Review article

Microorganisms in Arsenic Bioremediation with Special Reference to Filamentous Fungi: A Review

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Abstract: Arsenic pollution of groundwater and other water sources is one of the biggest environmental disasters people are facing presently. About 140 million people around the world have been exposed to arsenic contaminated groundwater. Due to its carcinogenic and toxic effects to human and animal's health, remediation of arsenic-contaminated water has become of prime importance. The north-eastern region of India has long been reported with high level of arsenic contaminations. In a preliminary survey conducted in Arunachal Pradesh (Papum Pare and Lower Subansiri districts) and Assam (North Lakhimpur district), arsenic contamination was detected as high as 193.2 ppb which is manifolds higher than the arsenic maximum contaminant level (MCL) set by Environmental Protection Agency (EPA) for public water supplies (10 ppb). Therefore, this paper is presented with the aims to review current status of arsenic pollution worldwide with reference to north eastern India along with various arsenic remediation techniques currently available (conventional and modern). In recent years, bioremediation techniques have emerged out as modern innovative technologies for the removal of arsenic from aqueous system. Many highly arsenic resistant microbes (bacteria, fungi and algae) have been reported with high arsenic tolerance capacity and/or ability to oxidize arsenite to less toxic forms. Among them, fungi could be potential agent of arsenic bioremediation due to their mycelia nature, high growth capacities and production of variety of enzymes, however less emphasis has been given to this group of organisms. Thus this review mainly emphasises the role of filamentous fungi as an effective agent and potentially be used for the bioremediation of arsenic from arsenic contaminated ground water.

Key words: Algae, Arsenic pollution, Bacteria, Bioremediation, Filamentous fungi

Introduction

Arsenic (As) is a toxic element widely distributed in nature. Arsenic pollution is currently a major environmental problem because metal ions persist in the environment due to their non-degradable nature posing threat to both soil and water resources at potentially harmful levels. In natural waters, it exists in both inorganic and organic forms. The inorganic salts of arsenic i.e. arsenite As(III) and arsenate As(V) are its most toxic forms than organic forms (Srivastava *et al.,* 2011). The detection of arsenic has threatened the use of groundwater as major source of drinking water throughout the globe (Bundschuh *et al.*, 2015). In addition to other forms, the oxides of arsenic are most hazardous for human health. Their origin in soil, water and air is due to various natural processes (Matschullat, 2000; WHO, 2001; Bhattacharya *et al.*, 2002). These forms are extracted into the groundwater as components of geologic formations. As (III) is dominant in more reduced condition whereas As(V) is dominant in oxidizing environment. The toxicity and bioaccumulation tendency of arsenic in the environment is a serious threat to human health. Skin lesions, rhagades, damaged mucous membrane, digestive, respiratory, circulatory and nervous systems and skin cancers etc. are some of the serious health hazards caused due to arsenic poisoning. The current evidence indicates that arsenic increases the risk of skin, liver and lung cancers (Wang *et al.*, 2001; Biswas *et al.*, 1998). It is also associated with non-cancer health effects such as diabetes, hypertension and other cardiovascular events. Although limited, the existing evidence also suggests that arsenic may have adverse reproductive effects in humans (Hopenhayn, 2006). Due to hazardous effects of arsenic on human systems, the World Health Organization (WHO) in 1993 and the United States Environmental Protection Agency (US EPA) in 2001 reduced the limit of arsenic in drinking water from 50 μg/L to 10 μg/L (Pokhrel and Viraraghavan, 2006).

Sources of arsenic pollution

Arsenic is the 20th most abundant element on earth. It is released into the environment in many ways such as weathering and volcanic eruptions, and may be transported over long distances as suspended particulates and aerosols through water or air due to various natural processes. Arsenic emission from industrial activity also accounts for widespread contamination of soil and groundwater environment (Jacks and Bhattacharjee, 1998; Juillot *et al.*, 1999). Arsenic is extracted into the groundwater as components of geologic formations. Arsenic emissions to the atmosphere are reported on global, regional and local scales (Nriagu, 1988; Pacyna, 2001). Once introduced into the atmosphere (including lithosphere and hydrosphere), it may circulate in natural ecosystems for a long time depending on the prevailing geochemical environments (Boyle, 1973; Yan chu, 1994).

