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REVIEW PAPER

Arsenic and Environment: A Systematic Review on Arsenic Sources, Uptake Mechanism in Plants, Health Hazards and Remediation Strategies

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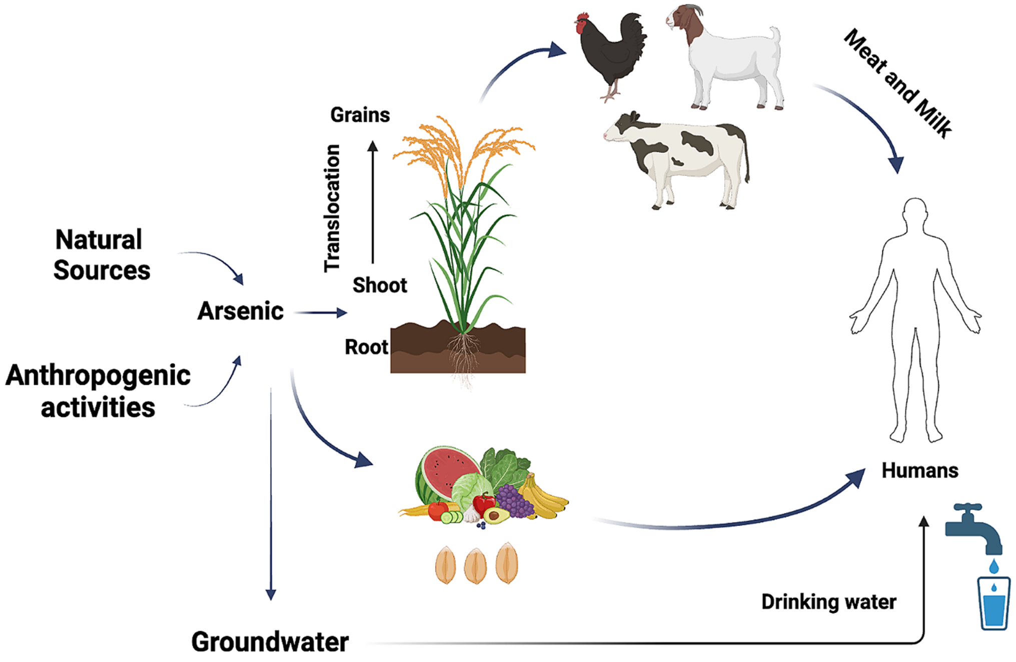
Abstract

Arsenic, a metalloid that exists by nature, reaches the earth either by natural or anthropogenic events and is considered an emerging pollutant. The existence of arsenic in soil systems is a fate to the environment since it is mobile and being transported to other systems because of its bioavailability and speciation process. Arsenic transformation in the soil and its thorough understanding of how it enters plant systems are crucial. Notably, transporters are responsible for most of the arsenic that enters the plant system. Consumption of crops or animals and drinking water polluted with arsenic are the prime factors in transmitting arsenic to people. Severe adverse effects on humans arise as an outcome of long-term contact with arsenic-rich foodstuff and water. An effort has been made to outline the several sources and their dynamics in the surroundings and health impact on humans in this review. In addition, various strategies have been practiced to remove arsenic in the soil and water systems is also addressed.

Graphical Abstract



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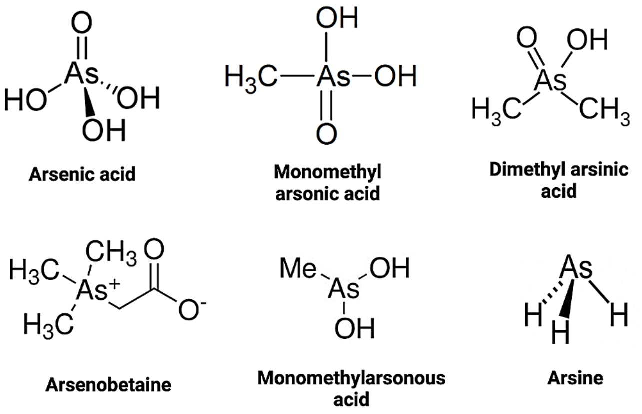
Keywords Arsenic · Speciation · Bioavailability · Mobility · Groundwater · Toxicity

1 Introduction

Arsenic (As) is one of the crucial metalloid elements and is recognized as the 20th most profuse element [1–3] present in the earth's crust. Arsenic holds three different allotropic forms in the environment such as grey, yellow, and black, and exists in 4 valence states −3, 0, +3, and +5 [4]. In the universe, arsenic occurs in inorganic and organic forms and exhibits both metallic and non-metallic properties. The prevalent inorganic forms of arsenic are arsenite [As (III)], arsenic acid, arsenate [(As (V)], and arsenious acid. Among them, arsenite is highly toxic and mobile (25–60 times) when compared with others [5]. Similarly, arsenic in organic form also occurs in the soil, and it can be transported readily. Monomethyl arsonic acid (MMA), arsenobetaine, and Dimethyl arsinic acid (DMA) are the most frequent organic forms of arsenic [6, 7]. The incidence of organic arsenic compounds in the natural world come about through methylation by microbes like bacteria, fungi, yeast, and animals [8]. The prevalence of inorganic arsenic is comparatively higher in the soil and groundwater than in the organic form. As (V) is preferably high in aerobic soils and As (III) in the anaerobic condition in the case of submerged soils [9]. However, interconversion happens between these two states due to biotic and abiotic processes further changed by pH and redox potential. In general, organic forms are less toxic at low concentrations rather inorganic forms of arsenic are extremely poisonous to humans, plants, and other organisms [10]. Arsenic is found to be phytotoxic, carcinogenic, and bio-toxic even at low concentrations [11], and the level of toxicity is associated with the degree of metabolic rate and its accrual in the tissues. In general, arsenic toxicity follows the order $AsH_3 > As^{3+} > As^{5+} >$ RAs - X. The structures of different arsenic compounds are schematically represented in Fig. 1.



Arsenic acid **Monomethyl arsonic acid** **Dimethyl arsinic acid**

Arsenobetaine **Monomethylarsonous acid** **Arsine**

Fig. 1 Structures of arsenic compounds

In nature, more than 200 arsenic-containing minerals occur [12] and are comprised of arsenolamprite, elemental arsenic, and para-arsenolamprite. The major classes of arsenic minerals are arsenites, arsenides, elemental arsenic, arsenates, and arsenosulfides as represented in Fig. 2. Arsenides and arsenosulfides are typically related to metamorphic and igneous rocks and anoxic hydrothermal ore deposits. Upon interaction with water molecule or oxygen, these minerals quickly transform into arsenates and arsenites. The most common mineral species containing arsenic is arsenopyrite [1]. Other minerals such as sulfides and sulfosalts contribute 20%, arsenates hold 60%, and arsenites, silicates, arsenides, oxides, and elemental arsenic contribute around 20% [13].

