



Technologies for Removal of Arsenic from Water: An Overview

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ABSTRACT

Arsenic contamination in drinking water is a major global issue. Arsenicosis may be caused due to chronic consumption of arsenic-contaminated water. Economical and convenient removal of arsenic from water has remained a great challenge. The most commonly employed technologies for the removal of arsenic from water are coagulation and flocculation, filtration, membrane separation, ion exchange and adsorption. Nanotechnology has the potential to play an important role in providing clean water for human utilization. Solar oxidation and removal of arsenic (SORAS) is a very simple technique to bring down arsenic content from contaminated water.

Keywords: Oxidation; Coagulation and Flocculation; Precipitation; Ion Exchange; Membrane Separation; Adsorption; SORAS.

1. INTRODUCTION

Groundwater is one of the most crucial natural resources for domestic, industrial as well as agricultural water supply. The natural occurrence of arsenic in groundwater is one of the biggest problems in providing safe drinking water globally. Arsenic is one of the most toxic elements in the environment and causes the highest number of morbidity and mortality worldwide (Cullen *et al.* 1989; Hudson-Edwards *et al.* 2004; Dermatas *et al.* 2004). According to World Health Organization, the permissible limit for arsenic is 10 µg/L in drinking water and 0.10 mg/L in irrigation water. Many Asian countries, including India, China, Myanmar, Pakistan, Vietnam, Nepal and Cambodia, have been found to have arsenic concentrations beyond permissible limits. In India, the extent of groundwater arsenic contamination in West Bengal has reached an alarming condition, as nine districts of West Bengal have been reported to have groundwater arsenic concentrations above 50 µg/L, and several people have been affected by arsenic poisoning - excessive and long-term ingestion of harmful inorganic compounds by humans. Arsenicosis, which is caused by arsenic in drinking water and food, can cause skin problems, skin cancers, internal cancers, diseases of the blood vessels of the legs and feet, diabetes, high blood pressure and fertility problems. Several natural and anthropogenic sources have been found to be responsible for arsenic contamination in groundwater. The main anthropogenic sources include mining, burning of fossil fuels, use of fungicides, herbicides and insecticides in agriculture and wood preservatives.

2. TECHNOLOGIES FOR ARSENICAL REMOVAL

Arsenic removal technologies should be such that they do not cause any adverse effect on the environment. Extensive research has been carried out to identify new technologies for arsenic removal. The presence of high-concentration arsenic-contaminated water sources can be analyzed in two distinct stages. The first stage consists of finding safe alternative sources with very low or no arsenic concentration and having acceptable physical, chemical and bacteriological quality. The second stage consists of adopting arsenic removal considering the presence of arsenite in the water source. The judicious selection of the most adequate alternatives should be based on a cost-benefit analysis conducted for each of the possible removal techniques. Coagulation-filtration and softening with lime addition techniques have been found to be cost-effective but are less efficient processes. Among the efficient techniques (with efficiency >95%), adsorption using aluminum carbonates was found to be cost-effective. The application of hybrid adsorbent can also be considered for arsenic removal because it is environment-friendly as well as cost-effective. Despite its effectiveness, the use of membranes for arsenic removal significantly increases the cost; hence it becomes unsustainable for small water supply systems. Research has also been carried out for the improvement of existing conventional technologies such as adsorption (Mohan *et al.* 2007) by modifying or using novel adsorbent materials (Pena *et al.* 2005; Boddu *et al.* 2008), or by introducing new chemical oxidation processes.

2.1 Physical-Chemical Technologies

Most of these technologies rely on the oxidation of arsenite followed by filtration through a porous material, where arsenic is removed through adsorption and co-precipitation.

TiO₂ immobilization, combined with co-precipitation of arsenic on iron (III) hydroxides (oxides), could be a competent approach for the removal of inorganic arsenic from water (Fostier *et al.* 2008). Because of their very strong affinity for arsenic, iron compounds are used by many removal systems. Recently research was carried out to arrive at a suitable iron to arsenic ratio in water to reduce arsenic to 5 ppb (or lower) through slow sand filtration. It was found that a ratio of 40:1 was necessary to ensure the desired arsenic concentration in the treated effluent (Pokhrel *et al.* 2009).