Arsenic in soil

Arsenic is known to occur naturally in the earth's crust, metal ores (soils and rocks) and sediments both in organic and inorganic forms (Stolz *et al.*, 2006) in detectable quantities. It may also occur as sulphides, oxides or salts of sodium, copper and iron among others (Tsai and Singh, 2009; Rosen and Liu, 2009). No clearly defined relationship exists between the arsenic content of soils and the parent material or climatic conditions under which the soils were formed. Extensive use of arsenate in copper smelting industries, metallurgical activities, pigments and insecticides are the major sources of arsenate in soil and natural waters (Bhargavi and Savitha, 2014).

Arsenic availability in ground waters

The arsenite and arsenate forms of arsenic occur most commonly in the aquatic environment. Arsenic is found in aqueous environments predominantly in oxidation states as 3+[As(III), arsenite] and 5+[As(V), arsenate]. The other oxidation states of arsenic include 0 (arsenic), 3" (arsine) (Jiang *et al.*, 2014). Arsenic contaminated water may also contain it in acid forms i.e. arsenous acid and arsenic acid or their derivatives. These acid forms are soluble forms of arsenic near neutral pH. These compounds are extracted from the underlying rocks that surround the aquifer. Arsenic reaches into groundwater during weathering of rocks and minerals followed by subsequent leaching and run-off. The main factors responsible for controlling arsenic speciation in groundwater include redox potential (Eh), adsorption/desorption, precipitation/dissolution, arsenic speciation, pH, presence and concentration of competing ions, biological transformation, etc. (Ghosh, 2010).

Arsenic pollution worldwide

Natural arsenic pollution is a global phenomenon. Occurrence of high concentrations of arsenic in environment has been recognized as a major public health concern in several parts of the world. The World Health Organization (WHO) in 2001 estimated that about 130 million people worldwide are exposed to arsenic concentrations above 50 μg/L whereas about 140 million people have been exposed to more than 10 μg/L arsenic in drinking water (Bagchi, 2007). Elevated arsenic level has been documented in 70 countries on all continents, except Antarctica. A total 42 countries have been detected with high arsenic pollution in which Asian countries are most affected. They are Bangladesh, China, India, Italy, Japan, Nepal, Taiwan, Thailand, Vietnam, Poland, Finland, Hungary, Spain, Canada, USA, Chile, Argentina, Mexico and New Zealand etc. (Jiang *et al.*, 2014; Shankar *et al.*, 2014). An estimated 36 million people in the Bengal Delta are at risk from drinking arsenic-contaminated water (Nordstrom, 2002). In Bihar, India, 40 % of 3000 tube wells exceed the WHO limit of arsenic levels and that 12% contained water at more than 20 times the limit (Pearce, 2003). WHO has described the situation of Arsenic contamination in Bangladesh as the largest poisoning of a population in history (Shankar *et al.*, 2014).

Arsenic contamination - Indian Scenario

In India, arsenic contamination of ground water was first detected in West-Bengal. After that many states, like Jharkhand, Bihar, and Uttar Pradesh in flood plain of the Ganga River; Assam and Manipur in flood plain of the Brahamaputra and Imphal rivers, and Rajnandgaon village in Chhattisgarh have chronically been reported with arsenic contaminated ground water. Ganga-Meghna-Bramhaputra basin of India is one of the major arsenic-contaminated hotspot in the world (Bhattacharya *et al.*, 2010). Nine districts in West Bengal have arsenic levels in groundwater above the WHO maximum permissible limit (Chowdhury *et al.*, 2000). Among the contaminated districts, Nadia district is severely affected with high level of arsenic contamination and large area coverage (Bhattacharya *et al.* 2009). The total number of arsenic-affected people in the country is about 1.48 crore as of March, 2017 as per current affairs (gktoday.in/tags/arsenic-contamination link).

