**Arsenic contamination in water and the recent removal techniques**

Malabika Borah Saiful Hassan Mollah

Department of Chemistry, B. N. College,  Department of Chemistry, Assam University,

Dhubri, Assam, India Silchar, Assam, India

Email id: malabikaborah@gmail.com Email id: saifulhassan105@gmail.com

**ABSTRACT**

Arsenic is the most hazardous element in the chemical world and its presence in drinking water is a matter of great concern. Severe and widespread contamination by arsenic (As) in groundwater and drinking water has been recently revealed in rural and sub-urban areas where expensive water treatment techniques are not affordable. Arsenic exists in organic as well as inorganic forms with varying valence states which plays an important role in its behaviour and toxicity in aqueous system.

Chronic arsenic exposure has devastating health effects such as cardiovascular diseases, cancer and the eventual death. Thus, the removal of arsenic from drinking water is strongly recommended. Many methods of arsenic removal have been studied, but every available process has its own limitations and it can serve to a limited extent only. This chapter is compiled to summarize the technologies currently being investigated to remove arsenic from drinking waters and to provide background material and a description of competing technologies currently described in the literature for arsenic removal.

**Keywords** – toxicity, arsenic, water

1. **INTRODUCTION**

Arsenic is a natural element having crystal shape metalloids which is brittle in nature and greyish white in colour. Arsenic rarely occurs in a free state and is found largely in combination with sulphur, oxygen and iron. Unlike other heavy metalloids and oxy anion forming elements, arsenic can be mobilized under a wide range of oxidizing and reducing condition at the pH values typically found in groundwater (pH =6.5-8.5). Arsenic has four main chemical forms having oxidation states -3, 0, +3 and +5. Arsenic mostly found in earth’s crust in both oxidation state which is trivalent arsenite, AsO33-,As(III) and pentavalent arsenate, AsO43-, As(V). Arsenic in both the forms is poisonous in nature1(Fig. 1). As(III) is generally more toxic to humans and four to ten times more soluble in water than As(V).



**Fig. 1: Structures of (a) arsenite and (b) arsenate.**

1. **SOURCES**

Arsenic occurs in many minerals, usually in conjunction with sulphur and metals and also as a pure elemental crystal. The main uses of metallic arsenic are for strengthening alloys of copper and especially lead used in car batteries. Release of arsenic in the environment is a result of both man-made and natural activities. Naturally occurring pathways of exposure include volcanic ash, weathering of arsenic containing minerals and ores and dissolved in groundwater. Much of its dispersion in the environment stems from mining and commercial uses. For example, in industry, arsenic is a by-product of the smelting processes for many metals ores such as cobalt, gold, lead and zinc. It is also used commercially, e.g. as alloying agents and wood preservatives. Combustion of fossil fuels is a source of arsenic in the environment through atmospheric deposition. The greatest threat to public health arises from arsenic in drinking water2.

1. **EFFECTS OF ARSENIC POISONING**

Alarming information has emerged in recent decades about the widespread presence of arsenic in groundwater used to supply drinking water in many countries on all continents. The presence of arsenic, even at high concentrations, is not accompanied by any change in taste, odour or visible appearance of water. The presence of arsenic in drinking water is therefore difficult to detect without complex analytical techniques. Hundreds of millions of people, mostly in developing countries, daily use drinking water with arsenic concentrations several times higher than the World Health Organization (WHO) recommended limit of 10 millionths of a gram per litre of water (10 μg/L)3.

Human exposure to arsenic can take place through ingestion, inhalation or skin adsorption; however, ingestion is the predominant form of arsenic intake. High doses of arsenic can cause acute toxic effects including gastrointestinal symptoms such as poor appetite, vomiting, diarrhoea etc., disturbance of cardiovascular and nervous systems functions such as muscle cramps, heart complains or death. Arsenic toxicity strongly depends on the form in which arsenic is present.

 The first visible symptoms caused by exposure to low arsenic concentrations in drinking water are abnormal black-brown skin pigmentation known as *melanosis* and hardening of palms and soles known as *keratosis*. If the arsenic intake continues, skin de-pigmentation develops resulting in white spots that looks like raindrops (medically described as *leukomelanosis*).

