized with bleaching powder was found to be almost identical to that of As(V). However, poor quality and unstable nature of the locally available bleaching powder is a cause of concern in its use as an oxidant. It has been found that for a sorbate/sorbent ratio (expressed as µg/L As per mg/L Fe) of about 50 or less, removal efficiencies exceeding 95 percent could be achieved, irrespective of the initial arsenic concentration. This can serve as a guideline value or thumb rule for estimating required doses of ferric chloride for effective arsenic removal. Removal of As(V) was found to be maximum in the neutral pH range and slightly depressed at higher pH values, exceeding 8. Phosphate was found to have a dramatic effect on arsenic removal from groundwater. Removal of arsenic present at an initial concentration of 0.10 mg/L (and treated with 10 mg/L of ferric chloride) came down from 92 percent (in the absence of phosphate) to about 46 percent in the presence of 2 mg/L of phosphate. Since significant fraction of arsenic in the groundwater of Bangladesh exists as As(III), it appears that arsenic removal technology based on ferric chloride coagulation must involve a pre-oxidation step for converting As(III) to As(V). Results obtained from this study, enabled determination of ferric chloride dose required for achieving a particular removal goal for arsenic present at different initial concentrations. In view of the presence of elevated levels of iron in many regions of the country, arsenic removal by coagulated flocs of ferric hydroxide could be a very effective technique for use in Bangladesh.

KEYWORDS: Arsenic contamination, arsenic removal, coagulation-adsorption-coprecipitation, pre-oxidation.

INTRODUCTION

In recent years widespread arsenic contamination of groundwater has become a major concern for the hand tubewell based drinking water supply, particularly in the rural areas. Awareness about the presence of arsenic has been growing since late 1993 when arsenic was first detected in the district of Chapai Nawabgonj bordering the West-Bengal district of India. Since then higher levels of arsenic (exceeding the WHO standard of 0.01 mg/L and Bangladesh standard of 0.05

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mg/L) have been detected in many regions of the country (GoB-BGS-MMD, 1991). Affected areas and estimates of affected population are being updated as more data are becoming available. Out of 64 administrative districts of Bangladesh, arsenic contamination has so far been reported in 61 districts and an estimated 40 million people are at risk of arsenic toxicity. In a recent study by the National Institute of Preventive and Social Medicine (NIPSOM), arsenic related diseases (arsenicosis) have been identified in 37 districts (Ahmad et al., 1998). A total of 6000 cases were identified in 162 villages in the 37 districts, mostly in the rural areas. Among the identified patients, 53% were male, 47% female, and the most affected age group was found to be 20 - 40 years.

Arsenic toxicity has no known effective medicine for treatment, but drinking of arsenic free water can help the arsenic affected people to get rid of the symptoms of arsenic toxicity. There is an urgent need to ensure supply of arsenic free drinking water to the millions of arsenic affected people in Bangladesh. The options that are commonly suggested as possible alternatives to arsenic affected groundwater include: (1) Arsenic free deep tubewell water, (2) Surface water, (3) Rainwater harvesting, and (4) Treatment of groundwater for arsenic removal. While arsenic-free deep aquifers have been identified in some places, this option appears to be too expensive for large-scale use in rural areas. The principal problem with surface water is bacteriological contamination. In addition, availability of surface water is not uniform throughout the year. Rainwater harvesting can be a probable alternative. But seasonal variation in rainfall pattern, proper storage of rainwater and public acceptance are some of the issues that need to be addressed adequately. Groundwater treated for arsenic removal is another very promising option to provide arsenic-free water to the rural population. Since people are already accustomed to using groundwater and millions of tubewells are already there in the rural areas, this option can make use of this available infrastructure. It should be noted that only water used for drinking and cooking purposes need to be treated; so volume of water that need to be treated would not be very high.