2.1.1 Oxidation

Arsenic occurs in groundwater as arsenite, As(III), and arsenate, As(V). Most of the arsenic treatment technologies are effective in removing arsenate, but the removal efficiency of arsenite is very low. Therefore, some treatment technologies include oxidation as a pre-treatment step to convert As(III) to As(V). In developing countries, atmospheric oxygen, hypochlorite and permanganate are commonly used for the oxidation of arsenic. Some other chemicals such as gaseous chlorine, ozone, and other oxidizing agents can also be used, which are capable of oxidizing rapidly.

2.1.2 Coagulation-flocculation

Coagulation is a conventional water treatment method used effectively for arsenic removal. In this method, coagulants (e.g., alum or ferric chloride) are added with rapid mixing, which results in the formation of micro-flocs. This is followed by gentle stirring for a few minutes (flocculation), resulting in the formation of larger settleable flocs. During the coagulation-flocculation process, arsenic also gets attached to the flocs. Subsequently, sedimentation and filtration (co-precipitation) are used to separate the flocs.

The procedure consists of three steps: moderate alkaline pH conditioning with NaHCO₃; oxidation of arsenite and ferrous ions with KMnO₄; and removal of arsenite and ferrous ions with KMnO₄. For simultaneous removal of arsenic and iron ions from water, self-precipitation as insoluble MnO₂ under pH conditions and coagulation with FeCl₃ have been used. The process removes iron, arsenic as well as other heavy metals, if present, without leaving any further toxic residue (Bordoloi *et al.* 2013). The process, which uses NaHCO₃, KMnO₄ and FeCl₃ as pH conditioners, oxidants and coagulants, respectively, and is based on Oxidation-Coagulation-adsorption at Optimized pH (OCOP); it is a competent and low-cost method for removing arsenic

from groundwater that has been gaining acceptance in India. In this method, a high dose of the oxidant is used when the groundwater contains a high concentration of coexisting iron for oxidizing all ferrous and arsenate ions. A field trial at different arsenic-affected rural areas has shown that the modified OCOP method is more efficient and reasonably priced than the OCOP method reducing both arsenic and co-existing iron concentrations (Bora *et al.* 2016).

2.1.3 Coagulation–flocculation–precipitation followed by Filtration

Ferric chloride is a preferred coagulant (Hu *et al.* 2012) due to its availability, low cost and low-risk usability (Hering *et al.* 1996). Arsenate and arsenite can form surface complexes with iron hydroxide sites in co-precipitated and adsorbed solids (Meng *et al.* 2000).

In electrocoagulation, electric current is used to generate metallic ions. The ions generated during the process polymerize rapidly and form precipitates with a high affinity for arsenic (van Genuchten *et al.* 2012; Mohora *et al.* 2012). Electrocoagulation is a promising approach and has gained much awareness for arsenic removal (Gomes *et al.* 2007; Balasubramanian *et al.* 2009; Kobya *et al.* 2011; Lacasa *et al.* 2011).

2.2 Membrane-based Processes

Membrane techniques like reverse osmosis, nanofiltration and electro-dialysis are capable of removing all kinds of dissolved solids, including arsenic, from water. In this process, water is passed through special filter media, capable of physically retaining the impurities in water. The oxidation from arsenite to arsenate is essential for carrying out nano-filtration and reverse osmosis. In a typical Donnan dialysis process, separation is based on an ion-exchange membrane. This ion exchange membrane separates two solutions (feed and stripping solutions) and excludes co-ions (ions with the same electrical charge as the ion exchange membrane) from permeating the membrane. Therefore, the flux of a counter-ion (ions with the opposite electrical charge to the ion exchange membrane) through the membrane caused by a concentration difference is always coupled with the transport of identical numbers of counter-ions in the opposite direction to maintain the electro-neutrality in both solutions (Sarkar *et al.* 2010). Anion-exchange membranes are required to remove arsenic from the feed solution, and an anionic counter-ion (most of the time, chloride) has to be present in the stripping solution. Several Donnan dialysis-based arsenic removal processes have been tested and they have demonstrated the feasibility and ease for implementation (Zhao *et al.* 2010; Velizarov *et al.* 2013).

