

Review

# Arsenic Detoxification by As(III)-Oxidizing Bacteria: A Proposition for Sustainable Environmental Management

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Arsenic (As), which is ubiquitous throughout the environment, represents a major environmental threat at higher concentration and poses a global public health concern in certain geographic areas. Most of the conventional arsenic remediation techniques that are currently in use have certain limitations. This situation necessitates a potential remediation strategy, and in this regard bioremediation technology is increasingly important. Being the oldest representative of life on Earth, microbes have developed various strategies to cope with hostile environments containing different toxic metals or metalloids including As. Such conditions prompted the evolution of numerous genetic systems that have enabled many microbes to utilize this metalloid in their metabolic activities. Therefore, within a certain scope bacterial isolates could be helpful for sustainable management of As-contamination. Research interest in microbial As(III) oxidation has increased recently, as oxidation of As(III) to less hazardous As(V) is viewed as a strategy to ameliorate its adverse impact. In this review, the novelty of As(III) oxidation is highlighted and the implication of As(III)-oxidizing microbes in environmental management and their prospects are also discussed. Moreover, future exploitation of As(III)-oxidizing bacteria, as potential plant growth-promoting bacteria, may add agronomic importance to their widespread utilization in managing soil quality and yield output of major field crops, in addition to reducing As accumulation and toxicity in crops.

**Keywords:** Arsenic, environmental pollution, arsenic detoxification, microbial arsenite oxidation, bioremediation

## Introduction

Decontamination of hazardous substances is a challenge both in technological and scientific reality [1]. Arsenic (As) is considered as global threat among such hazardous soil and water pollutants, which has a negative impact on human health [2]. Since the beginning of geological time, As is ubiquitous to earth's crusts, soil, sediments, aquifers, and living things. It has become a significant global environmental issue during last few decades.

Geographical area of 0.173 million Km<sup>2</sup> in West Bengal, India, where several million people are under the threat due to continuous As exposure [3]. Drinking water is the primary source of dietary exposure to inorganic As in humans, due to its natural occurrence in aquifers. Besides soil contamination with As due to various anthropogenic activities, irrigation with As-contaminated groundwater results in the accumulation in crops, eventually which enter the food chain and cause widespread exposure to As [4]. Therefore, for the general population, consumption of As containing food and As-contaminated groundwater are the major reasons for hazardous impact of As on human health. Environmentalists are facing a huge challenge for a sustainable approach to

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detoxify the environment contaminated with As, the most common methods rely on various physico-chemical techniques, however, currently As-resistant microorganisms have been shown to be both economically and environmentally sustainable [5]. Since As has been present on earth since the beginning of time and As-resistant genes have been found in microbiota, a variety of resistance mechanisms have been common, which could be a better option for developing As detoxification method. This review gives an insight of prevalent As bioremediation applications with an emphasis on perspectives of applying indigenous As(III) oxidizing bacteria for possible As detoxification.

## Global Arsenic Contamination

Arsenic (As), a metalloid, ranked as the 20<sup>th</sup> most plentiful element in the earth's crust, is toxic to most living organisms. The continental crusts typically contain 2 to 3 mg/kg of As on an average [6]. As-contaminations either from geogenic or anthropogenic sources are badly jeopardizing public health globally, especially it is a huge concern in the Bengal delta of south Asia [4, 7]. The alluvial soil tract of Bangladesh and Gangetic plain of India are the main geogenic sources of As, where reports of arsenic availability in soil or water are above the recommended level [4]. Out of several mineral forms of As, the principal forms can be classified into arsenates, and arseno-pyritic salts. As(III) and As(V) are the most prevalent oxidation states of As in soil and water. Generally, in an oxidative environment, As(V) predominates, whereas in a reducing environment, As(III) is abundant.