Various technologies have been used for removing arsenic from groundwater. The most commonly used technologies include co-precipitation with alum or iron; adsorptive filtration (e.g., using activated alumina); ion exchange; and membrane processes such as reverse osmosis. Ion exchange and membrane techniques appear to be too expensive for large-scale use in Bangladesh. Apart from cost, both ion exchange and membrane techniques would require higher levels of technical expertise on the part of the user for operation and maintenance. Presence of high concentrations of iron in the groundwater, which precipitates as ferric hydroxide solids after extraction, would definitely interfere with the efficiency of membranes. Microbial processes are still at a development stage.

Removal of arsenic by coagulation-adsorption-coprecipitation and by adsorption appears to be the most promising techniques for use in Bangladesh. However, recent experiences with adsorptive filtration devices designed for arsenic removal suggest that high iron concentration in groundwater of Bangladesh, which clogs the filter media, is a particular concern for such systems. Co-precipitation based systems can be developed with simple and easily available chemicals and may be cost-effective for use in Bangladesh.

Coagulation is a widely used technique for removing inorganic contaminants (e.g., heavy metals) from water. By addition of a coagulant (such as ferric chloride or alum), soluble arsenic can be removed through adsorption (association of the dissolved contaminant with the surface of the coagulated flocs), occlusion (entrapment of adsorbed contaminants in the interior of the growing floc particle), and solid-solution formation (incorporation of the contaminant into the bulk phase, rather than only onto the surface of the flocs). The consistent behavior of arsenic in adsorption (using pre-formed Hydrous Ferric Oxide as the adsorbent) and coagulation (using ferric chloride as coagulant) studies indicates that adsorption is a dominant mechanism for arsenic removal by ferric chloride (Hering et al., 1996). Arsenic is primarily removed by adsorption onto coagulated flocs of amorphous ferric hydroxide, which are formed upon addition of ferric chloride solution to water.

Many studies have been conducted to determine the efficiency of arsenic removal by coagulants. Most work has focused on removal of arsenate [As(V)], the thermodynamically stable form of inorganic arsenic in oxic waters. Arsenite [As(III)] removal during coagulation with alum, ferric chloride, and ferric sulfate has been shown to be less efficient than As(V) removal under comparable conditions (Shen, 1973; Gulledge and O'Conner, 1973; Sorg and Logsdon, 1978). For As(V), better removal is achieved during coagulation with Fe(III) than aluminum salts on a weight basis (Shen, 1973; Gulledge and O'Conner, 1973; Sorg and Logsdon, 1978). Removal efficiency is affected by initial concentration of arsenic, pH, coagulant dosages, oxidation state of arsenic, sorbate/sorbent ratio and the concentration of co-occurring solutes in the solution. In general, higher removal efficiency can be achieved with increased coagulant dosages (Cheng et al., 1994; Edwards, ,1994; Gulledge and O'Conner, 1973) and oxidative transformation, that is converting As(III) to As(V) (Frank and Clifford, 1986). Hering et al. (1996) reported almost complete removal of As(V) at initial concentrations of up to 0.10 mg/L with $FeCl_3$ dose of 4.9 mg/L; however, removal of As(III) present at the same concentrations were significantly lower. Shen (1973) showed that addition of 15 mg/L of chlorine followed by coagulation with 30 mg/L of $FeCl_3$ reduced arsenic concentration (0.8 mg/L) to trace amounts in the treated water. In pilot scale studies, addition of about 20 mg/L of chlorine during aeration process followed by coagulation with $FeCl_3$ (about 60 mg/L), settling and filtration resulted in an effluent arsenic concentration below detection limit from an initial concentration of 0.8 to 0.9 mg/L (Shen, 1973).

Effect of pH on arsenic removal was investigated in a number of studies. Decreased removal of As(V) was observed above pH 8 for ferric chloride and above 7 for alum (Sorg and Logsdon, 1978; Edwards, 1994). These decreases are probably related to the pH dependence of both adsorption and solubility of amorphous iron (III) and aluminum hydroxides. Kartinen and Martin (1995) found efficient removal of As(V) with ferric sulfate between pH 6 and 8.5.