In the environment, arsenic possibly interacts with iron, phosphorus, sulfur, and silicon and is considered vital. Involvement of iron in the arsenic biogeochemical cycle, with iron oxyhydroxides interact with root areas of wetland plants or soil particulate surfaces and serve as adsorbents for arsenic [14]. Under a reducing environment, adsorbed arsenic is released and made available to plants. Similarly, the phosphate analog of arsenic can enter the plant with the help of phosphate transporters and interfere with phosphate metabolism. Sulfur is crucial in detoxifying arsenic upon uptake by complexation with thiol-rich peptides. This complex stops the arsenic mobility from the root region to the shoot arena. The significant role of Si transporters is also identified in the absorption of arsenic [15]. This review paper will postulate the perception of the origin of arsenic, its various forms, and its impact on the mobilization into plant species via different transporters and subsequent changes in the plant species upon absorption and its effect on humans. Further various mitigation measures to eliminate arsenic is also focused.

2 Arsenic and its Sources

Arsenic discharged into the living world, either anthropogenically or by nature, will exist indefinitely and cannot be removed or degraded. Arsenic emissions from anthropogenic sources exist in the range of 52,000 to 112, 000 tons [16]. Industrial operations such as tannery processing, textile, food processing, and other activities lead to the manifestation of arsenic in water, soil, and the air [17]. Similarly arsenic reaches the environment from municipal wastes and mining works. Weathering of rocks, volcanic activity, and rainfall leaching, as well as other processes such as the use of arsenic-containing insecticide, herbicide, pesticide, feed additives, and wood preservatives [18], contribute arsenic in the soil. Several arsenic compounds are dissolved in water

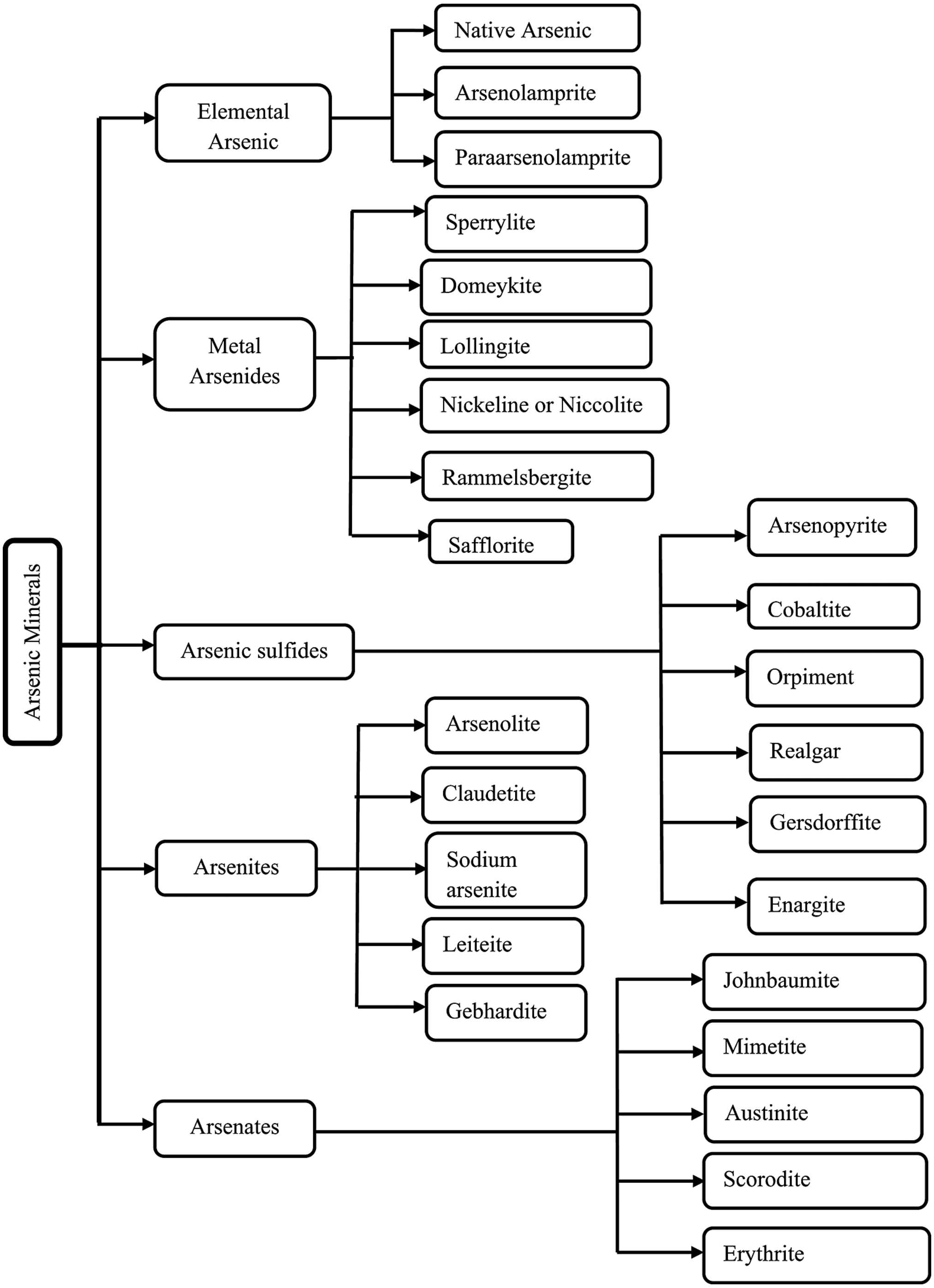
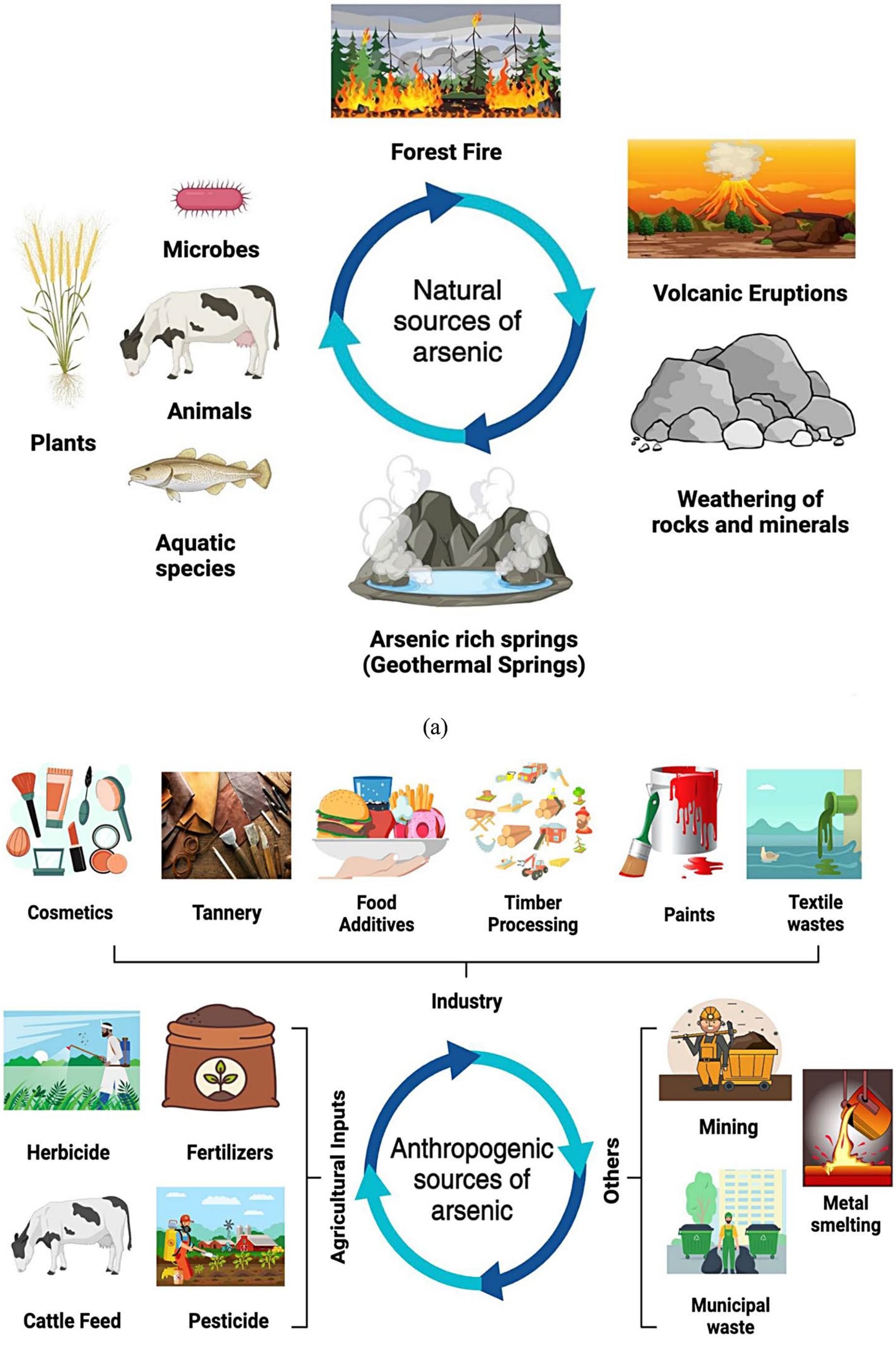