Long-term ingestion of arsenic in water can first lead to problems with kidney and liver function and then to damage to the internal organs including lungs, kidney, liver and bladder causing no visible external symptoms, making arsenic poisoning difficult to recognize. Elevated concentrations in hair, nails, urine andblood can be an indicator of human exposure to arsenic before visible external symptoms. The disease symptoms caused by chronic arsenic ingestion are called *arsenicosis* and develop when arsenic contaminated water is consumed for several years. Symptoms may develop only after more than ten years of exposure to arsenic, while it may take 20 years of exposure for some cancers to develop3.

1. **MECHANISM OF ARSENIC POISONING**

The mechanism of arsenic poisoning can be described with the help of the following ways:

1. **Glycolysis**

In this reaction mechanism, arsenate (AsO43-) takes the position of phosphate (PO43-) of the Glycolysis cycle and produces 1-arseno-3-phosphoglycerate instead of 1,3-bisphosphoglycerate (Scheme 1). Generally, in glycolysis process, the enzyme phosphoglycerokinase converts 1,3-bisphosphoglycerate to 3- phosphoglycerate by producing ATP. Here arsenate producing 1-arseno-3- phosphoglycerate undergo non-enzymetic hydrolysis to 3-phosphoglycerate by short change glycolysis one ATP per arsenate4.



 ***↓***

 Short- change glycolysis

 1 ATP per Arsenate

**Scheme 1: Glycolysis cycle, arsenate takes the position of phosphate4.**

1. **TCA Cycle**

In this mechanism, two thiol groups actually attach to the arsenic and form arsenite chelate on enzyme by removal of water as shown in scheme 2. The arsenite chelate on enzyme is very much poisonous and it stops the TCA cycle. Here 2,3- dimercaptopropanol acts as a antidote and restores the enzyme5.



**Scheme 2: TCA Cycle in which arsenite act as a poisoning5.**

The effects of *arsenicosis* are serious and ultimately life-threatening, especially as the long term ingestion of arsenic in water can lead to several forms of cancer. Several studies have shown that drinking arsenic-contaminated water is one of the major concerns for the health of mankind6. Thus, strategies to avoid arsenic contamination of ground water and/or to alleviate the impact of such contamination need to be developed in an attempt to reduce the health risk association with the intake of arsenic-contaminated water.

1. **REMOVAL TECHNIQUES**

Various treatment technologies have been developed for arsenic removal from drinking water. The commonly used technologies are classified as physical methods such as ion-exchange, adsorption, electrochemical techniques and membrane process; chemical processes such as coagulation, ozone oxidation, filtration and precipitation and biological methods such as bacterial removals and phytoremediation7.

1. **Adsorption**

Adsorption is one of the most effective methods to remove arsenic from the water. The process of adsorption is the accumulation of material at an interface or the liquid/solid boundary layer. Adsorption is a mass transfer process in which a substance is transferred from the liquid phase to the surface of the solid is bound through chemical or physical forces. In process of adsorption, purification of water depends on big specific surface area and high surface energy of the adsorbent. Strong adsorption ability depends on the properties of the material which is being used as the adsorbent. The most commonly used adsorbents are activated alumina, activated carbon, functional resin and metal oxide.

Xiao *et al.*­8 used activated alumina for arsenic removal. The principle is that the soluble arsenic (AsO43- and AsO33-) in the water can be adsorbed on the surface and occupies the aluminous octahedron crystal lattice sites. The maximum adsorptive capacity of activated alumina is 5-24 (mg As adsorbed/g media) at equilibrium arsenic concentrations of 0.05-0.2 ppm. Huang and Vane9 and Reed *et al*.10 used activated carbon for arsenic adsorption with various metal compounds—impregnating iron compound onto activated carbon and Zr treatment of activated carbon.

Metal oxides show strong adsorption capability due to their high surface area in comparison to many inorganic ions. Manning *et al.*11used amorphous hydrous ferric oxide, Raven *et al.*12 used crystalline hydrous ferric oxide (ferrihydrite), Jackson and Miller13 used α-FeOOH, Jain and Loeppert14 used hematite, Goldberg15 used magnetite and Goethite for arsenate and arsenite removal.

Altundogan *et al.*16 used liquid phase of red mud, Brunori *et al.*17 used red mud and Fuhrman *et al.*18 used seawater-neutralized red mud (bauxsol), activated bauxsol (ferric sulfate or aluminum sulfate) and normal bauxsol19 and chemically modified and activated bauxsol-coated sand20 as adsorbents for arsenic removal. Natural zeolites, volcanic stone, cactaceous powder and clinoptilolite-containing rocks are also applied for arsenic removal20. Lorenzen *et al*.21 used coconut-shell carbon and coconut-shell carbon pretreated with Fe(III) as adsorbent for As(III) and As(IV).