The presence of co-occurring inorganic and organic solutes has been found to influence the extent of arsenic adsorption onto oxide surfaces. Hering et al. (1996) reported slight decrease in As(V) removal in the presence of phosphate at relatively low concentration (about 0.76 mg/L). McNeille and Edwards (1997) also reported a slight decrease in As(V) removal in the presence of 0.032 mg/L phosphate. Phosphate has strong affinity for hydrous oxides of iron, manganese and aluminum and the adsorption characteristics of phosphate is very close to that of arsenate. Retention of arsenate and arsenite is therefore subjected to competition from phosphate (Livesey and Huang, 1981; Pierce and Moore, 1982). Decreased adsorption of As(V) on alumina in the presence of sulfate and on gibbsite in the presence of phosphate have been attributed to competition between these adsorbing species for adsorption sites on the oxide surfaces. Hering et al. (1996, 1997) reported only slight decrease in As(V) adsorption (during coagulation with 4.9 mg/L of $FeCl_3$) in the presence of very high concentration of sulfate (2.6 mM or about 250 mg/L). On the other hand, in case of As(III) removal, addition of the same amount of sulfate significantly reduced As(III) removal at pH 4 and 5 but had little effect at higher pH values. According to Hering et al. (1996) Calcium (at a concentration of 3 mM or about 120 mg/L) actually enhanced removal of As(V) at higher pH values. However, at concentrations normally encountered in the groundwater of Bangladesh, both sulfate and calcium are unlikely to have any significant effect on arsenic removal by ferric chloride. It is worth noting that Smedely et al. (1998) found a negative correlation between the presence of arsenic and sulfate in groundwater in some areas of Bangladesh. Besides, sulphate and calcium, silica can also influence adsorption of arsenic by competing for adsorption sites on ferric hydroxide flocs. However, data on competitive sorption of arsenic and silica are scarce. In Bangladesh, groundwater usually contains relatively high concentration of silica. Silica concentration in the groundwater samples used in this study was about 30 mg/L, which is typical of silica concentration in groundwater of Bangladesh. Chloride, at concentrations typical for groundwater in Bangladesh (except for the saline coastal zone), is not likely to influence adsorption of arsenic onto ferric hydroxide flocs. Bicarbonate is also unlikely to influence adsorption or removal of arsenic by ferric chloride.

In the presence of natural organic substances (i.e., fulvic acid), competitive effects resulting in decreased adsorption of As(V) on alumina have been observed, though the extent of competition varied markedly with pH, solid-solution ratio, and fulvic acid concentration (Xu et al., 1991). In coagulation tests with groundwater containing different concentrations of total organic carbon (TOC), As(V) was less efficiently removed by both ferric chloride and alum from the organic-rich groundwater and the effect was most pronounced at lower coagulant doses (Chang et al., 1994). Data on the presence of organic matter in the groundwater of Bangladesh are not available. In general, organic matter concentration in groundwater is usually low and it is unlikely to play a significant role (resulting from competitive effects) in the removal of arsenic from groundwater by ferric chloride.

Although significant work has been done on removal of arsenic by ferric chloride, majority of the reported work used low initial concentrations of arsenic (often less than 0.10 mg/L). In many studies synthetic water, rather than actual groundwater, was used. In view of the reported higher concentrations of arsenic in Bangladesh, effectiveness of ferric chloride in removing arsenic from groundwater need to be tested for arsenic concentrations typical of those reported in Bangladesh. The level of treatment achievable for higher initial arsenic concentration is also important since the World Health Organization (WHO) has already reduced its recommended guideline value for arsenic in drinking water from 0.05 mg/L to 0.01 mg/L. The limit is currently under review in a number of other countries and such a revision of arsenic standard may also be forthcoming in Bangladesh. Effects of source water composition (e.g., pH, PO_4) on arsenic removal by ferric chloride also needs to be evaluated keeping in view the typical composition of groundwater in Bangladesh.