Arsenic in north east India

Recent detection of arsenic in groundwater from large areas of north eastern region of India has ranged the bell of concern for millions of people. It was detected in parts of Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland Tripura and Sikkim (Singh, 2004; Devi *et al.*, 2009). A report (2007) of north eastern Regional Institute of Water and Land Management (NERIWALM) mentions arsenic levels in Assam, Manipur, Tripura and Arunachal Pradesh above 300 parts per billion (ppb). The 28,181 nos. of water sources located in Assam have been found contaminated with arsenic, iron and fluoride inorganic materials, followed by 2,931 in Tripura, 566 in Arunachal Pradesh, 136 in Nagaland, 124 in Meghalaya, 76 in Sikkim, 37 in Manipur and 26 in Mizoram (Devi *et al.*, 2009). In Assam (Chakraborti *et al.*, 2004), maximum arsenic concentration (490 μg/L) was observed in Jorhat (Titabor, Dhakgorah, Selenghat and Moriani blocks), Dhemaji (Sissiborgoan and Dhemaji blocks), Golaghat district (Podumani block) and Lakhimpur (Boginodi and Lakhimpur blocks) and Nagaon (Singh, 2004). In flood plain area of Assam viz. Barpeta, Dhemaji, Dhubari, Darrang, and Golaghat, the arsenic was found in between 100-200mg/L. In Manipur, arsenic was reported only in Kakching block area of Thoubal district. As per Agartala news (2007) arsenic (65-444mg/L) was found in Jirania and Bishalgarh in West Tripura district, Salema, Halahali, Kamalpur, Joynagar in Dhalai district, Sanitala, Rajbari, Dharmanagar, Kailishahar, Kanchanpur and Jampui in North Tripura district. In Nagaland, 7 locations in Mokokchung and 5 locations in Mon districts were detected with arsenic in groundwater (Singh, 2004). In Arunachal Pradesh, six districts were detected with arsenic contamination and maximum arsenic (618 mg/L) was found in part of Midland block of Dibang valley district. However, as per the investigation conducted in 2011 (Table 1), Papum Pare district of Arunachal Pradesh (which was earlier detected with high arsenic) was found safe from arsenic contamination, as compared to its neighbouring district of Assam i.e. North Lakhimpur where very high arsenic was detected in ground water.

Arsenic removal from ground water

The available arsenic removal methods may be grouped as:

1. Chemical/Physical Treatment Technologies (precipitation oxidation coagulation/filtration, adsorptive media, ion exchange, reverse osmosis),
2. Biological Treatment Technologies (using biological sulfate reduction to precipitate arsenic and heavy metals),

3. Modern Treatment Technologies (electrochemical arsenic remediation (ECAR), regenerating adsorptive media (AM), nanomaterials based arsenic removal system) and
4. Bioremediation Technologies (using microorganisms and plants).

In addition, three alternate arsenic removal technologies are also used viz. (i) Removal system based on alum and iron coagulation; (ii) Removal system based on sorptive filtration using iron coated sand filter, and (iii) Removal system based on sorptive filtration using gravel bed containing iron sludge (Reinsel, 2015) including sludge disposal.

Bioremediation of arsenic using microorganisms

Bioremediation is considered as an alternative processing technology for removing the arsenic ions from polluted area. It is the technique of reducing or converting environmental pollutants into less toxic forms via naturally living organisms/ their systems. Microorganisms reduce the toxicity of contaminants by using them in their metabolic processes as energy source. Many naturally occurring microorganisms such as bacteria, algae and fungi or even a few plant species hold potentials to degrade or detoxify hazardous ingredients. They have developed different mechanisms like arsenite methylation, arsenite oxidation, arsenic volatilization etc. to transform more toxic arsenite to less toxic arsenate (Qin *et al.*, 2006).