Fig. 2 Classification of arsenic minerals

and as a result, its prevalence in rivers, lakes, and subterranean water can be found. It was observed that arsenic presence in water can lead to different processes like precipitation, biotransformation, dissolution, oxidation-reduction reactions, sorption-desorption, and ligand exchange, all of which are affected by multiple parameters like pH, salinity, distribution, season, temperature, and the biota composition [3]. Sediment or soil can absorb arsenic from water which is retained in the soil and is being transported to plants and groundwater. Arsenic reaches the environment employing other such activities like forest fires and sea salt spray and is often produced as highly soluble oxides during the combustion process hence it is classified as atmospheric dust. The possible ways by which arsenic reaches the environment are illustrated in Fig. 3.

Fig. 3 Arsenic and its sources (**a**) natural sources (**b**) anthropogenic sources



3 Fate of Arsenic

Arsenic occurs via anthropogenic and natural activities remains a fate to the environment since it has multiple ways to reach other sources and results in high toxicity. Microbes, plants, animals, and humans are vulnerable to arsenic that exists in its form. The nature of the arsenic whether organic or inorganic form is vital since it determines its efficiency in the uptake by organisms. Arsenic fate in the soil environment is represented in Fig. 4.

4 Speciation and Bioavailability of Arsenic in the Environment

Speciation is the condition in which an element exists in multiple oxidation states, chemical forms, and mineral phases [19]. The speciation form of an element is crucial for its bioavailability and poisonousness. It is critical to examine the speciation form of arsenic than the overall concentration while assessing the bioavailability and toxicity. Understanding speciation is critical for comprehending the distribution, mobility, bioavailability, and toxicity of arsenic in their naturalistic setting. Another essential aspect of arsenic toxicity is its bioavailability, or the quantity of arsenic available for plant absorption. The bioavailability of arsenic is affected by soil features such as chemical and physical properties like cation-exchange capacity, organic matter, clay content, mineral content, texture, pH, and the presence of metal hydroxides and oxides such as Mn, Al, and others [20], bioaccumulation kinetics, ambient conditions, and rhizosphere soil modifications. Sequestration and age are the additional factors that alter the bioavailability of arsenic. Arsenic interaction with soil particles or co-precipitation with additional minerals reduces the bio accessibility in the soil.

5 Arsenic Dynamics in the Soil

The biogeochemical dynamics of arsenic are complex processes encompassing biotic and abiotic reduction-oxidation reactions and methylation-demethylation reactions. The arsenic geochemical cycle involves dissolution, precipitation, reduction, oxidation, bio methylation, demethylation, rain or dry deposit, and volatilization as depicted in Fig. 5.

Arsenic in its inorganic form arsenate, the mobility is often reduced in soil, however, arsenite has a significant degree of mobility. In contrast, organic compounds containing arsenic are immobile and its solubility in turn relies on soil pH, which changes over time and space. Other extraneous variables fertilizers or acid rain, tend to alter the soil pH. However, the manifestation of humus and clay mineral deposits in the soil may help to mitigate or even eliminate pH shifts [22].

Arsenic solubility in water subject to alter by oxygen presence in the soil. In water-saturated and muddy soils, free oxygen is often reduced. In contrast, the presence of oxygen in aerated soils such as sand leads to changes in the mineral identity. During the conversion of arsenite to arsenate in water, pH response and redox potential alterations on the movement of arsenic is noticed. In water, substantial amount of free oxygen, convert arsenite to arsenate under alkaline circumstances, similarly, arsenite to arsenate conversion occurs under acidic conditions in the excess amount of oxygen. Microorganisms, on the other hand, are capable

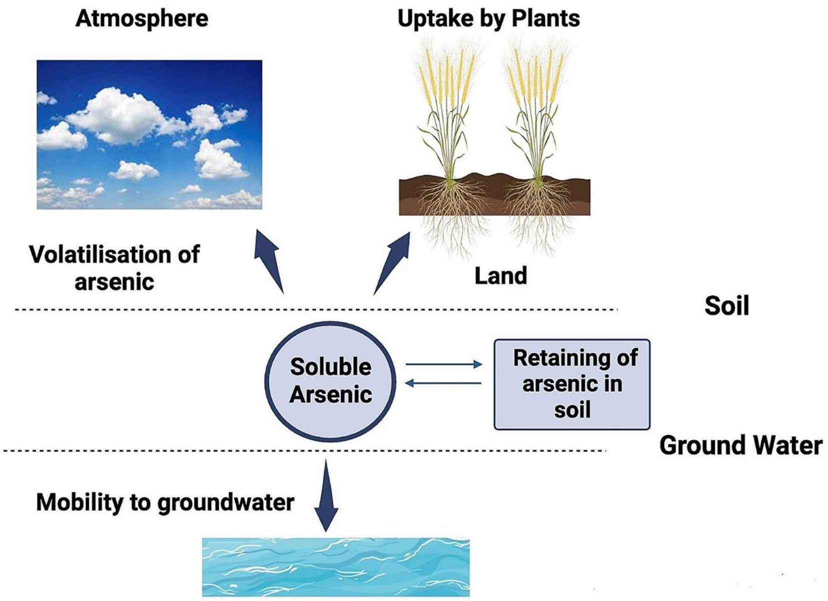
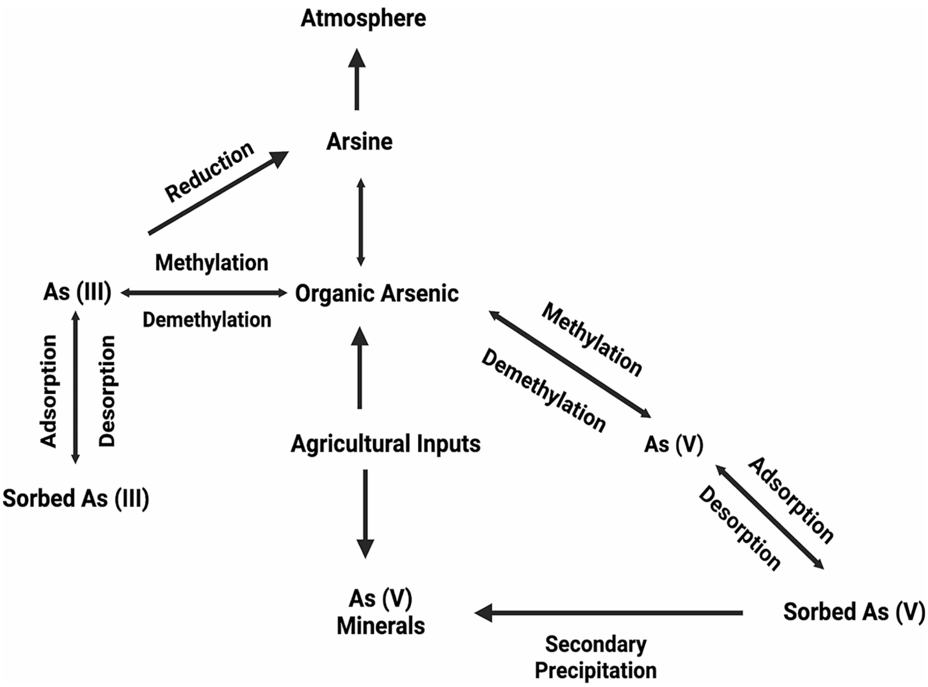