## Arsenic Exposure and Related Health Concerns in Humans

Globally, millions of people consume As above the permissible level through drinking water due to the existence of As-rich geological formation in aquifers and/or anthropogenic behaviours in certain geographical areas [2, 5, 7]. Several crops like rice accumulate high amount of As easily from contaminated soil, so regular consumption of As accumulated food grains creates huge health concern among the people dwelling in such area. Arsenic is classified as an established carcinogen by the

WHO-IARC, an arm of the World Health Organization [2]. Various health ailments were reported as the major consequences upon prolonged consumption of As-contaminated water or food, collectively called arsenicosis [7]. Higher amounts of As accumulation in body can produce severe intoxication, leading to gastrointestinal problems, cardiovascular problems, dysfunction of neuronal system, and even may results fatality. According to the most recent WHO assessment, As exposure to humans from drinking water is the main cause of kidney, skin, and bladder malignancies [2].

## Conventional Arsenic Removal Technologies

The physico-chemical treatment techniques make up the majority of the traditional arsenic removal methods to date. Coagulation-precipitation, adsorption, ion exchange, membrane filtration etc. are examples of physico-chemical technologies. In the coagulation-precipitation process, coagulants convert soluble As forms into insoluble solids [8]. Physical adsorption of As on the surface of appropriate adsorbent results immobilization of As in water. When treating contaminated water through an ion exchange column, synthetic resins are utilized as the solid phase because they are effective at adsorbing As ions [9]. This metalloid can be eliminated from a water system via membrane-filtration, that involves a number of distinct processes, including electrodialysis, reverse osmosis, ultrafiltration, and nano-filtration [9].

All of these conventional procedures are not always environment friendly or cost-effective, often result release of hazardous chemicals, and are often tedious and time consuming. Hence, as an alternative, biological treatment processes like phytoremediation and microbial remediation might be good options and are getting huge attention currently. Phytoremediation or microbe-assisted phytoremediation is now being considered as potential tools to get rid of hazardous chemicals including toxic metals/metalloids from the environment [10]. Plants those having high As resistance, hyperaccumulation ability, high propagating ability, potential biomass productivity, and widespread dispersion are reported to be useful for As phytoremediation [10]. Microbial remediation is the deployment of microorganisms to remove, and to change harmful substances into less hazardous

forms in the ecosystem [11].

### Bacterial Interactions with As for Possible Resistance and Detoxification

Microorganisms have a variety of ways to interact with different toxic metals, making their use in heavy metal disposal and environmental remediation unique. The success of the microorganism-based remediation

method mostly depends on the exploitation of microorganisms' ability to survive under toxic metal contaminated habitat [11]. Microbial transformation is a key component of the biogeochemical cycle of As (Fig. 1), which has an impact on the solubility and distribution of various As forms in nature [7, 12]. As a part of survival strategy in the As-contaminated habitat, bacteria have developed a number of As-resistance mechanisms that use incredibly precise metabolic pathways to guard