Buswell22 showed first the arsenic removal with metal salts. The most commonly used metal salts are aluminium salts such as alum and ferric salts such as ferric chloride or ferric sulphate. However, ferrous sulphate is less effective. Excellent arsenic removal is possible with either ferric or aluminium salts, with laboratories reporting over 99% removal under optimal conditions and residual arsenic concentrations of less than 1 µg/L23. Fullscale plants typically report a somewhat lower efficiency, from 50% to over 90% removal24-25. Bajpai and Chaudhuri reported that 54–57% of As(III) can be oxidized to As(V) in contaminated groundwater using air and pure oxygen whereas complete oxidation of As(III) can be obtained with ozone26.

1. **Ion exchange**

The synthesized ion-exchange resins are based on a polymer cross-linking matrix composed of polystyrene and cross-linked with divinylbenzene. Charged functional groups are attached to the matrix through covalent bonding. Various strong base anion exchange resins are available which can effectively remove arsenic from water, less than 1ppm.

Several resins were reported for arsenic removal, for example Matsunaga27 and Balaji28 used an iron(III) and zirconium(IV)-loaded chelating resin containing lysine and diacetic acid based functional groups for the adsorption of As(III) and As(V). Peleanu *et al*.29 used iron-loaded iminodiacetate chelating resin and a silica/iron (III) oxide composite materials for As(V) remediation. Wasay *et al*.30 used La(III) and yttrium carbonate resin to remove As(III) and As(V) between pH 4 and 9 with 98% and 100% efficiency. Chanda *et al.*31 used Impregnated iron to weaken base macroporous chelating resin for the removal of As(III) and As(V). Lenoble *et al*.32 used manganese dioxide, loaded on a polystyrene matrix anionic commercial resins for As(V) and As(III) simultaneous oxidation and removal.

1. **Coagulation**

Coagulation is a process by which the physical or chemical properties of dissolved colloidal or suspended matter are altered in a way to settle them out from the solution. Aluminium based coagulation with disinfection by chlorination is one of the commonly used treatment methods7. Yuan et al.33 studied combination system of ferric sulphate coagulation/sand filtration in arsenic removal. The method is economic and effective.

Scott *et al*.34 reported the full-scale study of the coagulation process by using ferric sulfate at the Metropolitan Water District of Southern California and achieved high removal of over 95%. Liu *et al*.35 reported the enhanced co-precipitation of arsenite by the coupling of FeCl3 with permanganate as the coagulant.



**Fig. 2: Removal of Arsenic through coagulation36.**

1. **Filtration**

The conventional filtration process is the separation of solid particles from water (liquid effluents) by passing the solution through a medium such as sand, activated carbon or paper that retains the solid on its surface and allows the water to pass through. Red soil (oxidized iron rich), clay minerals, iron ore, scrap iron or fillings and cellulose materials cartridges (containing jute and cotton fibers) were used for arsenic removal. Nikolaidis and Lackovic37 used iron filing filter system with 95% efficiency.

1. **Membrane process**

Several natural and synthetic membranes are likely to be used increasingly for arsenic removal because it is easy to obtain, produce, operate and maintain them. These membranes have billions of pores or microscopic holes that act as selective barriers. The structure of the membrane allows some constituents to pass through while others are excluded. Membrane filtrations are classified on the basis of applied pressure such as high driven pressure (50 to 1,000 psi). Examples are Reverse Osmosis (RO) and Nano Filtration (NF), while low-pressure membranes (5 to 100 psi) are Micro Filtration (MF) and Ultra Filtration (UF).

Clifford *et al.*38, Fox39 and Waypa *et al*.40 used cellulose acetate based RO membrane for the removal of arsenic. Sato *et al.*41 used polyamide whereas used cellulose acetate type membrane. NF membrane method is also a high-pressure process and is efficient in removing the dissolved arsenic from water due to the small size of the membrane pores. Waypa *et al.*42 used thin-film composite film NF membrane for arsenic removal. Vrijenhoek and Waypa43 used porous polyamide thin-film composite membrane (NF-45) for the removal of arsenic.