Membrane distillation is another innovative technology based on membranes, which has been studied for arsenic removal. This process is based on a non-

conventional technology and can be a feasible alternative to water with high arsenic content. The process operates in the temperature range of 40-80 °C and can be powered by heat generated from waste processes or low-grade renewable heat sources (Yarlagadda *et al.* 2011). The arsenic removal rates of over 99.7% have been reported (Qu *et al.* 2009; Pal *et al.* 2010), which is much better than other reported membrane filtration techniques like nano-filtration and ultra-filtration (Zwijnenberg *et al.* 2005).

2.3 Ion Exchange

Ion exchange is very effective, when As (V) is predominant in water. Otherwise, a pre-oxidation step is necessary. Arsenic removal is done by passing water under pressure through columns packed with strong-base anion (SBA) exchange resin. These resins are insensitive to pH in the range 6.5 to 9. The net surface charge of ions determines their exchange affinity. As a result, the efficiency of the anion exchange mechanism for removing As (V) is affected by the accumulation of other anions including sulphate and nitrates. Synthetic ion exchange resins are used in water treatment to remove undesirable ions. Various anion exchange resins capable of removing arsenic (arsenate) concentrations below 1 mg/L are commercially available.

High-efficiency Ion Exchange for Arsenic Removal treatment system is a commercially available technology capable of removing arsenic to non-detectable levels in drinking water. It can also remove other harmful contaminants such as nitrates, perchlorate, uranium, chromium VI and vanadium to non-detectable levels.

2.4 Adsorption

Adsorption is becoming more common as a means of removing toxins from water. In the years 1900-1901, modern activated carbon industrial manufacturing was developed to replace bone-char in sugar refining. In the early 19th century, powdered activated carbon was first commercially manufactured from wood in Europe, and it was commonly used in the sugar industry. Coconut shells, wood char, lignin, petroleum coke, bone char, peat, sawdust, carbon black and other materials have been used to make activated carbons. Adsorption potential is affected by the properties of activated carbon, the chemical properties of the adsorbate, temperature, pH, ionic strength and other factors.

The low-cost adsorbents can be obtained from various sources. Some of the commonly used low-cost adsorbents include agricultural wastes, industrial wastes, biomass, human hairs, chitin and chitosan, commercial adsorbents and biosorbents. Agricultural wastes are by-products, currently un-used or under-used for animal feed. Agricultural waste/by-products such as rice husks

were used for arsenic removal from water (Khalid *et al.* 1998).

Red mud has been explored as an alternate adsorbent for arsenic removal. Heat and acid treatments on red mud increased its adsorptive capacity. Arsenic adsorption on acid and heat-treated red mud is also pH-dependent (Soner Altundoğan *et al.* 2000).

A large number of commercial adsorbents are now available for the removal of As (III) and As (V). The fungus, *Penicillium purpurogenum*, has been examined for cadmium, lead, mercury and arsenic removal from water. Chitosan powder derived from shrimp shells was converted into beads and used for removal of As (III) and As (V) from water in both batch and continuous operations (Chen *et al.* 2006). Biomass-derived from the stem of *Acacia nilotica* has been found to remove As ions from surface water samples of different origins like lake, canal and river (Baig *et al.* 2010). The effects of various parameters *viz.* pH, biosorbent dosage, contact time and temperature on the biosorption processes were studied. The percent removal of As increased up to 95% when the dosage of biosorbent material was increased from 0.4 to 4 g/L, whereas a further increase in biosorbent material dosage up to 20 g/L had no effect on the percent removal of As. The increase in biosorbent material dosage (0.4–4 g/L) resulted in a rapid increase in the adsorption of As ions.