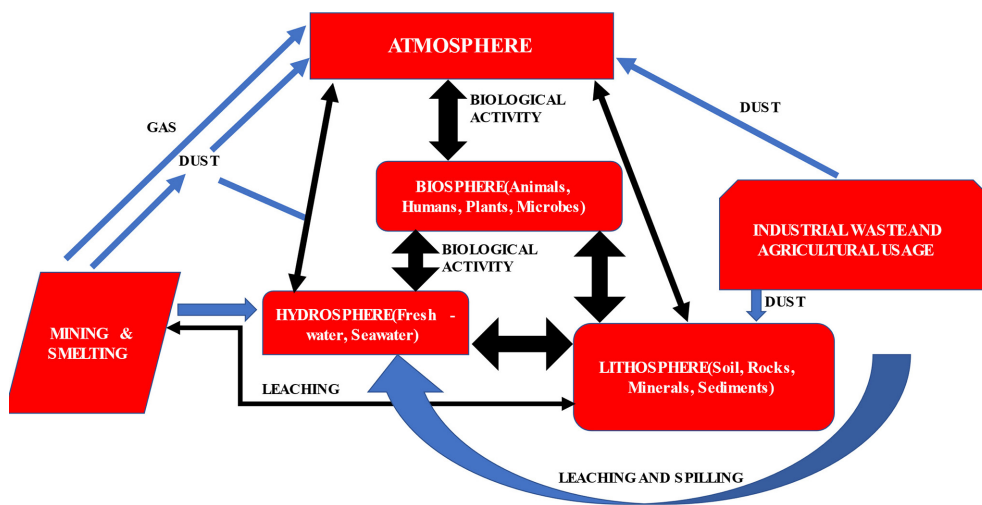


Fig. 1. Biogeochemical cycling of arsenic in nature.

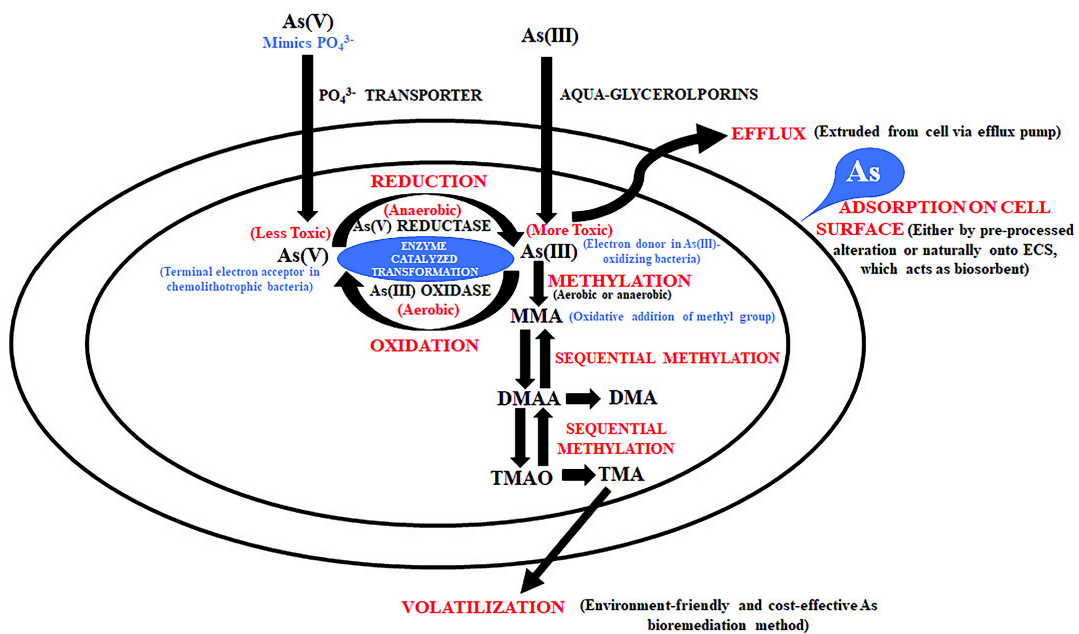


Fig. 2. Schematic presentation of various As-resistance mechanisms so far reported in bacteria. MMA: methylarsine; DMAA: dimethylarsinic acid; DMA: dimethylarsine; TMAO: trimethylarsine oxide; TMA: trimethylarsine; ECS: Extracellular substances.

against As toxicity [13, 14]. The principles of the mechanisms are briefly presented in Fig. 2.

Mobilization and immobilization —  $\text{Fe}^{+3}$ -reducing microbes produce energy by combining the reduction of  $\text{Fe}^{+3}$  with the oxidation of As(V)-containing electron sources. Arsenic is thus, mobilized into the environment, as a result of dissolution of minerals containing  $\text{Fe}^{+3}$  [15]. On the other hand, iron-oxidizing bacteria oxidizes  $\text{Fe}^{+2}$  to  $\text{Fe}^{+3}$  and the resulted electron oxidizes As(III) to immobilized As(V) [15]. Thus, both iron-oxidizing and iron-reducing bacterial community contribute in mobilization and immobilization of As species and play crucial role in geochemical cycle of As.