Low-pressure membranes used for particle removal (size 0.05 μm and molecular weight > 50,000) include MF and UF. Han *et al*.44 used mixed ester of cellulose acetate and cellulose nitrate MF membrane with pore size of 0.22 and 1.22 μm combined with both ferric chloride and ferric sulfate and cationic polymeric flocculants to investigate the arsenic removal efficiency.

1. **Electrocoagulation**

Electrocoagulation is a simple, efficient and promising technique that does not require the addition of any chemical species. In this process, flocculating agent is generated by electrooxidation on anode, which is made up of metal, generally iron or aluminum. Parga *et al*.45 and Hansen *et al*.46 reported maximum arsenic removal (more than 99.6%) by aluminum and iron electrodes. Maldonado-Reyse *et al.*47  reported a system with the combined use of both aluminum and iron in the same electrochemical cell. The efficiency varied from 78.9% to more than 99.6% at different initial arsenic concentrations. Kumar *et al.*48 and Parga *et al.*49 reported that the removal efficiency of both arsenic species with the help of iron electrode forming amorphous iron oxide and hydroxide complexes was more than 90% at different pH values 2, 6.5 and 11 at a constant current of 0.5-30 μA.

1. **Oxidation methods**

Oxidation involves the conversion of soluble arsenite to arsenate which alone does not remove arsenic from the solution, thus a removal technique, such as adsorption, coagulation or ion exchange must follow. For anoxic groundwater, oxidation is an important step since arsenite is the prevalent form of arsenic at near neutral pH. In addition to atmospheric oxygen, many chemicals, as well as bacteria, have already been used to directly oxidize arsenite in water. Different oxidants are used to oxidize arsenite to arsenate. Kim *et al*.50 reported oxygen and ozone for the oxidation of As(III). A large number of oxidants such as activated chlorine, chlorine dioxide, hydrogen peroxide etc. have been used51-53. Miller et al synthesised a TiO2 coated chitosan bead and applied for oxidation as well as removal of arsenic from aqueous solution. They observed a higher amount of adsorption of arsenic followed by UV radiation as compared to the solution that was not exposed to UV light(Fig. 3)54.



**Fig. 3: As removal by TiO2 beads using UV rays54.**

Criscuoli et al.found that the oxidation of As(III) by MnO2 coated nanostructured capsules had higher efficiency than conventional oxidation methods when the water contains a low level of arsenic. More than 99% oxidation was obtained at 100 to 300 ppb of initial arsenic concentration. However, increasing the concentration to 700 and 1000 ppb, only 90% and 73% of As(III) were oxidized, indicating a decreased oxidation efficiency of the particle with increase in the initial As(III) concentration55.

1. **Bioremediation**

There are two types of biological systems, which are currently in use for the removal of arsenic from water. The first of these uses cultured bacteria to oxidize and precipitate iron and manganese in water. The second method uses anaerobic, sulphate-reducing bacteria and other reducing bacteria to precipitate arsenic from solution as insoluble arsenic sulphide complexes. Elson *et al*.56 and Mcafee *et al*.57 studied chitosan, chitin, chitosan/chitin mixture and biomass from *Rhizopus oryzae* for removal of arsenic from contaminated drinking water.

Dead fungal biomass of *Lessonia nigrescens* (an algae), *Aspergillus niger* (fungus) coated with iron oxide, *Penicillium purpurogenum* were used for arsenic removal and the pre-treatment with hexadecyl-trimethyl ammonium bromide dodecylamine and a cationic polyelectrolyte was carried out to improve arsenate biosorption58-63.

Bacterial species coupling anaerobic oxidation of organic substrates to the reduction of arsenates have also been reported by several researchers. Such bacteria are known as dissimilatory arsenate reducing bacteria or arsenate respiring bacteria, for example, *Geospirillum arsenophilus, Geospirillum barnesi, Desulfutomaculum auripigmentum, Bacillus arsenicoselenatis and Crysiogenes arsenates*64-66.

Biological oxidation of As(III) can be applied as an alternative to the chemical oxidation. Iron and manganese are typical unwanted constituents in drinking water causing aesthetic problems known to play significant role in arsenic concentrations in groundwater. Several species of bacteria have been reported to carry out biological oxidation of arsenic67,68.