Iron is by far the most recurrent metal present in the sorbents. Iron oxides and oxy-hydroxides have been reported as effective sorbents for arsenic removal (Bowell *et al.* 1994). Some prepared iron oxide-based sorbents are commercially available and have been successfully employed for arsenic removal (Ahmed *et al.* 2018). More advanced and sophisticated options include nanotechnology for the production of nanocomposites. Arsenic removal by zero-valent iron (ZVI) is a distinguished process based on the adsorptive properties of the compounds generated by the corrosion of ZVI in water (Lackovic *et al.* 2000; Lien *et al.* 2005; Ye *et al.* 2011; Calo *et al.* 2012; Eslamian *et al.* 2013).

The removal of arsenic from water by zeolites is well-reported (Shevade *et al.* 2004; Misaelides *et al.* 2011), but recent efforts have been focused on modifying their surface properties. Among all the possible alternatives for these modifications, the use of surfactants has gained application (Yusof *et al.* 2009; Swarnkar *et al.* 2012).

Titanium dioxide-based materials are well-known for arsenic photocatalytic oxidation and adsorption, but some future needs for this technology have been proposed, including the reduction of the treatment cost, the decrease in the operational complexity of the technology or the disposal of the arsenic-bearing treatment wastes (Guan *et al.* 2012).

2.5 Biological Technologies

Biological processes can play an important role in enhancing many of the chemical processes. Biological and microbiological methods have been found to be environment-friendly and cost-effective for arsenic removal. Two major biological mechanisms can describe the reduction of arsenate into arsenite. The first mechanism is related to the detoxification of the cells. Arsenate ions enter the cells *via* phosphate transporters due to structural homologies with phosphate ions. After reaching the cytoplasm, As (V) is reduced into As (III) by the enzyme before being excreted from the cell (Wang *et al.* 2012). The second process, known as dissimilatory ArsC reduction, has been described in bacteria belonging to various phylogenetic groups, including obligate or facultative anaerobic micro-organisms (Páez-Espino *et al.* 2009). Biosorption is capable of removing traces of heavy metals and other elements from dilute aqueous solutions. It is crucial to distinguish between biosorption and bio-accumulation.

The passive immobilization of metals by biomass is known as biosorption (or bio-adsorption). Cell surface sorption mechanisms are founded on physico-chemical interactions between metal and functional groups of the cell wall and are independent of cell metabolism. Polysaccharides, lipids and proteins make up the microorganism's cell membrane, which has numerous metal binding sites. Metal binding is a swift mechanism that is independent of metabolism. Bioaccumulation, on the other hand, is a phenomenon that entails metal binding on intracellular compounds, intracellular precipitation, methylation and other processes. Bioaccumulation can also be thought of as a second stage in the metal sequestration mechanism carried out by living biomass. It is also known as aggressive biosorption, which is the polar opposite of passive biosorption. It can be blocked by metabolic inhibitors such as low temperature and a lack of energy sources because it is dependent on cell metabolism. The passive mode is used for metal absorption by dead cells. For heavy metal absorption, living cells use both active and passive modes. Many industrial fermentation methods use fungi, which could act as a cost-effective adsorbent for arsenic removal. Fungi can also be efficiently grown in large quantities using simple fermentation methods and low-cost growth media. Lignin has also been used to remove metal ions.

The biological oxidation of As (III) to As (V) by iron and manganese-oxidizing bacteria have been reported and it has been confirmed that As (III) could be mitigated without any additional use of chemicals (Casiot *et al.* 2003).

Anaerobic microorganisms play an important role in the release of arsenic in iron-rich aquifers, where arsenic is typically sequestered by iron minerals. New

developments in the biotechnological field have focused on phyto-remediation and bio-filtration processes (Katsoyiannis *et al.* 2004; Murugesan *et al.* 2006) which were found to be efficient and environmentally sustainable. In phytoremediation, plant and fungal biomass are used as a renewable adsorbing material in a process that is similar to chemical compound removal. The adsorbing capacity of this biomass is superior to that of activated carbon and some synthetic resins used in water treatment.