Bacteria

A large number of bacteria have been reported to remove arsenic from liquid medium (Table 2). The bacteria strains with the ability to resist arsenic include *Acinetobacter, Agrobacterium, Alcaligene, Alkaliphilus oremlandii, Arthrobacter, Bacillus, Bosea, Bradyrhizobium, Citrobacter, Chromobacter, Clostridium, Cupriavidus, Desulfomicrobium, Enterobacter, Escherichia coli, Microbacterium oxydans, Ochrobactrum anthropi, Polyphysa peniculus, Pseudomonas, Psychrobacter rhodobium, Rhodococcus, Sinorhizobium, Staphylococcus, Sulfurospirillum, Thiobacillus, Vibrio, Wolinella,* an arsenic reducing bacteria from *Flavobacterium-Cytophaga* group and a ferum reducing bacteria such as *Geobacter* species (Lim *et al.,* 2014; Mumford *et al.,* 2012; Liao *et al.,* 2011). However, most of the bacteria could remove arsenic contents comparatively in lower percentages. *Lactobacillus casei* (DSM20011) can remove only 7.8±1.7% to 38.1±9.0% of As(V) from liquid medium (Halttunen *et al.*, 2007). A special type of enzyme 'arsenic oxidase' present in the protoplasm of arsenic oxidizing bacteria is responsible to oxidize arsenite to arsenate (Andreoni *et al.,* 2012). Bacterial strain named *Aneurinibacillus aneurinilyticus* can remove 51.99% of arsenite and 50.37% of arsenate from liquid medium (Dey *et al.,* 2016). A number of *Bacilli* have been used by many researchers (Dey *et al.*, 2016; Lim *et al.*, 2014; Ghodsi *et al.*, 2011) that could remove maximum 51-60 % of arsenic. The bacterial strain *Pseudomonas putida* (MTCC 1194), *Ralstonia eutropha* (MTCC 2487) could remove 60% and 67 % arsenic respectively (Mondal *et al.*, 2008). Iron oxidizing bacteria was removing 80 % of arsenic from aqueous medium (Katsoyiannis *et al.,* 2002). A genetically engineered *Escherichia coli* expressing ArsR gene could remove 98% of arsenic. ArsR is a metalloregulatory protein, which offers high affinity and selectivity toward arsenite, was overexpressed in *Escherichia coli* and resulted in elevated levels of arsenite bioaccumulation but also a severe reduction in cell growth (Kostal *et al.*, 2004), however; bacterial strain *Marinomonas communis* has removed 100% arsenic i.e. 45% in cytosol fraction, and 55% in membrane-associated fraction (Takeuchi *et al.,* 2007). *Sulfurospirillum arsenophilum* and *Chrysiogenes arsenatis* are notable arsenic metabolising bacteria. Instead of respiring with oxygen, *Chrysiogenes arsenatis* respires using the most oxidized form of arsenic, arsenate hence can be used in bioremediation (Afkar, 2012).

Algae

A few species of algae such as *Ankistrodesmus convolutes, Chlorella vulgaris, Euglena gracilis, Fucus gardneri, Lessonia nigrescens, Spirulina platensis* etc. have also been reported to possess bioremediation capabilities (Table 2). The species *Tetraselmis chuil* (Irgolic *et al.,* 1977) has shown high tolerance against arsenic. *Ankistrodesmus convolutes*, *Chlorella vulgaris, Euglena gracilis, Scenedesmus bijuga, Spirulina platensis* and a mixed culture of Oscillatoria-Lyngbya could remove 43% to 64% of arsenic after 21 days of incubation from liquid medium at 0.1mg/L concentration (Samal *et al.*, 2004). Other algal species include *Ankistrodesmus convolutes, Euglena gracilis, Fucus gardneri, Lessonia nigrescens, Spirulina platensis* which have removed 43 – 64 % of arsenic at 0.1mg/L concentration, *Spirulina platensis* after 21 days of incubation. *Scenedesmus abundans* could remove high (70%) arsenic contents (Jahan *et al.,* 2006). *Lessonia nigrescens* (Hansen *et al.,* 2006) have maximum removal capacities of 45.2 mg/g (pH = 2.5), 33.3 mg/g (pH = 4.5), and 28.2 mg/g (pH = 6.5). A *Chlorella* strain could also remove 50% of arsenite from a solution (Beceiro-Gonzalez *et al.,* 2000). *Fucus gardneri*, a brown algae, was also found to be arsenic tolerant (Lim *et al.*, 2014). *Spirogyra hyalina* dried biomass was used as biosorbent for removal of arsenic (Kumar and Oommen, 2012).