Adsorption — The most effective methods for employing microbes to detoxify different hazardous metals are adsorption approaches [16]. Since As(V) is present in neutral aqueous solutions as oxide anions, while As(III) behaves neutrally so far the charge is concern and thus both do not adsorb on microbial cell surface. Therefore, in order for As to be adsorbed, the microbes' surfaces either need to be altered through pre-processing [16], or it could happen naturally as a result of cell surface components-extracellular substances [17].

Methylation and volatilization — There are several publications on the methylation of As by fungus and other eukaryotes; conversely, there are few reports on the methylation of As by bacteria [18, 19]. It is seen to be a difficult possibility to use arsenic methylation to potentially bioremediate a polluted environment by volatilization. As(V) is converted to volatilized arsines through a series of reactions that begins with its reduction, and ends with inclusion of  $-\text{CH}_3$  group by oxidation [19]. The resulted methylated arsenicals may vary conditionally on the nature of the  $-\text{CH}_3$  group donor and the reaction process [18, 19]. Arsenic volatilization has been attributed by the function of *arsM* gene expression through its product ArsM, the As(III) S-adenosine methyl transferase [20–22].

Oxidation and reduction — A variety of microbiological metabolic processes contribute in As cycling, including both reduction and oxidation, in soil, sediment, and natural water systems [12, 13, 23]. As(III) and As(V) are the only ecologically significant inorganic As species, however, the biological processes contributing in As bio-recycling are rather multifaceted. In major cases, As(III) is more hazardous than As(V). Numerous chemolithoau-

trophic and heterotrophic bacteria participate in the transformation of As(III) to comparatively non-hazardous compound As(V) known as arsenate [24]. As(V) can be reduced by two separate physiological groups, each serving a different function. As(V) can be used as a terminal acceptor of electrons by various chemolithoautotrophic bacteria, including *Geospirillum arsenophilus*, *Sulfurospirillum barnesii*, *Desulfotomaculum auripigmentum*, and others [5, 7, 25]. This particular anaerobic respiration, known as dissimilatory reduction of As(V), is involved in the production of As(III), and subsequently, As leaching. Such microbial community can simply be selected using anaerobic settings and are found to be phylogenetically diversified group, indicating their anaerobic niche occupancy in the particular habitat [26]. The primary goal of the other group of bacteria that may reduce As(V) through cellular accumulation of As(V), eventually its reduction to As(III), and subsequently environmental release by efflux systems [25].

## As(III) Oxidizing Bacteria

Green first reported on As(III) oxidizing bacteria [27], and thereafter many environmental microbiologists documented As(III) oxidation by various bacterial communities [28, 29]. Majority of such bacterial strains were cultivated as lithotrophs and continued to be able to employ As(III) as the specific electron donor [30]. As(III)-oxidizing heterotrophic bacteria can receive energy through As(III) oxidation and as a result, arsenic detoxification occurred [31].

For the detoxification of waste or ground water contaminated with As, the biological oxidation of As(III) using bacteria is of special importance. By turning more harmful As(III) into less mobile and less toxic As(V) molecules, microbial oxidation of As is a crucial link in the global As cycle [31]. To date numerous As(III)-oxidizing bacteria from various aquatic and soil habitats have been isolated, and were reported to be phylogenetically diverse (Table 1) [5, 28, 32–57].