The major objectives of this research work (Chowdhury, 1999) were: (1) to evaluate the removal efficiency of arsenate [As(V)] and arsenite [As(III)] by coagulation with ferric chloride; (2) to evaluate the effects of various parameters (i.e., initial arsenic concentration, sorbate/sorbent ratio) on arsenic removal; (3) to evaluate the effect of pre-oxidation of arsenite (to arsenate) on its removal; (4) to evaluate the effect of source water composition, especially effect of pH and phosphate, on arsenic removal by ferric chloride.

MATERIALS AND METHODS

Efficiency of $FeCl_3$ in removing As(V) and As(III) from groundwater was evaluated in a series of jar tests. All jar tests were conducted in 1 L glass beakers using arsenic-free groundwater spiked with As(V) and As(III) standard solutions. The arsenic-free groundwater was collected from the groundwater supply at Bangladesh University of Engineering and Technology (BUET), Dhaka. As(V) stock solution was prepared by dissolving its sodium salt $Na_2HAsO_4.7H_2O$ in distilled water, while As(III) stock solution was prepared by dissolving arsenic trioxide (As_2O_3) in distilled water containing sodium hydroxide (NaOH). Required quantity of As(V) or As(III) stock was added to the beakers to achieve the desired initial arsenic concentrations. Ferric chloride stock solution (prepared by dissolving $FeCl_3.6H_2O$ to distilled water) was then added to the beakers to achieve iron concentrations ranging from about 1 to 25 mg/L. No attempt was made to adjust pH of the samples. The beakers were then subjected to 1 minute of rapid mixing, 15 minutes of slow mixing, and the flocs were then allowed to settle for 30 minutes. Clear supernatant samples were then collected using a pipette from about 2 cm below the liquid surface. The supernatant samples were analyzed for arsenic and iron concentrations. In the jar tests, initial pH of groundwater and final pH after coagulation were recorded. To evaluate the effect of pH, pH adjustments were made with sodium hydroxide or hydrochloric acid solutions in similar experiments. Effects of phosphate on arsenic [As(V)] removal were also evaluated in similar experiments where the beakers were spiked with standard solution of potassium dihydrogen phosphate to attain desired phosphate concentration. In all cases, removal of arsenic was calculated by subtracting arsenic concentration in the clear supernatant from the initial concentration. Concentration of iron present as ferric hydroxide flocs was calculated by subtracting the residual iron present in the supernatant solution from the iron added to water as ferric chloride. Arsenic concentrations were measured using Silver Diethyldithiocarbamate Method (AWWA, 1985). Iron concentrations were determined by colorimetric method (potassium thiocynate method). Detailed characterization of groundwater used in this was carried out by analyzing it for pH, conductivity, alkalinity, hardness, chloride, phosphate, nitrate, sulfate, iron, manganese, calcium, magnesium, sodium and potassium.