Fungi

Fungi are being increasingly investigated for mycoremediation of arsenic due to their abilities to remove, sequester, and/or detoxify arsenic by more efficient and environmentally sound methods than traditional metal remediation and by other microorganisms (Singh, 2006). Owing to specific properties of fungi, like their mycelia nature, high growth capacities and production of variety of enzymes also make them a potential agent of arsenic bioremediation; however less emphasis has been paid to this group of organisms. The ability of filamentous fungi to volatilize arsenic is demonstrated by many scientists as compare to unicellular yeasts. Fungi, being able to grow in diverse environments and have tolerated high amount of arsenic, showed fast growth with high cell wall binding and high metal uptake capacities (Visoottiviseth and Panviroj, 2001; Vala and Sutariya, 2012; Rodriguez *et al.*, 2013). Zafar *et al.* (2007) have observed that fungi are able to tolerate, biosorb and detoxify metals by several mechanisms including valence transformation, extra and intracellular precipitation and active uptake. Recently Lim et al. (2014) has reported arsenic resistant filamentous fungi *Fomitopsis pinicola*, *Penicillium gladioli*, *Fusarium oxysporum meloni* and *Scopulariopsis koningii*.

Many fungal species are capable of transforming inorganic arsenic compounds, arsenite and arsenate by biomethylation, into methylated arsenic species such as monomethylarsonic acid (MMA), dimethylarsinic acid (DMA), trimethylarsine (TMA), and trimethylarsine- oxide (TMAO). Three of these, MMA, DMA and TMAO, are less toxic than arsenate, arsenite and TMA (Visoottiviseth and Panviroj, 2001). *Penicillium* and *Aspergillus* spp. are the two most metal tolerant species, showing enhanced growth even at high concentrations (2000 mg/L) of heavy metals (Valix *et al.*, 2001). A number of arsenic resistant *Penicilli* with 24 different fungi and 7 bacterial species were isolated from arsenic contaminated ground waters (Shrivastava *et al.,* 2012). The main factors that affect biovolatilization by fungi such as cultivation time, chemical treatment, live/dead cells etc. A strain of *Aspergillus candidus* isolated from waters of Bhavnagar coast, Gulf of Cambay, west coast of India could remove high amount of arsenic after 3 days cultivation (Vala, 2010). It was amounted in *Scopulariopsis brevicaulis* which was able to biovolatilize 0.007-0.014mg/L of arsenic after 7 days cultivation from culture medium (Pearce *et al.*, 1998). The filamentous fungi *Penicillium coffeae* was able to remove 66.8 % of arsenic from liquid medium after treating with alkali (Bhargavi and Savitha, 2014). Arsenic removal using modified fungal biomass of *Aspergillus niger* (ATCC # 11414) treated with iron oxide (Pokhrel and Viraraghavan, 2006) could remove up to 95% As(V) and 75% As(III). Not only live fungal cells but autoclaved fungal mats collected as waste product during black tea fermentation have also been used to remove arsenic after pre-treatment with $FeCl_3$. It had removed 100% of As(III) and Fe(II) after 30 min and 77% of As(V) after 90 min contact time (Murugesan *et al.*, 2006). Iron oxide coated fungal biomass of *Paecilomyces* species collected from polluted air with industrial vapors in Mexico could remove 8.4% of arsenic after 24 hours incubation at pH 7 (Rodriguez *et al.*, 2013). Fungal biomass of 10 out of 15 fungal strains collected from agricultural soils of West Bengal, India removed 10.92% to 65.81% arsenic biologically from the liquid medium (Srivastava *et al.*, 2011). Two arsenic resistant strains of *Aspergillus flavus* and *A. niger* were isolated from polluted sites of Kolkata were capable of removing 50%-76% of arsenic from different arsenic enriched medium (Mukherjee *et al.*, 2013). *Aspergillus niger, Trichoderma viride*, and *Penicillium glabrum* (Urik *et al.*, 2007) have removed 0.010 to 0.067 μg/L arsenic whereas *Penicillium purpurogenum* could remove 3.4 mg/g of arsenic (Say *et al.*, 2003). Cernansky *et al.*, 2009 showed that fungal species *Neosartorya fischeri, Aspergillus clavatus* and *Aspergillus niger* isolated from soil samples of a mining site highly contaminated with arsenic can volatile approximately 23% of arsenic from all arsenic rich culture medium. *Aspergillus clavatus* had biovolatilzed 20-22.1% of arsenic (Urik *et al.*, 2007). Edvantoro *et al.*, (2004) used augmentation of particular arsenic volatilizing fungal strains (*Penicillium* sp. and *Ulocladium* sp.) for bioremediation of cattle-dip site soils contaminated with arsenic. After chemical modification, *Penicillium chrysogenum* reported with higher removal ability as compare to unmodified biomass (Loukidou *et al.*, 2003). Three filamentous fungi viz. *Aspergillus niger, Serpula himantioides* and *Trametes versicolor* were investigated for their potential abilities to accumulate (and possibly solubilize) arsenic from an agar environment consisting of non-buffered mineral salts media amended with 0.2, 0.4, 0.6 and 0.8% (w/v) arsenopyrite (FeAsS). Arsenic solubilisation was observed in order of *A. niger*>*S. himantioides*>*T. versicolor* with *T. versicolor* as the most effective species. *Aspergillus niger,*