Fig. 4 Fate of arsenic in the soil environment

Fig. 5 Schematic representation of arsenic dynamics in the soil [21]



of reducing arsenate through two distinct mechanisms: dissimilatory reduction and detoxification [23]. For example, during anaerobic respiration As (V) acts as an electron acceptor, and the transformation of As (V) into As (III) happens in the detoxification mechanism. Figure 6 illustrates the various methods used to convert inorganic arsenic.

6 Uptake and Transportation of Arsenic in Plants

Arsenic is typically consumed by plant roots in large amounts because of its obtainability in the soil environment and water. Arsenic mobility into plant occur using root nodules and is translocated from root to shoot and subsequently to grains. Growth and production are often harmed when arsenic accumulates in the plant parts. Arsenic uptake, translocation, and bio magnification in vegetable species and agricultural plants pose a substantial concern to human health. According to studies, arsenic transit to shoots is not effective, and the quantity of arsenic in edible plant components is generally modest (<2 mg kg^{-1}). But several plants used to build up elevated levels of arsenic with the range 5–40 mg As/kg in the soil, which is near the background level as mentioned by Adriano, 1986 [25]. In rice straw, arsenic accrues up to 149 mg kg^{-1}, which is a leading health threat in humans [26]. In recent times it was witnessed that arsenic interconversion shows a predominant part in transformation from one tissue to another tissue.

Inorganic arsenic are harmful to plants, however, from the soil system, it is absorbed by plants through root absorption which acts as the predominant route, comparable to the absorption of trace elements and other nutrients. Translocation from root to shoot system happens after absorption and then it is redistributed among different tissues via xylem transport. In general, plant roots and tubers accumulate a large amount of arsenic, however, significant differences occur among plant species such as paddy, maize, etc. [27]. It is widespread that arsenic contamination has been detected in plant crops such as sprouts, brussels sprouts, rice, and other vegetables [28].

A comprehensive understanding of the major routes for the transportation of arsenic into the plant system is essential. In general, diverse transporters assist the uptake of arsenic because of their similarity. One such possible pathway for the mobilization of arsenic is via phosphate transporters. Since, As (V) is analog to phosphate, movement into plants occurs through phosphate transporters as a result of homology [29]. Likewise, various Pi transporter proteins (PHT) especially PHT1, act as the chief components of phosphate channels and have a predominant function in As (V) uptake by plants [30]. It is reported that plants possess little to great affinity for phosphate transport [31].

Another possible route for the entry of arsenic into plants is with the help of the enzyme arsenic reductase, ACR2, which could diminish intracellular As (V) into As (III) [32, 33]. Upon reduction, clearing of As (III) is achieved by complex development with peptides rich in thiol or effluxes aside the cell (Liu et al., 2012). Formation of As (III) – thiol-rich peptides and successive deposition in vacuoles especially in the root system subsequently lowers efflux and extended transport to other tissues.