Specific indigenous bacteria mediating biological oxidation of arsenic are known as “iron and manganese oxidizing bacteria”. These bacteria have been successfully applied for the biological arsenic oxidation directly in continuous ground water treatment69-71(Fig. 4). The biological oxidation of iron by two bacteria, *Gallionella ferruginea and Leptothrix ochracea,* has been found to be a promising technology for effective removal of arsenic from groundwater72.



**Fig. 4: Removal of arsenic by using coliform bacteria73.**

1. **Phytoremediation**

Phytoremediation is a new approach for arsenic removal from groundwater and soil, which involves two different mechanisms. The first utilizes plants to remove the arsenic ions and the second is biological treatment that utilizes microorganisms. The techniques are based on the potential of certain plant species to accumulate high concentrations of arsenic in their aerial tissue. Visoottiviseth *et al*.74 used cottonwood, sunflower, Indian mustard, maize, ryegrass, prairie grasses and hyper-accumulating ferns are the plants used in this process for arsenic removal from water.

Young plants of water lettuce, *Garcinia combogia* (indigenous plant), *Pista stratiotes* L. (aquatic plant), water hyacinths (*Eichhornia crassipes*) and dried roots of water hyacinths (harvested from a pollution free pond and hydroponically cultured) are also used for the simultaneous and rapid remediation of arsenic, cadmium, mercury and lead from polluted water at effective concentration75,76.

Recently *Pteris vittata,* *P. cretica,* orange juice waste (containing cellulose, pectins, hemicellulose, chlorophyll pigments and other low molecular weight compounds like limonene) residue and phosphorylated cross-linked orange waste are also used for arsenic removal77-79. Murugesan *et al*.80 reported the use of industrial waste autoclaved tea fungal mats and pretreated tea fungal by FeCl3 for As(III) and As(V) removal from groundwater samples. Wasiuddin *et al*.81 reported the use of human hair to remove arsenic due to their ability to absorb arsenic from contaminated water.

1. **Nanotechnology**

Now-a-days, nano particles are highly used in the arsenic removal in drinking water. Tang *et al*.82 synthesized ultrafine α-Fe2O3 nanoparticles using a solvent thermal process to treat laboratory-prepared and natural water samples contaminated with arsenic. The kinetics study revealed that As(III) and As(V) removal by α-Fe2O3 nanoparticles can be achieved very rapidly.

1. **PREVENTIVE MEASURES**

Arsenic poisoning can be prevented either through the fixing arsenic removal system in homes or periodically testing drinking water for arsenic, rain water harvesting and digging wells that are adequately deep. The problem of ground water being contaminated with arsenic can be mitigated to a large extent by installing filters at community level. Care must be taken to see that these filters are cleaned and maintained regularly and that the sledge generated by these filters is disposed off properly. Those who are exposed to arsenic for longer periods of time must be monitored periodically for early signs of damage.

1. **CONCLUSION**

Arsenic contamination in drinking water is an alarming problem on a global scale. As the arsenic in drinking water is having a major human impact in several part of the world, in present literature survey, we tried to elaborate various remediation method based on conventional, modern and hybrid technologies for removal of arsenic. But we should bear in mind that the various approaches described have their own advantages and disadvantages. Most of the existing technology removal of arsenic involved the direct removal of arsenic(V) or converting the arsenic(III) to arsenic(V) followed by removal of arsenic(V). The technologies discussed are quite effective overall and are safe for arsenic removal from water, but need promotion for wider implementation in acute arsenic problem areas to avoid ingestion of excessive arsenic through tube well water.

Arsenic-free drinking water is a necessity for human health, so we should emphasize on the purification of water through the several discussed techniques. Among all the techniques, the polymeric support technique is found to be more effective which offers innovative materials for arsenic separation. In this technique, designing functional polymers is a key requirement; it can be assisted by chemical modification and graft modification as well. High degree of binding groups may be incorporated through this technique. However, research efforts are still needed to develop inexpensive, rapid, sensitive and reproducible technologies for arsenic removal.

REFERENCES

[1] P. L. Smedly, D. G. Kinniberg, *Applied Geochemistry* **2002**, 17, 517-568.

[2] A. Georges, O. Bersillon, J. Blachot, A. H. Wapstra, *Nuclear Physics A* **2003**, 729: 3–128.

[3] D. Mohan, C. U. Pitmann Jr., Arsenic removal from water/wastewater using adsorbents, a critical review, *Elsevier* **2007**, 1-42.