RESULTS AND DISCUSSION

Effects of Coagulant Dose and Initial Arsenic Concentration

Figure 1 shows removal of As(V) as a function of iron (used as ferric chloride) dose for three different initial arsenic concentrations - 0.10, 0.25, and 0.50 mg/L. These concentrations are typical of arsenic concentrations reported for groundwater in Bangladesh. Figure 1 shows that removal of As(V) increases with increasing coagulant (or iron) dose. At lower coagulant (or iron) doses, removal efficiency appears to decrease with increasing As(V) concentration. For higher coagulant (or iron) doses, removal efficiencies appear to be independent of initial arsenic concentration. At coagulant (or iron) dose beyond 25 mg/L of ferric chloride (or 5.165 mg/L of iron), removal efficiencies exceeding about 95 percent were achieved for all three initial concentrations of As(V). Similar effects can also be observed for pre-oxidized As(III) as shown in Fig. 2 . Thus it appears that for higher coagulant (or iron) doses, removal is independent of initial arsenic [As(V) or pre-oxidized As(III)] concentration. This result can be explained by the Langmuir expression, which indicates that as long as the surface sites are not saturated by adsorbed As (or any other adsorbate), the percent of arsenic (or adsorbate) removed for a given coagulant dose is independent of the initial As (or adsorbate) concentration (Hering et al., 1996). Result from this study is also consistent with the observations of As(V) removal from source water by ferric chloride in modified jar tests (Cheng et al., 1994) and with previous studies of As(V) removal from synthetic waters by ferric chloride (Hering et al., 1996). At lower coagulant (or iron) dose, arsenic removal appears to be limited by the availability of adsorption sites.

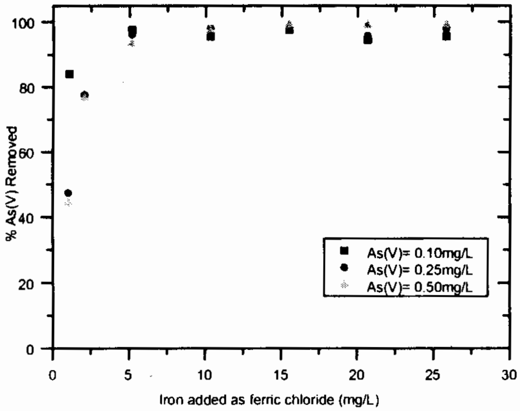

Fig 1. Removal of As(V) as a function of iron dose (added as ferric chloride)

Effects of Pre-oxidation on Removal Efficiency of As(III)

Figure 2 shows removal of As(III), pre-oxidized As(III) and As(V) for an initial concentration of 0.25 mg/L as a function of iron (added as ferric chloride) dose. This figure shows that although removal of As(III) increases with increasing coagulant (i.e., iron) dose, removal efficiency of As(III) is far less than that of As(V). Lower removal efficiency of As(III) compared to As(V) was observed in a number of other studies (e.g., Shen, 1973; Jekel, 1986; Edwards, 1994; Hering et al., 1996, 1997). Figure 2 shows that even with a iron dose as high as 25.83 mg/L (i.e., ferric chloride dose of 125 mg/L), removal efficiency approaching only 80% could be achieved.

In this study, pre-oxidation of As(III) to As(V) was performed with bleaching powder. Bleaching powder is a common disinfectant and is widely used in Bangladesh. Chlorine in bleaching powder can oxidize As(III) to As(V) according to the following reaction:

$$H_2AsO_3 + HOCl = HAsO_4^{2-} + Cl^- + 3H^+ \qquad (1)$$

Commercial bleaching powder available in the local market with chlorine content varying from about 15% to 35% (on a weight basis) was used in this study. From stoichiometric consideration (Eq. 1), about 0.47 mg/L of chlorine is required for oxidation of 1mg/L of arsenic. In this study, jar tests were conducted with chlorine dose 3 to 4 time that calculated from stoichiometric consideration. This was done partly due to possible presence of unknown reducing constituents and partly due to the very unstable nature of commercial bleaching powder. Figure 2 shows that pre-oxidation with bleaching powder significantly improved removal efficiency of As(III). As shown in Fig. 2, removal of As(V) and pre-oxidized As(III) are almost identical. This probably suggests that complete oxidation of As(III) to As(V) was achieved by commercial bleaching powder within the time frame of the experiments, i.e., about 45 minutes. Very efficient removal of pre-oxidized As(III) even at concentrations as high as 2.0 mg/L suggest that commercial bleaching powder can effectively oxidize As(III) to As(V). However, poor quality and unstable nature of bleaching powder is a major concern in this regard.