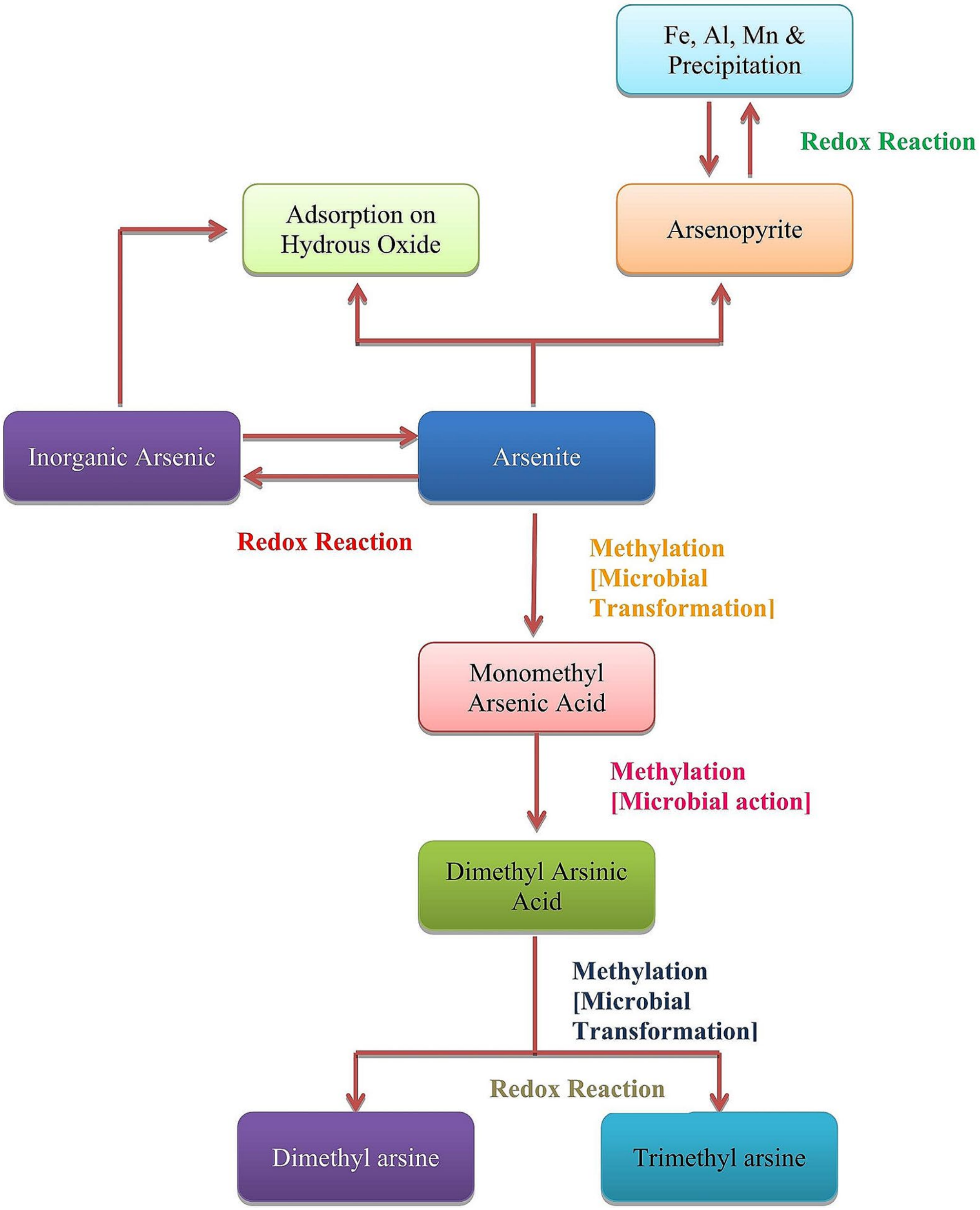


Fig. 6 Arsenic transformation in the soil environment [24]

Alongside, As (III) enters the plant through nodulin-26-resembling intrinsic proteins (NIPs). PHT transporters are one-directional, whereas NIP transporters are bi-directional. When arsenic concentrations fluctuate, As (III) may travel in both ways among the plant cells. Additionally, silicon (Si) transporters are also involved in getting As (III) because of the resemblances between silicon and As (III). Further down Si deficiency, the function of influx Si transporter (Lsi1) rises in plants [34, 35]. In plants, the increase of Si is primarily directed by Lsi1, an influx Si transporter and Lsi2, an efflux Si transporters and are confined at adjacent and lateral portion of endodermal and epidermal cells [36], which assists in arsenic movement alongside the cells and subsequently to tissues.

Even though the organic form of arsenic doesn't contribute much, their entry into plants is also notable. Several research postulate the absorption mechanism of organic forms of arsenic with the involvement of transporters. Especially methylated arsenic species entry into the plant roots occurs via aquaporin NIP2;1 [37] while the rate of transformation is slower than the inorganic forms. The mobility in its methylated form is higher from the root portion to shoots via xylem transport [38]. Redox changes by microbes in the rhizosphere phase of soil have an impact on the uptake of arsenic in rice [39, 40]. Though microbial species contribute much to arsenic reduction and oxidation, communication with the root surface is not well characterized. Arsenic entry into the plants is postulated in Fig. 7.

6.1 Detrimental Effect of Arsenic in Plants

Arsenic entry through root and its translocation and subsequent accumulation in plants are of serious concern and make the plants toxic to humans and other animals. In plants, arsenic toxicity has been recently described by several scientists in their study. Significant variations in seed germination, shoot, and root length were observed in plants affected with arsenic. Several studies demonstrate the impact of arsenic on plant development, physiology, and yield. Table 1 highlights the adversarial effects on plants upon arsenic uptake. To highlight in an experiment by Tripathi et al. 2013, shown that a consequence of Si supplementation on arsenic accumulation, and other growth parameters were monitored [45]. Experiments were conducted with rice seedlings pre-treated with As (III) and Si at a range of 0, 10, and 25 µm concentration and 0, 0.5, and 1 mM concentration in solution culture. Reduction of growth was experienced while subjecting the plants to higher concentration of arsenic. However silicon supplementations along with arsenic treatment results in increased biomass and shoot length. Similarly, Gupta et al., 2013 witnessed the impact of arsenic stress at different concentrations for short and long treatment periods on *Arabidopsis thaliana* plants deficient in NADPH oxidase C [54]. Plants subjected to arsenic treatment for 5 days exhibited reduced leaf growth and root length.

6.2 Arsenic-induced Biochemical and Molecular Changes in Plants

Arsenic presence in the plants generally disturbs the biological system through two different pathways, i.e. deactivation of significant enzymes directly, and sulfhydryl groups or using substitution of compulsory ions in active sites, or by employing disintegration of reactive oxygen species (ROS), which results in a flow of permanent injuries in plants [31] indirectly. Arsenic induced biochemical and molecular effects are presented in Table 2. Different metabolic pathways occurring in diverse cellular sections, such as peroxisome, chloroplast, and mitochondria, can constantly leave ROS as byproducts in the period of normal aerobic metabolism [72–74]. ROS can result in extensive oxidation of lipids, enzyme inactivation, carbohydrates, DNA damage, proteins, and membrane leakage [72].

6.3 Arsenic and its Detoxification Mechanism in Plants

Plants do possess several built-in mechanisms to detoxify arsenic after its uptake from the environment. Anionic arsenic such as arsenate and arsenite enter into the plants readily and can induce metal-binding proteins formation such as phytochelatins (PCs) and metallothioneins which will eventually help detoxification in plant species [80, 84]. Removal of toxic compounds from cells occurs via exact transporters or compartmentalization [85, 86]. Along with these effects during stress conditions, the defense system of the plant (especially enzymatic and non-enzymatic) goes