[4] F. Dickens, F. Simer, *Biochem J* **1929**, 23(5), 936-958*.*

[5] R. K. Crane, F. Lipmann, *J. Biol. Chem.* **1953**, 201-235.

[6] US Environmental Protection Agency (EPA), Research plan for Arsenic in drinking water-Treatment, Technologies and Costs for Removal of Arsenic from drinking water, National Primary Drinking Water Regulation, Office of Ground Water and Drinking Water (**1998, 1999, 2000, 2001**).

[7] T. S. Y. Choong, T. G. Chuah, Y. Robiah, F. L. G. Koay, I. Azni, *Desalination* **2007**, 217, 139-166.

[8] T. F. Xiao, B. Hong, Z. H. Yang, *Geological Science and Technology Information*, **2001**, Vol. 20, No. 1, pp. 71-76.

[9] C. P. Huang, L. M. Vane, *J. Water Pollution. Contr. Federation*, **1989**, Vol. 61, pp. 1596-1603.

[10] B. Reed, E. R. Vaughan, L. Q. Jiang, *J. Environ. Eng. Div.,* Am. Soc. Civ. Eng., **2000**, Vol. 126, pp. 869-873.

[11] B. A. Manning, S. E. Fendorf, S. Goldberg, *Environmen. Sci. Technol.*, **1998**, Vol. 32, pp. 2383-2388.

[12] K. P. Raven, A. Jain, R. H. Loeppert, *Environ Sci.Technology*, **1998**, Vol. 32, pp. 344-349.

[13] B. P. Jackson, W. P. Miller, *Soil Sci. Soc. Am.* *Journal*, **2000**, Vol. 64, pp. 1616-1622.

[14] A. Jain, R. H. Loeppert, *J. Environ. Quality*, **2000**, Vol. 29, pp. 1179-1184.

[15] S. Goldberg, *Soil Sci. Soc. Am. Journal*, **2002**, Vol. 66, pp. 413-421.

[16] H. S. Altundogan, S. Altundogan, F. Tumen, M. Bildik, “Arsenic Adsorption from Aqueous Solutions by Activated Red Mud Waste Management”, **2002**, Vol. 22, pp. 357-363.

[17] C. Brunori, C. Cremisini, P. Massanisso, *J. Hazard. Material*, **2005**, Vol. 117, No. 1, pp. 55-63.

[18] H. G. Fuhrman, J. C. Tjell, D. McConchie, O. Schuiling, *J. Colloid Interf. Sciences*, **2003**, Vol. 264, pp. 327-334.

[19] H. G. Fuhrman, J. C. Tjell, D. McConchie, *J. Colloid Interf. Sci*., **2004**, Vol. 271, No. 2, pp. 313-320.

[20] H. G. Fuhrman, J. C. Tjell, D. McConchie, *Environ. Sci. Technol.*, **2004**, Vol. 38, No. 8, pp. 2428-2434.

[21] L. Lorenzen, J. S. J. Deventer, W. M. Landi, *Miner. Eng.*, **1995**, Vol. 8, No. 45, pp. 557-569.

[22] A. M. Buswell, *Journal American Water Works Association* **1943**, 35(10), 1303.

[23] P.-Y. Chen, J. G. Hering, J. Wilkie, M. Elimelech, *Journal of Environmental Engineering* **1997**, 123(8), 800-807.

[24] M. R. Jekel, *Removal of arsenic in drinking water treatment*, John Wiley & Sons, Inc., New York, **1994**.

[25] J. G. Hering, P. Y. Chen, J. A. Wilkie, M. Elimelech, S. Liang, *Journal of the American Water Works Association* **1996**, 88(4), 155-167.

[26] S. Bajpai, M. Chaudhuri, *Journal of Environmental Engineering* **1999**, 125, 8, 782–784.

[27] H. Matsunaga, T. Yokoyama, R. J. Eldridge, B. A. Bolto, *React. Polymer*, **1996**, Vol. 29, pp. 167-174.

[28] T. Balaji, T. Yokoyama, H. Matsunaga, *Chemosphere*, **2005**, Vol. 59, No. 8, pp. 1169-1174.

[29] I. Peleanu, M. Zaharescu, I. Rau, M. Crisan, A. Jitianu, A. Meghea, *Sep. Sci. Technol*., **2002**, Vol. 37, No. 16, pp. 3693-3701.