Serpula himantioides and *Trametes versicolor* accumulate and solubilize high arsenic from agar media with non-buffered mineral salts (Adeyemi, 2009). Four out of fifteen fungal species isolated from arsenic-contaminated agricultural fields in West Bengal, India, the isolates of *Westerdykella, Trichoderma, Rhizopus* and *Lasiodiplodia* improved soil nutrient content and enhanced plant growth in arsenic infested area when inoculated in plants. The use of these fungi has been recommended as bio-inoculants for plant growth promotion and improved soil properties in arsenic-contaminated agricultural soils (Edvantoro *et al.*, 2004; Srivastava *et al.*, 2012). Higher As bioaccumulation and biovolatilization has been observed in seven fungal strains, *Aspergillus oryzae*; three *Fusarium* spp., *Aspergillus nidulans*, *Rhizomucor variabilis* and *Emericella* sp. These strains have shown significant plant growth promotion in some plants species (Singh *et al.*, 2015). Other highly arsenate tolerant strains (up to 10000 mg/L) belong to *Rhizopus*, *Microdochium*, *Chaetomium*, *Myrothecium*, *Stachybotrys*, *Rhizomucor*, *Fusarium*. The arsenic resistant fungal species of *Penicillium*, *Aspergillus*, *Neosartorya* and *Gliocladium reseum* and a yeast *Candida humicola* have also been reported as potential agents

Table 1. Arsenic concentration in ground water samples

Sl. No.	Site of collection	Coordinates Latitude	Longitude	Arsenic concentration (ppb)
North Lakhimpur District, Assam				
1.	Gandhalipar1	N27°11.293´	E94°02.366´	193.2
2.	Khanajan	N27°13.335´	E94°01.739´	161.1
3.	Nalkata1	N27°16.846´	E94°03.592´	103.55
4.	Gosaipathar 1	N27°00.976´	E93°54.176´	44.9
5.	Bogolijan,	N27°08.710´	E93°45.031´	23.95
6.	Lakhimpur Town	N27°14.446´	E94°04.969´	20.63
7.	Bihlanganiya	ND	ND	09.92
8.	Gandhalipar 2	N27°221.258´	E93°44.726´	7.76
9.	Rangajan	N27°00.070´	E93°53.290´	4.88
10.	Nalkata 2	N27°15.159´	E94°04.698´	2.58
11.	Kachikata	N27°00.210´	E93°53.974´	<2.0
12.	Gosaipathar 2	N27°02.038´	E93°53.512´	<2.0
13.	Rajbari Tinali	N27°01.818´	E93°52.944´	<2.0
Arunachal Pradesh				
14.	Doimukh 2, Papum Pare	N27°08.710´	E93°45.031´	23.04
15.	NERIST 1, Nirjuli, Papum Pare	ND	ND	09.92
16.	Doimukh 3, Papum Pare	N27°08.750´	E93°45.141´	9.8
17.	Doimukh 6, Papum Pare	N27°08.437´	E93°45.979´	4.71
18.	Yazali 2, Lower Subansiri	N27°32.495´	E93°48.932´	2.44
19.	Yazali 1, Lower Subansiri	N27°27.44´	E93°45.855´	<2.0
20.	Zero 1, Lower Subansiri	N27°35.745´	E93°50.370´	<2.0
21.	Zero 2, Lower Subansiri	ND	ND	<2.0
22.	Zero 3, Lower Subansiri	N27°07.785´	E93°44.303´	<2.0
23.	NERIST (5 spots) Nirjuli, Papum Pare	N27°07.590´	E93°44.218´	<2.0
24.	Doimukh 1, Papum Pare	N27°08.664´	E93°45.216´	<2.0
25.	Doimukh 4, Papum Pare	N27°08.663´	E93°45.274´	<2.0
26.	Doimukh 5, Papum Pare	N27°08.545´	E93°45.810´	<2.0