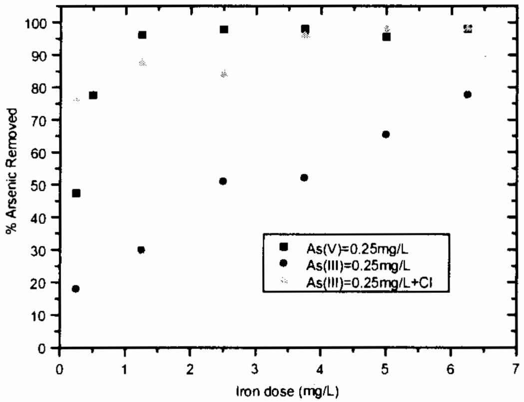

Fig 2. Removal of As(V), As(III) and pre-oxidized As(III), present at an initial concentration of 0.25 mg/L, as a function of ion dose.

Effects of Sorbate/Sorbent Ratio and Adsorption Density

Figure 3 shows removal efficiency of As(V) as a function of sorbate/sorbent ratio (expressed as µg/L As per mg/L Fe). From Fig. 3 it appears that for a sorbate/sorbent ratio of about 50 or less, removal efficiencies exceeding 95 percent can be achieved, irrespective of the initial As(V) concentration (for a initial arsenic concentration of up to 0.50 mg/L). This result gives the adsorption capacity of ferric hydroxide flocs (formed upon coagulation with ferric chloride) at the optimum sorbate/sorbent ratio. This sorbate/sorbent ratio can serve as a guideline value or thumb rule for estimating required doses of ferric chloride for effective arsenic removal. No such trend could be observed for As(III).

Figure 4 shows adsorption density (expressed as µg As/ mg Fe) as a function of iron dose (added as ferric chloride) dose for three different As(V) concentrations. For a fixed arsenic concentration, as iron concentration increases, adsorption density decreases. With increasing iron concentration, adsorption density is decreased because of the increasing number of adsorbent sites. A maximum adsorption density of about 353 µg As/mg Fe was achieved with a As(III) (pre-oxidized) concentration of 2.0 mg/L and ferric chloride concentration of 25 mg/L.

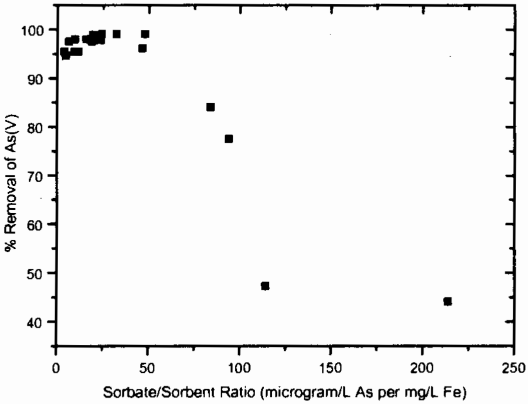

Fig 3. Removal of As(V) as a function of sorbate/sorbent ratio (expressed as µg/L As per mg/L Fe)

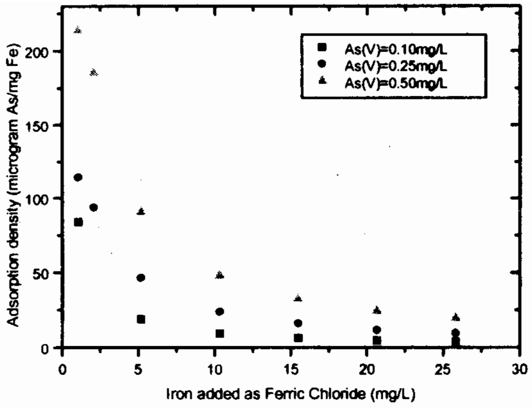

Fig 4. Adsorption density of arsenic (μg As/ mg Fe) as function of iron dose (added as ferric chloride)