[30] S. A. Wasay, M. J. Haron, A. Uchiumi, S. Tokunaga, *Water* *Res.*, **1996**, Vol. 30, No. 5, pp. 1143-1148.

[31] M. Chanda, K. F. Driscou, G. L. Rempel, *Reactive Polymers*, **1988**, Vol. 8, pp. 85-89.

[32] V. Lenoble, C. Laclautre, B. Serpaud, *Science of the Total Environment*, **2004**, Vol. 326, pp. 197-207.

[33] T. Yuan, Q. F. Luo, J. Y. Hu, S. L. Ong, W. J. Ng, *J*. *Environ*. *Science* *&* *Health*; *Part* *A*, *Toxic*/*Hazardous* *Sub*. *Environ*. *Eng*. **2003**, 38, 1731-1744.

[34] K. N. Scott, J. F. Green, H. D. Do, S. J. Mclean, *Journal of American Water Work Association*, **1995**, pp. 114-126.

[35] R. P. Liu, X. Li, S. J. Xia, *Environment Science*, **2005**, Vol. 26, No. 1, pp. 73-76.

[36] M. Edwards, *Chemistry of Arsenic removal during coagulation and Fe-Mn oxidation,* **2002**, 98.

[37] N. P. Nikolaidis, J. Lackovic, “Arsenic Remediation Technology: AsRT”, International Conference on Arsenic Pollution of Ground Water in Bangladesh: Causes, Effect and Remedies, Dhaka, **1998**, pp. 8-12.

[38] D. A. Clifford, C. C. Lin, “As(III) and As(V) Removal from Drinking Water”, Project Summary EPA/600/S2-91/011, US Environmental Protection Agency Risk Reduction Engineering Laboratory, Lincinnati, **1991**.

[39] K. R. Fox, *J. of AmericanWater Works Associations*, **1989**, Vol. 81, pp. 94-101.

[40] J. J. Waypa, M. Elimelech, J. G. Hering, *Journal of American Water Works Association*, **1997**, Vol. 89, No. 10, pp. 102-114.

[41] Y. Sato, M. Kang, T. Kamei, Y. Magara, *Water Res*., **2002**, Vol. 36, pp. 3371-3377.

[42] J. J. Waypa, A. Seidel, M. Elimelech, *Environ. Eng. Sci*., **2001**, Vol. 18, No. 2, pp. 105-113.

[43] E. M. Vrijenhoek, J. J. Waypa, *Desalination*, **2000**, Vol. 130, pp. 262-277.

[44] B. Han, T. Runnells, J. Zimbron, R. Wickramasinghe, *Desalination*, **2002**, Vol. 145, pp. 293-298.

[45] J. R. Parga, D. L. Cocke, J. L. Valenzuela, *J. Hazard. Material,* **2005**, Vol. 124, Nos. 1-3, pp. 247-254.

[46] A. R. Hansen, E. Mateus, *Miner. Eng.*, **2006**, Vol. 19, No. 5, pp. 486-490.

[47] A. Maldonado-Reyse, C. Montero, O. Solorzo-Ferea, *Journal of Env. Monitoring*, **2007**, Vol. 9, pp. 1241-1247.

[48] P. R. Kumar, S. Chaudhari, K. C. Khilar, S. P. Mahajan, *Chemosphere*, **2004**, Vol. 55, No. 9, pp. 1245-1252.

[49] J. R. Parga, D. L. Cocke, J. L. Valenzuela, *J. Hazard. Material,* **2005**, Vol. 124, Nos. 1-3, pp. 247-254.

[50] M. Kim, J. Nriagu, *Sci. Total. Environ*. **2000**, 247, 71–79.

[51] C. Hu, H. Liu, G. Chen, W. Jefferson, J. Qu, Environ. Sci. Technol. **2012**, 46, 6776–6782.

[52] S. Sorlini, F. Gialdini, Water Res. **2010**, 44, 5653–5659.

[53] M. Pettine, L. Campanella, F. J. Millero, Geochim. Cosmochim. Acta **1999**, 63, 2727–2735.

[54] S. M. Miller, J. B. Zimmerman, *Water Research* **2010**, 44, 19, 5722–5729.

[55] A. Criscuoli, S. Majumdar, A. Figolietal, *Journal of Hazardous Materials* **2012**, 211-212, 281–287.