ND- Not detectable

Table 2. Microorganisms showing arsenic bioremediation ability

Group of microorganisms	Arsenic removal/tolerance capacity	Reference
Bacteria	**Bacteria**	**Bacteria**
Aneurinibacillus aneurinilyticus, *Bacillus* sp.	Removed 51.99% and 51.45% of arsenite and 50.37% and 53.29% arsenate respectively	Dey *et al.*, 2016
Alkalilimnicola ehrlichii, *Bacillus sphaericus*	Arsenite oxidation by *ArxA* and resistance by *ars C* genes	Lim *et al.*, 2014
Bacillus selenitireducens, Chrysiogenes arsenatis, Pyrobaculum arsenaticum, Sulfurospirillum arsenophilum, Sulfurospirillum barnesii	Reduced arsenate to arsenite under anaerobic condition	Afkar, 2012
Bacillus macerans,B. megaterim,Corynebacterium vitarumen	Removed 60%, 38% and 43% arsenite	Ghodsi *et al.*, 2011
Neisseria mucosa, Rahnella aquatilis	Reduced arsenate and selenate	Youssef *et al.*, 2009
Bacillus indicus Pseudomonas putida Ralstonia eutropha	Removed 61%, 60% and 67% arsenic from liquid medium	Mondal *et al.*, 2008
Lactobacillus casei DSM20011	Removed arsenate (7.8 % to 38.1 %)	Halttunen *et al.*, 2007
Marinomonas communis	100% arsenic removal (45% in cytosol and 55% in membrane)	Takeuchi *et al.*, 2007
Escherichia coli containing ArsR gene	Removed 98% arsenite	Kostal *et al.*, 2004
Iron oxidizing bacteria	Removed 80% Arsenic	Katsoyiannis *et al.*, 2002
Alcaligenes faecalis, *Comamonas terrae*	Oxidized Arsenite to arsenate	Philips and Taylor, 1976; Chitpirom *et al.*, 2009
Algae		
Spirogyra hyalina	Highest arsenic uptake peak at 40 mg/L in 120 min	Kumar and Oommen, 2012
Chlorella vulgaris Beijerinck var. vulgaris	Removed 40 ppm arsenic	Maeda *et al.*, 2006
Lessonia nigrescens	Removed 45.2, 33.3 and 28.2 mg/g arsenic at 2.5, 4.5, 6.5 pH respectively	Hansen *et al.*, 2006
Scenedesmus abundans	Removed 70% of arsenic	Jahan *et al.*, 2006
Ankistrodesmus convolutes, Chlorella vulgaris, Euglena gracilis, Oscillatoria-Lyngbya mixed culture, *Scenedesmus bijuga, Spirulina platensis*	Removed arsenic 64%, 50%, 47%, 45% and 43% each respectively	Samal *et al.*, 2004
Chlorella sp.	Removed 50% arsenite	Beceiro-Gonzalez *et al.*, 2000
Fungi		
Chaetomium sp.*Fusarium* sp.*Microdochium* sp.*Myrothecium* sp.*Rhizomucor* sp.*Rhizopus* sp.*Stachybotrys* sp.	Tolerates high arsenate (upto 10 000 mg/L)	Singh *et al.*, 2015
Penicillium coffeae	Arsenic adsorption with alkali treated biomass (66.8 %) and with untreated dead biomass (22.9 % - 60.2 %)	Bhargavi & Savitha, 2014
Aspergillus flavus,Aspergillus niger	Removed 50% - 76 % arsenic	Mukherjee *et al.*, 2013
Paecilomyces sp.	Removed 8.4 % of arsenic at pH 7	Rodriguez *et al*, 2013
Westerdykella sp. *Trichoderma* sp., *Rhizopus* sp.*Lasiodiplodia* sp.	Used as bioinoculants in arsenic-contaminated agricultural soils	Srivastava *et al.*, 2012
Aspergillus flavus Rhizopus sp.	Higher biomass accumulation in As(III) medium	Vala and Sutariya, 2012
Aspergillus (3 species), *Neocosmospora* (2 species) *Penicillium* spp. (2 species), *Rhizopus* sp., *Trichoderma* sp.,Mycelia sterila	Remove 10.92 to 65.81% arsenic	Srivastava *et al.*, 2011
Aspergillus candidus	Removed high amount of arsenic	Vala, 2010
Aspergillus niger, Serpula himantioides Trametes versicolor	Accumulated and solubilize arsenic from agar media with non-buffered mineral salts	Adeyemi, 2009
Aspergillus clavatusAspergillus nigerNeosartorya fischeri	Each volatilized 23% arsenic	Cernansky *et al*, 2009
Aspergillus niger	Removed 0.010 - 0.0675Øßg/L arsenic	Urik *et al*, 2007
A. niger A	Biovolatilized arsenic (25.2 – 26.8%)	
A. niger B	Biovolatilized arsenic (9.2 – 10.3%)	
Aspergillus clavatus	Biovolatilized arsenic (20 – 22.1%)	
Penicillium glabrum	Biovolatilized arsenic (25.2 – 26.2 %)	
Trichoderma viride	Biovolatilized arsenic (4 – 9.3%)	
Aspergillus niger treated with iron oxide	Removed 95% As(V) and 75% As(III)	Pokhrel and Viraraghavan, 2006
Penicillium sp. *Ulocladium* sp.	Bioremediation of arsenic contaminated soils	Edvantoro *et al.*, 2004