Requirement of Ferric Chloride

Figure 5 shows requirement of ferric chloride to attain a residual arsenic concentration of 0.05 mg/L for different initial arsenic (arsenate and pre-oxidized arsenite) concentrations. Figure 5 shows that for an initial arsenic concentration of 0.1 mg/L, a ferric chloride dose as low as 5 mg/L can bring down the arsenic concentration below the Bangladesh standard of 50 μg/L. On the other hand, for an initial arsenic concentration of 0.5 mg/L, a ferric chloride dose of 25 mg/L is required. The corresponding requirements for satisfying the WHO guideline value of 10 g/L are 25 mg/L and 75 mg/L, respectively. It is apparent that ferric chloride requirement for satisfying the WHO guideline value is significantly higher that required for satisfying the Bangladesh standard.

Effects of pH and Phosphate

Figure 6 shows the influence of pH on the removal of As(V) at an initial concentration of 0.25 mg/L with 25 mg/L of ferric chloride. From this figure removal of arsenic appears to be maximum in the neutral pH range (close to 95% at a pH of about 7) and slightly depressed both at higher and lower pH values. This result is consistent with those reported in the literature (e.g., Sorg and Logsdon, 1978; Hering et al., 1997).

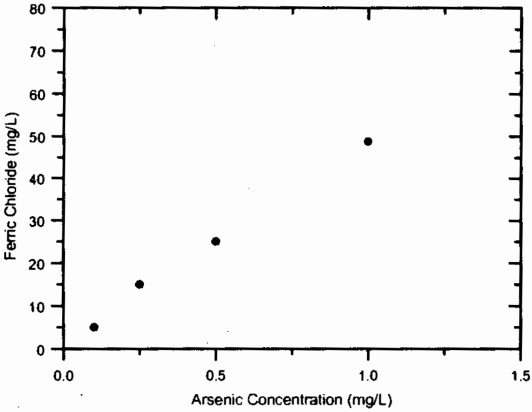

Fig 5. Requirement of ferric chloride for attaining a residual As concentration of 0.05 mg/L for different initial arsenic concentration

Figure 7 show the influence of phosphate on removal of As(V) present at an initial concentration of 0.10 mg/L by 10 mg/L of ferric chloride. Figure 7 shows a steady decrease in As(V) removal with increasing phosphate concentration. For example, phosphate present at 2.0 mg/L reduced arsenic removal from more than 90 percent (in the absence of phosphate) to about 46 percent; while at a phosphate concentration of 5.0 mg/L, removal came down to about 37 percent.

The effect of phosphate on As(V) removal observed in this study are much more dramatic than those observed by Hering et al.(1996) and McNeille and Edwards (1997). This is probably due to the fact that both Hering et al.(1996) and McNeille and Edwards (1997) used very low concentrations of phosphate (0.076 mg/L and 0.32 mg/L, respectively); while phosphate concentration used in this study ranged from 1.0 to 10.0 mg/L. It is worth mentioning that relatively high concentrations of phosphate, reaching as high 5.8 mg/L, have been found in some places of Bangladesh (Ali et al., 1997).

CONCLUSIONS

In Removal of both As(V) and As(III) was found to increase with increasing coagulant dose. At lower coagulant (ferric chloride) dose, arsenic removal appears to be limited by the availability of adsorption sites. For higher coagulant doses, removal efficiencies appear to be independent of initial arsenic concentration. Removal efficiency of As(III) was found to be significantly lower than that of As(V). However, removal efficiencies of As(V) and As(III), pre-oxidized with bleaching powder, were found to be almost identical. Since significant fraction of arsenic in the groundwater of Bangladesh can exist as As(III) (Smedely et al., 1998; Safiullah et al., 1998), it appears that arsenic removal technology based on ferric chloride coagulation must involve a pre-oxidation step for converting As(III) to As(V). Although commercial bleaching powder was found to be very effective for pre-oxidation of As(III), the unstable nature of bleaching powder is a cause of concern in its use as an oxidant.