[56] C. M. Elson, D. H. Davies, E. R. Hayes, *Water Res.*, **1980**, Vol. 14, No. 9, pp. 1307-1311.

[57] B. J. Mcafee, W. D. Gould, J. C. Nedeau, A. C. da Costa, *Sep. Sci. Technol.*, **2001**, Vol. 36, No. 14, pp. 3207-3222.

[58] A. I. Zouboulis, I. A. Katsoyiannis, *Ind. Eng. Chem. Res.*, **2002**, Vol. 41, No. 24, pp. 6149-6155.

[59] M. X. Loukidou, K. A. Matis, A. I. Zouboulis, M. Liakopoulou-Kyriakidou, *Water Research*, **2003**, Vol. 37, No. 18, pp. 4544-4552.

[60] S. Ridvan, Y. Nalan, D. Adil, *Sep. Sci. Technol.*, **2003**, Vol. 38, No. 9, pp. 2039-2053.

[61] A. R. Hansen, E. Mateus, *Miner. Eng.*, **2006**, Vol. 19, No. 5, pp. 486-490.

[62] G. S. Murugesan, M. S. Kumar, K. Swaminathan, *Bioresour. Technology*, **2006**, Vol. 97, No. 3, pp. 483-487.

[63] D. Pokhrel, T. Viraraghavan, *Water Res.*, **2006**, Vol. 40, No. 3, pp. 549-552.

[64] R. S. Oremland, J. F. Stolz, *Trends in Microbiology* **2005**, 13, 2, 45–49.

[65] R. S. Oremland, C. W. Saltikov, F. Wolfe-Simon, J. F. Stolz, *Geomicrobiology Journ*a*l* **2009**, 26, 7, 522– 536.

[66] F. Battaglia-Brunet, M.-C. Dictor, F. Garrido et al., *Journal of Applied Microbiology* **2002**, 93, 4, 656–667.

[67] J. M. Santini, L. I. Sly, R. D. Schnagl, J. M. Macy, *Applied and Environmental Microbiology* **2000**, 66, 1, 92–97.

[68] E. O. Kartinen Jr., C. J. Martin, *Desalination* **1995**, 103, 1-2, 79–88.

[69] A. I. Zouboulis, I. A. Katsoyiannis, *Industrial & Engineering Chemistry Research* **2002**, 41, 24, 6149–6155.

[70] Katsoyiannis, A. Zouboulis, H. Althoff, H. Bartel, *Chemosphere* **2002**, 47, 3, 325–332.

[71] I. A. Katsoyiannis A. I. Zouboulis, *Water Research* **2004**, 38, 1, 17–26.

[72] I. A. Katsoyiannis, A. Zikoudi, S. J. Hug, *Desalination* **2008**,224, 1–3, 330–339.

[73] P. Xiaohong, G. Qinghaihua *, Journal of Hazardous Material* **2012**, 215 -216, 1-16.

[74] P. Visoottiviseth, K. Francesconi, W. Sridokchan, *Environ. Pollution*, **2002**, Vol. 118, pp. 453-461.

[75] M. Misbahuddin, A. Fariduddin, *Arch. Environ. Health*, **2002**, Vol. 57, No. 6, pp. 516-518.

[76] C. T. Kamala, K. H. Chu, N. S. Chary, *Water Res.*, **2005**, Vol. 39, No. 13, pp. 2815-2826.

[77] J. W. Huang, C. Y. Poynton, L. V. Kochian, M. P. Elless, *Environ.* *Sci. Technology*, **2004**, Vol. 38, No. 12, pp. 3412-3417.

[78] M. Srivastava, L. Q. Ma, J. A. G. Santos, *Sci. Total Environ*., **2006**, Vol. 364, pp. 24-31.

[79] K. N. Ghimire, K. Inoue, K. Makino, T. Miyajima, *Sep. Sci. Technol.*, **2002**, Vol. 37, No. 12, pp. 2785-2799.

[80] G. S. Murugesan, M. Sathishkumar, K. Swaminathan, *Bioresour. Technology*, **2006**, Vol. 97, No. 3, pp. 483-487.

[81] N. M. Wasiuddin, M. Tango, M. R. Islam, *Energy Sources*, **2002**, Vol. 24, pp. 1031-1041.

[82] W. Tang, Q. Li, S. Gao, J. Shang, Mater. **2011**, 192, 131–138.