The application of biological processes for the removal of arsenic from water is an emerging field that shows great potential, mainly because it is an environmentally compatible treatment option (Li *et al.* 2013). Biological activity can remove arsenic by various different mechanisms such as sorption, biomethylation-demethylation, complexation, co-precipitation or oxidation-reduction processes. Besides, a diversity of organisms shows potential for its application for arsenic removal, including bacteria (Fukushi *et al.* 2003; Zouboulis *et al.* 2005) fungi (Tani *et al.* 2004), yeasts and algae (Cherian *et al.* 2005; Hansen *et al.* 2006; Dickinson *et al.* 2009; Shen *et al.* 2012; Sulaymon *et al.* 2013), lichens (Huang *et al.* 2004; Cherian *et al.* 2005; Dickinson *et al.* 2009) and complex biological communities as constructed wetlands (Buddhawong *et al.* 2005; Lizama A. *et al.* 2011; Arroyo *et al.* 2013; Llorens *et al.* 2013) or even waste biomass (Teixeira *et al.* 2005; Czerniczyniec *et al.* 2007).

Constructed wetlands have been employed extensively around the world during the last decades for improving water quality, including the removal of heavy metals. The main removal pathways of As in constructed wetlands are biologically-mediated precipitation, co-precipitation and sorption, but the importance of plants and microorganisms present in the medium also needs to be assessed (Zurita *et al.* 2012).

Biological methods are efficient in the treatment of arsenic-contaminated waters but, until now, most biotechnological treatments for arsenic removal have only been investigated in laboratory studies under well-defined conditions. Further full-scale demonstrations are required to demonstrate their technical viability in more complex real systems; the corresponding cost-effectiveness analysis needs to be conducted to assess their applicability (Wang *et al.* 2009). Human hairs' propensity to adsorb arsenic from polluted drinking water was investigated by Wasiuddin *et al.* (2002). Human hairs have been tested as an adsorbent in both static and dynamic simulations, as well as computational simulation. At a 360 g/L arsenic concentration, the maximum adsorption potential of 12.4 g/g was recorded.

The ability of *Garcinia cambogia* to remove trivalent arsenic from solution has been studied and found that the kinetic property and uptake capacity of

fresh biomass is significantly enhanced by immobilization. The pH of the solution had no impact on the absorption of As (III) by fresh and immobilized biomass, with optimum biosorption occurring around a pH of 6 to 8 (Kamaruddin *et al.* 2015).

Using a dip-coating technique, a biosorbent was created by coating ceramic alumina with the natural biopolymer chitosan. Adsorption on the biosorbent at pH 4.0 was used to investigate the removal of arsenic (III) and arsenic (V). For As (III) and As (V), the sorbent has adsorption capacities of 56.50 and 96.46 mg/g of chitosan, respectively. On the basis of arsenic speciation at pH 4, the disparity in adsorption potential for As (III) and As (V) was clarified (Boddu *et al.* 2008).

The sorption property of the Shelled *Moringa oleifera* seeds (SMOS) for decontamination of arsenic from water bodies was explored. Maximum sorptions for As (III) and As (V) species were 60.21% and 85.60%, respectively. (Kumari *et al.* 2006).

The study has been conducted for the removal of As (V) on bone char in batch as a function of pH, adsorbent dose and contact time. Uptake of As (V) ion by bone char was rapid in the first 30 min and equilibrium time was independent of initial As (V) concentration. The duration of arsenic adsorption was kept 30 min and optimum adsorption was achieved in the pH range of 9 to 13 (Chen *et al.* 2008).