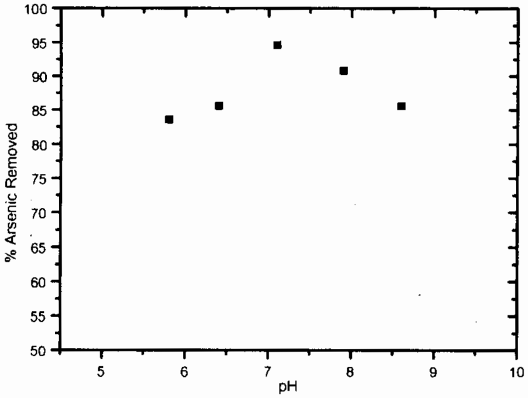

Fig 6. Effect of pH on removal of As(V) present at an initial concentration of 0.25 mg/L with 25 mg/L of ferric chloride

Results obtained suggest that for a sorbate/sorbent ratio (expressed as µg/L As per mg/L Fe) of about 50 or less, removal efficiencies [for As(V) and pre-oxidized As(III)] exceeding 95 percent can be achieved, irrespective of the initial As(V) concentration (for a maximum initial concentration of 0.50 mg/L). This can serve as a guideline value or thumb rule in estimating required dose of ferric chloride for effective arsenic removal. It was found that for a fixed arsenic concentration, as iron concentration increases, adsorption density decreases.

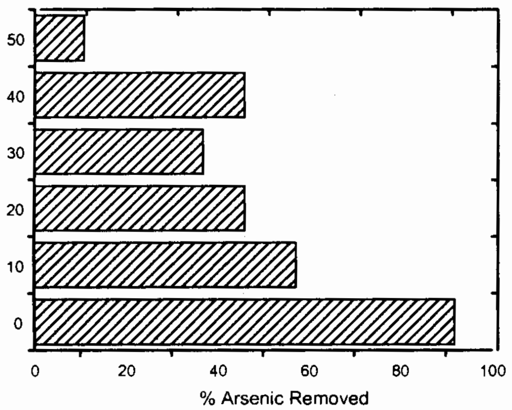

Fig 7. Effect of phosphate on removal of As(V) present at an initial concentration of 0.10 mg/L with 10 mg/L of ferric chloride

Removal of As(V) appears to be maximum in the neutral pH range and slightly depressed at higher pH values, exceeding 8. Reduction of adsorption at higher pH values is likely to be more pronounced at higher sorbate/ sorbent ratios. Since pH of groundwater usually falls between 6 and 8 in Bangladesh, pH is not likely to play a major role in determining the removal of arsenic from groundwater by ferric chloride.

Phosphate appears to have a dramatic effect on arsenic removal from groundwater. Arsenic removal was found to decrease significantly with increasing concentration of phosphate, which competed for adsorption sites on ferric hydroxide flocs. Apart from its influence in the removal of arsenic from groundwater, phosphate can play an important role in the mobilization of arsenic by promoting desorption of arsenic from iron oxyhydroxide in the subsurface environment. The principal source of phosphate in groundwater of Bangladesh is the phosphate fertilizer used in agriculture. More study is needed to understand the geochemistry of arsenic release in the subsurface and the role of phosphate, if any, in the mobilization process.

It was found that ferric chloride requirement for satisfying the WHO guideline value (10 µg/L) was significantly higher than that required for satisfying the Bangladesh standard of 50 µg/L. Thus the cost of arsenic removal by ferric chloride would depend on the water quality standard it is designed for. This is important in view of the fact that a number of countries have already reduced the safe limit of arsenic in drinking water and Bangladesh will also have to deal with this issue in the near future. Results from this study suggest that while ferric chloride can reduce arsenic concentrations (present at initial concentrations typical of those found in Bangladesh) below the current WHO guideline of 10 µg/L, a much higher dose of the coagulant is needed to achieve that goal. This will in turn significantly increase the cost of removal and will also add to the sludge problem.

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