Fig. 7 Different modes of arsenic uptake by plant roots

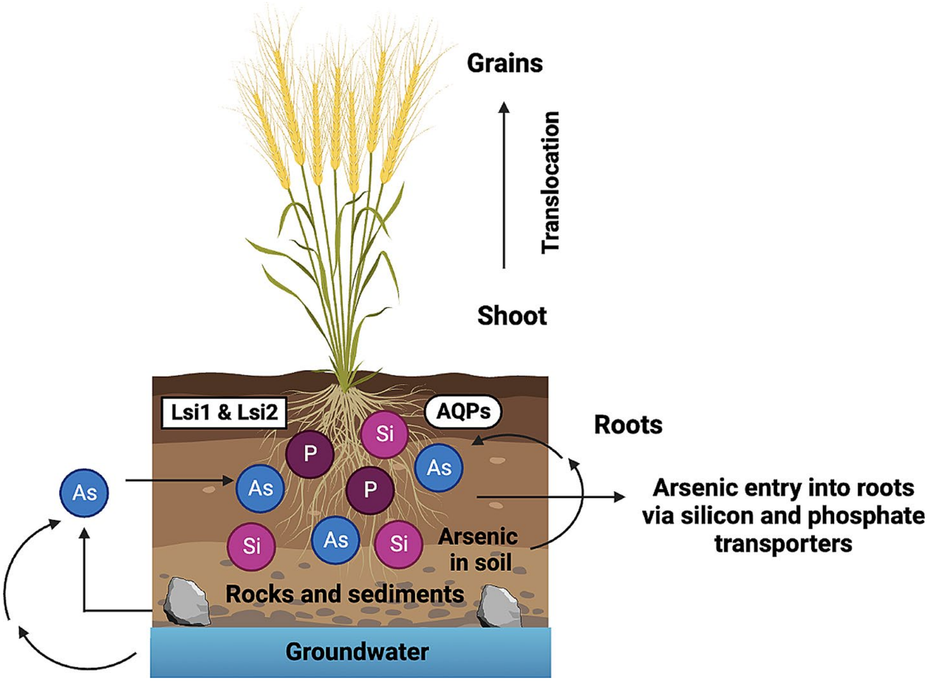


Table 1 Consequences of arsenic on the progress of diverse plants

Plant variety	Type of arsenic and its dose and its presence	Duration of arsenic exposure	Adverse effects	References
Oryza sativa	As: 40 mg/kg	30 days	Reduced shoot and dry root weight	[43]
Triticum aestivum	As: 20 mg/kg	7 days	Reduction in germination percentage (95%), germination energy (90%), vitality index (53%), germination index (89%), and Chlorophyll content.	[44]
Oryza sativa	As (III): 100 mM	10 days	Drop in percentage of germination, fresh weight, and difference in growth such as root and shoot length.	[45]
Phaseolus aureus	As: 50 µM	7 days	Reductions in root-to-shoot ratio, shoot and root length.	[46]
Brassica juncea	As: 25 µM	96 h	Reduction in dry weight of root and shoot, shoot length, and root length	[47]
Cicer arietinum	As: 60 mg/kg	90 days	Reduction in dry weight and fresh weight	[48]
Brassica rapa	$NaAsO_2$: 67 µM	14 days	Reduction of dry weight of 61.1% in roots and around 72.1% in shoots	[49]
Brassica juncea	As (III): 30 mg/ kg	30 days	Reduced carotenoid content, total ChI, and fresh weight	[50]
Zea mays	As (V): 668 µM	8 days	Reduced shoot and root length	[51]
Festuca arundinacea	As: 25 µM	4 days	Higher leakage of relative ion and decreased dry weight	[52]
Pteris vittata	As: 50 mg/kg	45 days	Reduction in biomass production and germination percentage	[53]
Arabidopsis thaliana	As (V): 500 µM	7 days	Reduction in fresh weight	[54]
Atriplex atacamensis	As (V): 1000 µM	14 days	Rise in NPT and free soluble polyamine	[55]
Phaseolus aureus	As: 10 µM	10 days	Increased electrolyte leakage, content of Chl, shoot and root growth reduction	[56]
Leucaena esculenta	As: 100 mg / kg	60 days	Reduction in the area of the leaf, shoot length, dry weight of shoot, seed yield, seed pod^{-1}, ChI content, Rate of photosynthesis, seed yield/plant, pods/plant	[57]
Trigonella foenumgraecum	As: 30 mg/ kg	9 weeks	Dry weight of root, root length, plant height, dry weight of shoot, ChI content, leaf photosynthetic rate, seed yield/plant, pods/plant	[58]
Luffa acutangula	As: 50 µM	7 days	Reduced length of root and shoot, plant fresh weight, carotenoid, ChI a and b	[59]
Oryza sativa	As: 25 µM	10 days	Reduction in dry weight and shoot length	[41]
Arabidopsis thaliana	As: 50 µM	5 days	Reduction of growth in root and leaf	[42]
Triticum aestivum	Na_2HAsO_4: 0.25 and 0.5 mM	72 h	Reduction of ChI and RWC content	[60]
Oryza sativa cv. BRRI hybrid dhan 1	As: 90 mg As/kg soil	-	Yield reduction about 57%	[61]
Solanum tuberosum	As: 120 mg/kg in the soil medium	-	Yield reduction about 21.25%	[62]
Fagopyrum esculentum	Na_2HAs0_4: 100 µg/g mixed in the soil medium	-	Yield reduction about 12.5%	[63]
Amaranthus retroflexus L.	As_2O_3: 50 mg/l in irrigation water	-	89.20% yield reduction	[64]
Triticum aestivum cv Jimai	(Na_3AsO_4 .12H_2O: 100 mg As/kg soil	-	10.72% (grains per ear) yield reduction	[65]
Oryza sativa cv. BRRI dhan29	$Na_2HAsO_4.7H_2O$: 30 mg As /kg in the soil	-	Yield reduction: Grain: 67.89% / Straw: 65.19%	[66]
Vigna radiate	As: 10 ppm in irrigation water	-	87.22% yield reduction	[67].
Zea mays cv. 31H50	As: 50 mg As/kg soil	-	97% (dry matter yield) reduction	[68]
Brassica napus	Na_2HAsO_4: 100 mg/kg in the soil	-	8.9% yield reduction	[69]
Oryza sativa cv. BR-11	As: 4 mg/l in irrigation water	-	Yield reduction: Grain 69.03% / Straw 14.25%	[70]
Triticum aestivum	Na_2HAsO_4: 100 mg/ kg in the soil	-	35.33% yield reduction	[69]
Zea mays L	As: 100 mg As/kg in the soil	-	Yield reduction: Grain 39.12%	[71]

Table 2 Biochemical and physiological changes in plants upon treatment with Arsenic

Plant variety	Nature of Growth medium	Treatments with As (III) or As (V) and its concentration	Effects	References
Zea mays L.	Use of soil medium	Two different As (III) Concentration 0 and 150 µM	Decrease in attributes of gas exchange (stomatal conductance, photosynthetic rate, transpiration rate) and concentrations of chlorophyll.	[75]
Brassica juncea and *Brassica napus*	Use of soil medium	As (V) with a concentration 0 mg As/kg, 25 mg As/kg, 50 mg As/kg and 75 mg As/kg	Decreased photosynthetic pigments and growth effects (plant height, leaf number, dry biomass of root and shoot, leaf area, stomatal conductance, gas exchange factors (rate of transpiration, photosynthesis, and), and water use efficiency (WUE).	[76]
Cicer arietinum L.	Use of soil medium	As (V) concentration such as 0, 20 mg As/kg	Essential and non-essential amino acids and iron concentrations were found to be decreased. Increased expression levels of dehydration-responsive genes (DRE, PGIP, and MIPS). Decreased levels of enzymes with antioxidant activities (GPX, APX, SOD, CAT, and GR).	[77]
Zea mays L.	Use of soil medium	As (V) concentration ranges 0, 40, 80, 120 mg/kg	Decline in total chlorophyll, growth factors, rise of arsenic in shoot and concentrations of P, decline in chlorophyll a, and chlorophyll b).	[78]
Vigna mungo L.	Use of soil medium	Three concentration of As (V) like 0, 100 and 200 µM	Total chlorophyll, carotenoids Chlorophyll a, and b declined with the degree of increasing concentration of As. Increased rate of lipid peroxidation. The anti-oxidative enzyme activities such as POD, APX, and SOD, except CAT found to be increased.	[20]
Glycine max	Use of soil medium	Concentration of As (III) and As (V): 0 µM, 25 µM, 50 µM, 100 µM and 200 µM	Decrease in the content of chlorophyll and increase in lipid peroxidation rate. Drop in broken cells and cortex area of root and cell death in the tips of the root occurs. Deposits within cell walls of phloem and xylem vessel elements and in cortex cells.	[79]
Oryza sativa L.	Hydroponic medium	As (V) concentration of 0 and 50 µM	High escape of electrolytes and increase in the activity of root arsenate reductase. In addition, comparatively lesser root-to-shoot As a transfer in As tolerant rice genotype BRRI 33 when compared with sensitive genotype BRRI 51. Increased content of PCs in roots and decreased Pi content.	[80]
Aquatic plants (*Lemna minor, Vallisneria gigantean, and Azolla filiculoides*.)	Hydroponic medium	As (V) concentration of 2 ppm	Damage to photosystem II and changes in fluorescence spectra.	[81]
Pisum sativum L.	Hydroponic medium containing NaHS in the range of 0, 100 µM	As (V) concentration of 0 and 50 µM	Uptakes of As result decrease in the fluorescence nature of chlorophyll, nitrogen content concentrations of nitric oxide (NO) and H_2S. Nitrate reductase and cysteine desulfhydrase activity were also reduced. A rise in ROS damages the proteins, cell membranes, and lipids.	[82]
Oryza sativa L.	Hydroponic medium	As (III) concentration such as 0 µM, 50 µM, 150 µM, and 300 µM	Reduced seed germination; genomic stability, shoot and root length, and protein and chlorophyll content.	[83]

high and thus managed on top of ROS, a significant booster of cellular injury [87–89]. Arsenic-mediated harmful effects are detoxified using generation and subsequent buildup of appropriate solutes or osmolites like glycine betaine in the plant species (*A. thaliana*, *H. lanatus*, Brassica species, etc.), proline [90], and mannitol [91].