Since As(III) can operate as an electron donor during this process, As(III) oxidation is an energy-producing reaction [13, 23, 25]. To date diverse microbial community have been reported to obtain energy by redox processes of As oxyanions [14]. The rapid oxidation of As(III) in a hot spring habitat has been attributed to microbial mats

**Table 1. As(III) oxidizing bacterial diversity and their environmental sources.**

As(III) oxidizing bacteria	Source environment	References
<i>Pseudomonas</i> sp. AK9	Soil	32
<i>Ensifer adhaerens</i> M8	Gold tailings soil	33
<i>Thiobacillus</i> spp.	Soils and sediments	34
<i>Anaeromyxobacter</i> spp.		
<i>Citrobacter</i> sp. B5.12	Soil	35
<i>Delftia</i> spp. BAs29	Shallow aquifer	36
<i>Rhodococcus</i> sp.	Ground water	37
<i>Hydrogenophaga</i> sp. H7	Mine soil	38
<i>Bosea</i> sp. AS-1	Mine slag	39
<i>Micrococcus</i> sp. KUMAs15	Contaminated soil	40
<i>Bacillus</i> spp. As1	Shallow aquifers	41
<i>Ancylobacter</i> sp. TS-1	High Andean watershed	42
<i>Staphylococcus haemolyticus</i> HMR1	Fly Ash Pond	43
<i>Staphylococcus pasteurii</i> HMR2		
<i>Staphylococcus hominis</i> HMR11		
<i>Brevibacillus borstelensis</i> HMR16		
<i>Micrococcus</i> sp. HMR9		
<i>Bacillus subtilis</i> strain HMR5		
<i>Microvirga indica</i> S-MI1b sp. nov.	Industrial waste	44
<i>Acidothiobacillus ferrooxidans</i>	Soil	45
<i>Shinella</i> sp. N1S1	Contaminated soil	46
<i>Brevibacterium</i> sp. YZ-1	Contaminated soil	47
<i>Pseudomonas</i> sp. HN-2	Contaminated soil	48
<i>Pseudomonas</i> sp.	Rhizosphere	49
<i>Aliihoefler</i> sp. 2WW	Contaminated soil	50
<i>Arthrobacter</i> sp. Datong-1	Shallow aquifer	51
<i>Variovorax</i> sp. MM-1	Contaminated soil	5
<i>Herminiimonas arsenicoxydans</i> ULPAs1	Industrial sludge	52
<i>Agrobacterium tumefaciens</i>	Soil	53
<i>Microbacterium lacticum</i>	Sewage sample	54
<i>Agrobacterium albertimagni</i> AOL15	Aquatic macrophyte	28
<i>Thermus</i> HR13	Terrestrial geothermal habitat	55
<i>Hydrogenobacter acidophilus</i>	Hot spring	56
$\alpha$ -Proteobacteria NT-26	Gold mine	57

made primarily of filamentous microorganisms [56]. Evidence for As(III)-assisted anoxygenic photosynthesis was reported among the mat-forming photosynthetic bacteria in lentic ecosystem [58]. Additionally, they offered proof of purple bacteria growing photoautotrophically, assisted by As(III) oxidation to As(V). As(III) is used as an energy source in chemolithoautotrophic microbes [57]. As(III) was also reported to be oxidized

outside the cells As(III) oxidase [56] and is currently gaining importance for enzymatic oxidation under cell-free conditions.

Oxidation by As(III) Oxidase — As(III) is converted to As(V) through the process of oxidation, which is carried out by the enzyme As(III) oxidase, a product of *aiiBA*. As(III) oxidase is extensively present in heterotrophic and chemolithoautotrophic bacteria, was first identified

in *Alcaligenes faecalis*, though there may be some other additional features in the As(III) oxidase depending on the bacterial sources [52, 57, 59–61]. The chemolithotrophic bacterial strains showing As(III) oxidase activity, were earlier reported from the genera *Agrobacterium*, *Pseudomonas*, *Alcaligenes*, *Achromobacter*, and *Thiobacillus*, and were isolated from an environment contaminated with arsenic [62]. Most bacterial strains that oxidize As(III) are heterotrophic, which means they get their energy from oxidizing As. In phylogenetically different microbes, including those belonging to the  $\alpha$ -,  $\beta$ -,  $\gamma$ -Proteobacteria, Actinobacteria, Aquificae, Bacteroidetes, Chlorobi, Chloroflexi, Crenarchaeota, *Deinococcus*, *Thermus*, *Firmicutes*, and *Nitrospira*, homologs of the genes for AioBA have been discovered thus far [63].