Penicillium chrysogenum	Higher arsenic removal by chemically modified than unmodified fungal biomass	Loukidou *et al.*, 2003
Penicillium purpurogenum	Removed 3.4 mg/g of arsenic	Say *et al.*, 2003
Scopulariopsis brevicaulis	Biovolaitlized 0.007–0.014 mg/L of arsenic	Pearce *et al.,* 1998

for arsenic removal through bioaccumulation and biovolatilization (Visoottiviseth and Panviroj, 2001; Urik *et al.*, 2007; Cernansky *et al.*, 2009; Srivastava *et al.*, 2011). Table 2 indicates different fungal species with their arsenic removal/ tolerance capacities described so far. The experiments conducted in our lab with 10 arsenic tolerant filamentous fungi (Pramanik *et al.,* 2016) isolated from arsenic contaminated groundwater showed that all were able to remove high Arsenic contents (>80%). Out of 10 fungi, 6 could remove > 85% of Arsenite and 9 could remove >85% of arsenate from the arsenic enriched liquid media (data not published).

Conclusions

Recent research focussed in this review suggests that the problem of arsenic contamination of drinking water is assuming global dimensions and posing serious threat to human health. In India, northeast region have long been reported with arsenic contaminated ground water above WHO's permissible limit (10 μg/L). In spite of various precautionary and corrective measures adopted so far, new arsenic affected areas have been regularly reported. The control strategies (conventional and modern), thus, need to be reviewed and strengthened by schematic scientific patronages. Microorganisms such as bacteria, algae and fungi have shown great affinity towards many heavy metals including arsenic and reported as arsenic tolerant/resistant hence being utilised effectively for arsenic bioremediation. Although bacteria have developed various mechanisms to grow in arsenic environment, filamentous fungi have shown more promising results to remove arsenic from liquids. This review, hence, highlights the contributions of the various filamentous fungi which are potentially effective and readily available for arsenic removal. Many of these fungi are ubiquitous in nature hence can be easily accessed and utilized, however; a sustainable approach still needs to be developed in the form of an appropriate, economic and easy 'ready to use' technology for arsenic removal by these fungi.

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