7 Arsenic and its Recommended Limit

Arsenic release from natural and anthropogenic activities in the soil can lead to its presence in ground/drinking water and foodstuffs such as rice, wheat, buckwheat, oats, corn vegetables, fruits, etc. upon absorption by plants [92]. The acceptable limit of arsenic is 24 mg/kg as per the guidelines of the US – Environmental Protection Agency (US-EPA) in the soil. The maximum limit in drinking water should be 10 parts per billion (ppb) according to the World Health Organization (WHO), US-EPA, and EU [93, 94]. However, the level of arsenic dramatically varies from 1 to 10 µg/L in surface water and drinking water. Nearly more than 70 countries were found to have elevated levels either in surface water or groundwater. Likewise, the concentration of arsenic in various foodstuffs and its recommended limit differs and liable to the nature of foodstuff. Elevated levels of arsenic beyond the permissible limit pose severe risks to individuals. The amount of arsenic in human being is influenced by intake of arsenic-rich food and water. It was estimated that more than 230 million persons suffer from arsenic toxicity globally [95]. Arsenic concentration exceeding from the permissible limit is life-threatening to animals, especially humans. The necessity of pure water and food is vital for humans to get rid of arsenic toxicity.

8 Impact of Arsenic on Humans

Numerous studies have been demonstrated to determine arsenic harmfulness and its consequences on human healthiness [96, 97]. Arsenic reaches humans primarily by water intake with arsenic and secondly by using food rich in arsenic. Arsenic presence in the soil paves the way for entry into plants where it accumulates in the grains. Groundwater augmented with arsenic is recycled for the irrigation of crops, vegetables, and fruits where it enters small animals and finally to humans via the food chain [98–100]. Both foodstuffs in their daily diet and water are the major routes where humans encounter arsenic. As a result, human being are prone to several health-related problems such as hyperkeratosis, leuco-melanosis, gangrene, keratosis, melanosis, nonpetting edema, skin cancer and dorsum. Humans exposed to chronic arsenic toxicity develop different disorders in the biological system such as the respiratory, renal, digestive, hematopoietic, cardiovascular, reproductive, endocrine, and neurological, and eventually bring cancer [101, 102] as highlighted in Fig. 8.

Long standing experience to inorganic arsenic greater than 0.05 mg/L in humans results in arsenicosis, a general

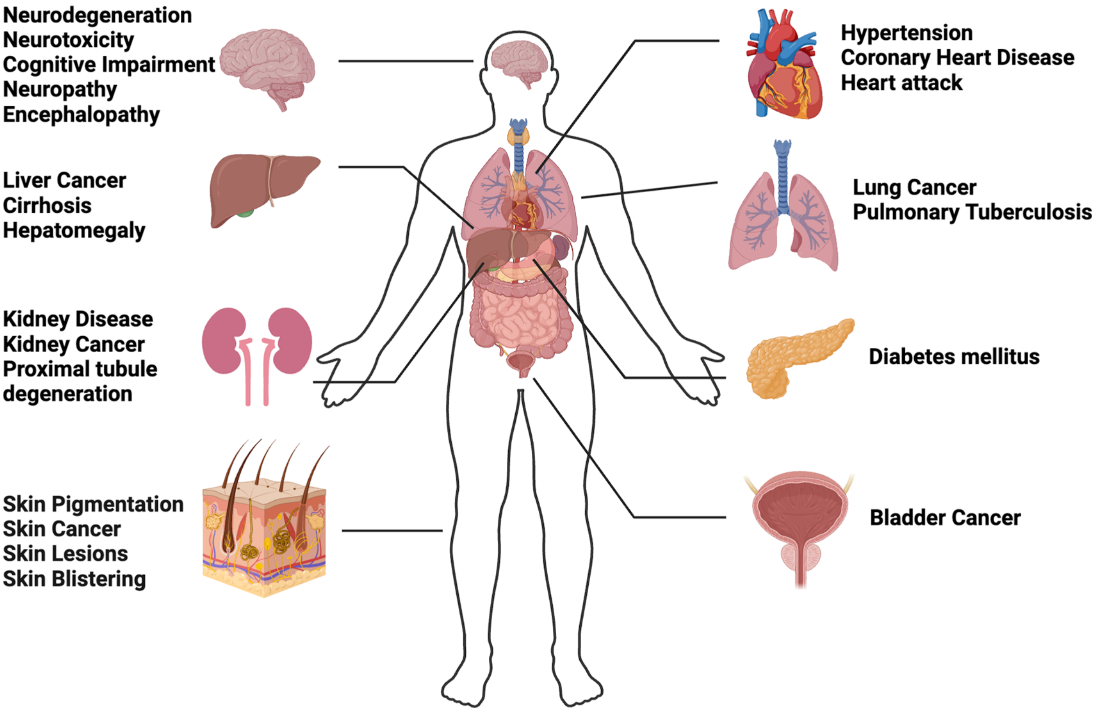


Fig. 8 Adverse health effects of arsenic on humans

term used to describe arsenic-related health hazards such as skin cancer, high blood pressure, diabetes, reproductive disorders, diseases related to blood vessels of legs and feet (Blackfoot disease) [103].

9 Arsenic Detection Strategies

Revealing the existence of arsenic in the soil, drinking water, and other foodstuffs is of prime importance as it causes serious health hazards in humans. It is essential to emphasize the different detection strategies so that the level of arsenic can be quantified. The development of a novel system with a fast, economical, reliable, and accurate prediction of arsenic is essential, and is challenging to detect whether the sample is contaminated with arsenic or not. The need for safe drinking water is of major concern and could be achieved with substantiated methods. Arsenic presence could be identified with various analytical techniques such as spectroscopic, biological, colorimetric, chromatographic, electrochemical, and coupled techniques as illustrated in Fig. 9.

To be specific, spectroscopic methods such as atomic fluorescence spectroscopy (AFS), inductively coupled plasma mass spectrometry (ICP-MS), X-ray fluorescence (XRF) laser-induced breakdown spectroscopy (LIBS) [104], and chemiluminescence (CL) [105], atomic absorption spectroscopy (AAS), becomes the excellent method of choice for the trace amount of arsenic. [106–110].

Chromatographic methods like reversed-phase liquid chromatography (RP-LC), ion-pair chromatography (IPC), size exclusion chromatography (SEC), ion-exchange chromatography (IEC) and hydrophilic interaction liquid chromatography (HILIC) also could be employed in arsenic detection [111, 112]. Colorimetric methods like the Gutzeit method and molybdenum blue-based method [113, 114], sulphanilic acid and N-(1-naphthyl) ethylenediamine dihydrochloride (NEDA), and paper-based sensors [115] find its importance in the detection of arsenic.