The biosorption characteristics of As (III) and As (V) from aqueous solution using the macro-fungus (*Inonotus hispidus*) biomass were investigated as a function of pH, biomass dosage, contact time and temperature. The biosorption capacities of *Inonotus hispidus* for As (III) and As (V) were found to be 51.9 and 59.6 mg/g, respectively at optimum conditions of pH 6 for As (III) and pH 2 for As (V), contact time of 30 min and temperature of 20° C (Sarı *et al.* 2009). The characteristics of As (III) biosorption from aqueous solution was studied using the green algae (*Ulothrix cylindricum*) biomass as a function of pH, biomass dosage, contact time, temperature and its biosorption capacity was found to be 67.2 mg/g. At pH 2–6, the biosorption efficiency was increased by 80–96%, and when pH was increased from 6 to 9, it decreased from 96% to 85%. The maximum biosorption was found to be 98% at pH 6 (Tuzen *et al.* 2009). Biosorption of arsenic using algae as sorbent was investigated. Maximum adsorption capacities were estimated to be 45.2 mg/g (pH = 2.5), 33.3 mg/g (pH 4.5), and 28.2 mg/g (pH 6.5) indicating better adsorption at the lower pH. These values are high in comparison with other arsenic adsorbents reported. The kinetics was observed to be independent of pH during the first 120 minutes of adsorption (Hansen *et al.* 2006). The tea fungus, a waste produced during black tea fermentation, has been examined for its capacity to sequester the metal ions from groundwater samples. FeCl₃-pretreated and autoclaved fungal mats removed 100% of As (III) and Fe (II) after 30 min of contact time and 77% of As (V) after 90 min of contact time. The

results revealed that the FeCl₃ pre-treated fungal mats could be used as an effective biosorbent for As (III) and As (V) (Murugesan *et al.* 2006).

A biomass-derived from the plant *Momordica charantia* has been found to be very efficient in arsenite adsorption. An attempt was made to use this biomass for arsenite removal under different conditions. The parameters optimized were contact time (5-150 min), pH (2–11), the concentration of adsorbent (1-50 g/L) and the concentration of adsorbate (0.1-100 mg/L). It was observed that the pH had a strong effect on biosorption capacity. The biomass of *Momordica charantia* was found to be effective for the removal of As (III) with 88% sorption efficiency (Yang *et al.* 2017). Char pine leaves (*Pinus roxburghii*) were also considered for the removal of As (V) ions from aqueous solutions. The influence of different sorption parameters such as the adsorbent dose, solution pH, contact time, agitation speed and initial arsenic concentration was studied thoroughly to evaluate the optimum conditions. Maximum adsorption was observed at pH 4.0, while equilibrium was achieved in 35 min. Maximum adsorption capacity was 3.27 mg/g (Shafique *et al.* 2012).

Dried plants have been used for the removal of As(V) from aqueous solution under different experimental conditions. For this purpose, micro-particles of both *Calami rhizoma* and *Withania frutescens* plants were separately used without pre-treatment as natural adsorbents. Effect of various process parameters, such as adsorbent dose, contact time, initial As (V) concentration, temperature and pH have been studied. The amount of As (V) adsorbed increases very rapidly up to about 120 min and slowly reaches saturation at about 180 min (Mohamed Chiban *et al.* 2012).

Orange juice residue and phosphorylated crosslinked orange waste have been used to remove As (III) and As (V). Cellulose, pectins, hemicellulose, chlorophyll pigments and other low molecular weight compounds like limonene are all found in orange waste. The carboxylic groups in pectins are believed to be the active metal binding sites. The initial orange waste's carboxylic group content is insufficient to bind enough Iron (III) to adsorb arsenic. As a result, the cellulose content of the waste is phosphorylated in order to turn the waste's plentiful hydroxyl groups into phosphoric acid groups, which have a strong affinity for ferric iron. The chemically modified adsorbents were then loaded with iron (III) in order to create a medium for arsenate and arsenite chelation. Arsenite removal was favored under alkaline conditions for both the gels. The orange waste gel showed some removal capability even at pH 7.0. Conversely, arsenate removal took place under acidic conditions at pH 2–3 and 2–6 for the cellulose gel and orange waste gel, respectively (Ghimire *et al.* 2002).

2.6 Arsenic Removal using Nano-Particles

Advances in nanoscience and nanotechnology have recently paved the way for the manufacture of various nanomaterials for tainted water remediation. Nanoparticles have received substantial environmental

interest as novel adsorbents of toxins such as heavy metals and arsenic from aqueous solutions due to their high specific surface area, high reactivity and high specificity. For the treatment of arsenic-contaminated water, carbon nanotubes and nano-composites, titanium-based nanoparticles, iron-based nanoparticles and other metal-based nanoparticles are among the most commonly used and studied nanoparticles.