**As(III) Oxidase Genes** — The As(III) oxidase is a heterotetramer AioBA catalytic protein, which is made of a large (AioA) and a small subunit (AioB) encoded by *aioA* and *aioB* respectively [23]. AioA is consisted of four domains, the domain I interacts molybdenum and a Rieske subunit, while rest of the domains are responsible for [3Fe-4S] cluster binding [64]. The Rieske [2Fe-2S] domain present in AioB is also reported to associated with various oxidase or components of electron transfer chains [64]. According to a recent study, AioBA also functions as an antimonite oxidase, demonstrating the complexity of AioBA's role [65]. Other As(III) oxidase like ArxA was also reported in certain bacteria inhabiting in lakes with high salinity and alkalinity [66]. *In vitro*, ArxA possesses dual function for both oxidation and reduction depending on the redox state of arsenic, and it represents a unique evolutionary branch of As(III) oxidases [67, 68]. Additionally, trivalent organoarsenicals such roxarsone and methylarsenate are usually added hazardous over inorganic counterparts [69, 70]. Arsenic resistance operons in many bacteria contain *arsH*, which encodes ArsH, a representative of the NADPH-dependent FMN oxidoreductase superfamily that oxidizes trivalent organoarsenicals [69]. As(III) oxidation-related genes have been amplified and cloned in large numbers [71].

## Novelty of As(III)-Oxidizing Microbes in Environmental Arsenic Remediation

Capacity of enzymatic oxidation of As(III) by various

As(III)-oxidizing bacteria are considered to be the prospective candidates for detoxification of areas having higher level of arsenic [72]. As(III)-oxidizing bacteria can directly alter the redox states of arsenicals, though they can also facilitate the accumulation of As by plants. For instance, alfalfa showed increased growth and arsenic-uptake efficiency when inoculated with *Ensifer* sp. M14 strain in the soil [73], this feature could be another approach for removing As from soil, popularly known as microbe-assisted phytoremediation. Microbial As(III) oxidation or leaching in some cases is dependent on the availability of iron in the environment. As(III)-oxidizing microbes are utilized as biological tools in association with iron for As detoxification and to stabilize arsenic level in soil [74, 75]. *Brevibacterium* sp. YZ-1, an As(III)-oxidizing bacterium, and biogenic schwertmannite may be able to immobilize As in the extremely contaminated environment [75]. Oxidation of As depends on iron-oxidizing bacteria as well. Iron-oxidizing bacteria *viz.* *Bacillus* sp. T2, *Bacillus* sp. TF1-3, *Pseudomonas* sp., and *Yangling* I4, those are resistant to As, could increase reduce As accumulation in brown rice [76]. Combining chemical treatments with As(III)-oxidizing bacteria are potential methods for removing or immobilization of As.

## Conclusion

Due to its toxicity, endurance, and bioaccumulation, As is a hazardous metalloid, just like other toxic metals. In nature, bacteria contribute a huge role in chemical cycling of As owing to their acquired resistance, and thus could be the potential tools in As decontamination, especially in the affected area. Oxidation of As(III) to As(V) is generally perform by As(III)-oxidizing microbes, leading to higher rate of immobilization of arsenic on solid surfaces. Additionally, immobilized As(V) could easily be separated from the ambient condition, especially for the detoxification of drinking water by eco-friendly physico-chemical methods. Further exploitation of this ability of As(III)-oxidizing bacteria by utilizing them as Plant Growth Promoting Rhizobacteria, may result in reduction of As accumulation and toxicity in plants, thereby avoiding human As exposure via crops. It is another aspect of the novelty of As(III)-oxidizing bacteria in environmental As remediation. Thus, it can be concluded that As(III)-oxidizing bacteria are probably

one of the most preferable tools for As bioremediation in the present scenario for environmental sustainability.

## Conflict of Interest

The authors have no financial conflicts of interest to declare.

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