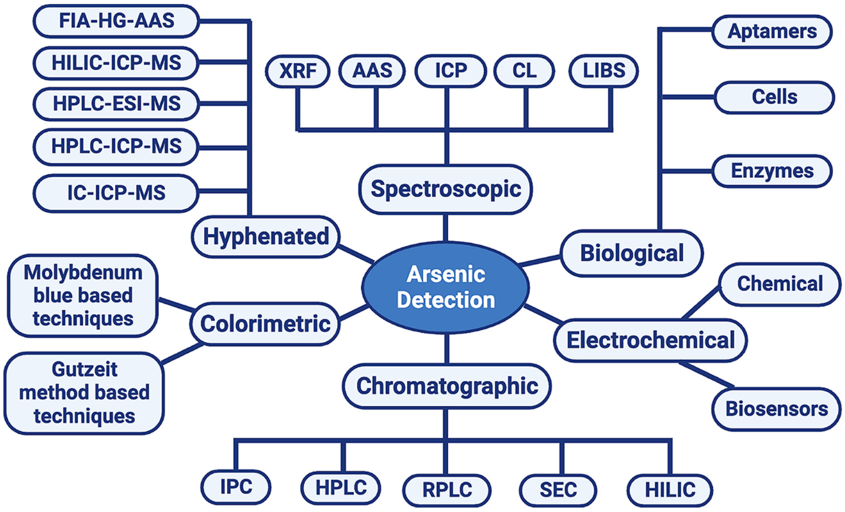
Similarly, biological methods with the involvement of cells, enzymes, and aptamers can be preferred for arsenic detection [116]. For example, whole cell biosensors (WCB) [117], and biomolecules related biosensors (aptasensors) such as fluorescent and colorimetric aptasensors are predominantly used for arsenate and As (III) detection in the samples. It works on a unique principle and enhances the result in detecting the arsenic compound.

Electrochemical choices including chemicals and biosensors are also widely employed with innovations in nanotechnology. Fabrication of sensors with the involvement of nanomaterials by their enhancing physical and chemical properties makes easy detection of arsenic in the samples. Electrodes modified with nanomaterials possess better conductivity, catalytic activity, and biocompatibility thereby enhancing the performance of arsenic detection [118].

10 Remedial Measures of Arsenic in the Environment

Even though a minimal arsenic level does not pose much problem, a limit above the recommended limit should be acknowledged since it is the origin of major health issues in humans. To tackle this issue and minimize the toxicity associated with it, novel remediation strategies should be focused on alleviating its toxicity. Removal of arsenic from the contaminant soil could be the best choice in eradicating the arsenic so that entry into plant species and other animals can be hindered and finally arsenic reaching the humans via food chain and drinking water can be avoided. The development of innovative techniques with efficient, cost-effective processes needs to be focused on clearing the arsenic in the environment. To address

Fig. 9 Possible methods of arsenic detection



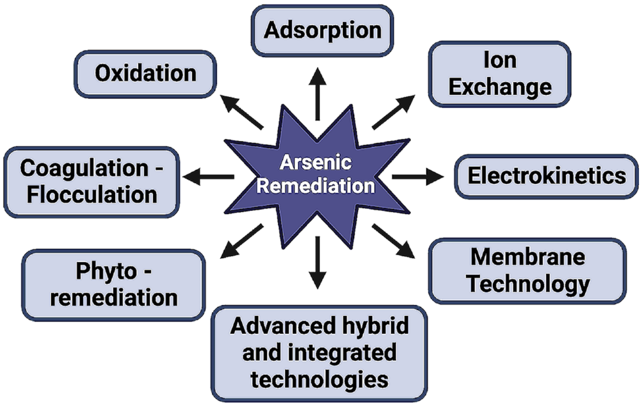


Fig. 10 Remedial strategies of arsenic in the environment

this, several measures have been practiced to eliminate arsenic in the soil and water system. Adsorption, coagulation–flocculation, electro-kinetics, oxidation, phytoremediation, ion exchange, and membrane technologies are presently employed to target arsenic compounds in the contaminated site as illustrated in Fig. 10.

The adsorption process utilizes solid particles for the removal of the target from liquid or solid solutions. Adsorbents such as alumina, iron oxides, activated carbon, clays, and zeolites can be used to remove contaminants generally. To achieve arsenic removal, iron-based sorbents, indigenous filters and cartridges, activated alumina, zero-valent iron, and other adsorbents are preferred.

Soluble As (III) is transformed into As (V) by the oxidation process to make it unavailable to plants and hence its uptake by root is prevented [119]. Different oxidation strategies practiced so far are oxidation and filtration, photocatalytic oxidation, photochemical oxidation, and biological and in situ oxidation to convert arsenic to its oxidized state. Another approach phytoremediation, utilizes plants and microbes to remove arsenic from contaminated sites. For example, arsenic-resistant plants can be cultivated in areas rich in arsenic to facilitate hyperaccumulation and for long-term removal of arsenic. Phytofiltration, phytostabilization, phytoextraction, and phytovolatilization-based remediation of arsenic is practiced to achieve substantiate results as it is eco-friendly and environmentally cheap [120]. Coagulant addition results in the formation of flocs, thereby removing arsenic in the contaminated groundwater [121]. Aluminum salts like aluminum sulfate, ferric salt, ferric chloride, or ferric sulfate can be preferred because of their ease of handling and low cost. Nanofiltration, reverse osmosis, microfiltration, advanced hybrid technologies, and ultrafiltration, can also be preferred for the elimination of arsenic [122]. Ion exchange is another choice for the removal of arsenic especially in drinking water wherein ions in the solid resin are exchanged with similarly charged ions with higher affinity [123]. Pre-oxidation to As (V) from As (III) will enhance the ion exchange efficiency and prevent the matrix from damage due to sensitive ions. Electro-osmosis, electromigration, and electrophoresis are the main processes involved in electrokinetic remediation. Low-level current induces transport reactions (electromigration, electroosmosis, and electrophoresis) and electrochemical reactions (electrodeposition and electrolysis) and acts as a “cleaning agent” [124]. This technique offers many advantages and achieves a removal efficiency of more than 90%. Advanced hybrid technologies such as membrane distillation, and forward osmosis could also be considered.

11 Conclusion

Arsenic presence in the soil environment is a fate, and its dynamics and subsequent transformation by microbes, mobility, and methylation are vital in predicting its presence in plants and drinking water. Inorganic forms of arsenic accumulate in different species via the food chain in addition to its presence in nature and pose detrimental effects on humans. The primary sources of arsenic and its speciation form and the mobility to plants via transporters are discussed. While concerning its effect in humans several techniques have been practiced to detect the arsenic in food stuffs and drinking water to assess its toxicity. Techniques available for the finding of arsenic in several sample is crucial. To provide a long-term solution, remedial measures have to be taken to make the contaminated site arsenic-free. Novel efficient cost-effective techniques could be adopted to overcome the drawbacks associated with present techniques for better clean-up of the environment. However, extensive study has to be made to design a newer approach without limitations to make the environment arsenic-free.

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Ethics Approval Ethical committee approval is not needed for this present study.

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