Studies suggest that cupric oxide (CuO) nanoparticles effectively adsorb aqueous arsenic species. Batch adsorption kinetic experiments were conducted to determine the time course of uptake of arsenic by CuO nanoparticles (Reddy *et al.* 2013). In another study, a red waste mud (bauxite residue) sample was evaluated for the synthesis of Fe₃O₄ nanoparticles (NPs) in ammonia solution that can be used to remove As (V) from both synthetic and natural underground water samples. The results showed that synthesized Fe₃O₄ NPs from red waste mud have satisfactory magnetic properties and As (V) sorption capacity, especially at low equilibrium arsenate concentrations (Akin *et al.* 2012). Magnetite nanoparticles were used to treat arsenic-contaminated water. Because of their large surface area, these particles have an affinity for heavy metals by adsorbing them from a liquid phase. The results of the study showed that the maximum arsenic adsorption occurred at pH 2, with a value of approximately 3.70 mg/g for both As (III) and As (V), when the initial concentration of both arsenic species was maintained at 2 mg/L. The study showed that, apart from pH, the removal of arsenic from contaminated water also depends on the contact time, the initial concentration of arsenic, the phosphate concentration in the water and the adsorbent concentration (Chowdhury *et al.* 2011). Magnetic magnetite nanoparticles are potential sorbents for arsenic removal in drinking water. The adsorption and desorption of arsenite and arsenate using magnetite nanoparticles and the effect of dispersion of the nanoparticles were investigated (Cong *et al.* 2005). The effect of Fe₃O₄ particle size on the adsorption and desorption behavior of As (III) and As (V) was studied. The results show that the nanoparticle size has a dramatic effect on the adsorption and desorption of arsenic. As particle size is decreased from 300 to 12 nm, the adsorption capacities for both As (III) and As (V) increase nearly 200 times (Mayo *et al.* 2007).

2.7 Alternative Technologies

Some alternative options have been applied in West Bengal and Bangladesh, including clay filters, deep tube wells, dug wells, surface and rainwater harvesting and solar distillation. Solar distillation techniques use the sun's energy to evaporate water, which is then re-condensed. This process of evaporation and re-condensation separates all chemicals, including arsenic, from the water. In recent years, the search for novel technologies for the removal of arsenic in order to reduce the cost of operation, non-hazardous compounds and its applicability in a remote and rural area, is being done. Other than the conventional techniques, other handy technologies like bio-remediation, foam flotation and solvent extraction can also be used for arsenic removal. A few of the most promising emerging technologies use

UV radiation, solar radiation and/or biological processes (bacterial or plant action) for arsenite removal. For example, the conversion of arsenite surpasses 95% when UV or solar radiation is used in the presence of iron or sulphites (Zaw *et al.* 2002).

2.7.1 Solar Oxidation and Removal of Arsenic (SORAS)

SORAS is a simple method of solar oxidation of arsenic in transparent bottles to reduce the arsenic content of drinking water. Solar oxidation and reduction of arsenic is an easy process that reduces arsenic levels in drinking water by exposing water to sunlight in PET or other UV-A clear bottles. The SORAS method is based on photochemical oxidation of As (III) followed by precipitation or filtration of As (V) adsorbed on Fe (III) oxides. SORAS has been used in the rural Andes regions in Latin America. It is based on the adsorption of As (V) onto iron oxides and hydroxides using UV radiation (Herbel *et al.* 2006; Saalfeld *et al.* 2009) and the addition of citrate as a catalyst for the formation of oxidizing radicals which allows the conversion of arsenite to arsenate.

Combination of solar oxidation with adsorption might be an application development towards an alternative to arsenic removal. The goal would be to optimize the SORAS process by incorporating complementary conventional techniques, thereby increasing its reliability.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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