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A review on arsenic in the environment: bio-accumulation, remediation, and disposal

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Arsenic is a widespread serious environmental pollutant as a food chain contaminant and non-threshold carcinogen. Arsenic transfer through the crops-soil-water system and animals is one of the most important pathways of human exposure and a measure of phytoremediation. Exposure occurs primarily from the consumption of contaminated water and foods. Various chemical technologies are utilized for As removal from contaminated water and soil, but they are very costly and difficult for large-scale cleaning of water and soil. In contrast, phytoremediation utilizes green plants to remove As from a contaminated environment. A large number of terrestrial and aquatic weed flora have been identified so far for their hyper metal removal capacity. In the panorama presented herein, the latest state of the art on methods of bioaccumulation, transfer mechanism of As through plants and animals, and remediation that encompass the use of physicochemical and biological processes, *i.e.*, microbes, mosses, lichens, ferns, algae, and macrophytes have been assessed. Since these bioremediation approaches for the clean-up of this contaminant are still at the initial experimental stages, some have not been recognized at full scale. Nonetheless, extensive research on these primitive plants as bio-accumulators can be instrumental in controlling arsenic exposure and rehabilitation and may result in major progress to solve the problem on a worldwide scale.

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Introduction

Arsenic (As) is a major source of environmental threat due to its high toxicity, contamination, many different pollution sources, non-biodegradability, and high concentrations in the environment and accumulation; it is also an element that is very costly and difficult to recover and dispose of from its environment.¹ Arsenic is present in the environment in various inorganic and

organic chemical forms: arsenite (As III), arsenate (As V), monomethylarsonic acid (MMA), dimethylarsinic acid (DMA), trimethyl arsine oxide (TMAO), and arsenobetaine (AsB), *etc.*² The toxicity, mobility, and solubility differ among species in such a way that inorganic As(III) is more toxic than As(V), and in turn, organic As species are less toxic.³ The polluting and toxicity levels of the inorganic form of arsenic within these species are a concern because the metalloid does not degrade and cannot be destroyed in the environment. Today, it is reported that the arsenic concentration in drinking water in more than 42 countries of the world exceeds the limit value (10 $\mu\text{g L}^{-1}$) for drinking water determined by the World Health Organization and included in the standard guidelines.^{4,5}

Arsenic is widely distributed in air, water, soil, and plants. Air is a potential source of As exposure in industrial areas mainly due to the emission of airborne particulate matter from the smelting of ores and coal combustion. Related to this subject, the potential pathways of arsenic exposure and their reduction were reviewed before by Chung *et al.* 2014 and Raju 2022.^{6,7} Also, the arsenic chemistry and factors controlling the sorption/desorption, mobility, uptake of As by plants and reduction of translocation in plant tissues and release of As from sediments into groundwater have been reviewed by Aftabtalab *et al.* 2022, Dadwal and Mishra 2017, and Pigna *et al.* 2015.⁸⁻¹⁰

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Exposure of arsenic to mammals, aquatic biota, and wildlife is of major concern to human health.^{11,12} Arsenic contamination of the environment (*i.e.*, water soil, sediment, and biomass) is a great concern for widespread problems due to increased awareness of the health risks. Various methods, *i.e.*, immobilization, flash pyrolysis, adsorption-pyrolysis, *etc.* for the treatment of As-contaminated samples have been reported.¹³

For this reason, it is important to investigate and disinfect arsenic pollution in all kinds of environments. Conventional techniques, including oxidation, coagulation–flocculation, and membrane techniques are frequently used for the removal of arsenic from water.¹⁴ Several methods, *i.e.*, chemical, physical, and biological including membrane and nanoparticles for the removal of As from water and soil were reviewed.^{14–17} However, some of the options are financially infeasible in developing countries, where natural adsorbents (in particular, waste materials/by-products and microalgal and fungal biomass) can offer sustainable and cost-effective remediation solutions.¹⁸ Arsenic biotransformation in the environment occurs *via* three major modes: redox transformation between As(III) and As(V), reduction and methylation of As, and bioproduction of organic arsenic compounds.^{19–22}

The aim of the review is to provide up-to-date information on arsenic contamination of plants and animals, transfer mechanism, bioaccumulation measurement, remediation technologies, and disposal of contaminated materials. The important scientific knowledge gaps and critical areas are figured out for future research.

Results and discussion

Biota accumulation

Accumulation potential, mechanism, and biotransformation of As in biota, *i.e.*, terrestrial and aquatic plants and animals, and primitive plants, are presented as follows.

Terrestrial plant. Arsenic is a non-essential element accumulated in plants *via* oxidative and/or genotoxic mechanisms depending upon several factors. It can enter plants through soil, water, and air, entering the food chain, where accumulation and

biomagnification occur.²³ In fact, plants – particularly rice, wheat, maize, and vegetables – are the main source of exposure for the general population.²⁴ Moreover, as a non-essential element, arsenic also causes adverse effects in crops, such as interference with various metabolic pathways by inactivation of enzymes or competitive inhibitors of phosphate (Pi), a burst of reactive oxygen species (ROS), photosynthetic efficiency, damage of lipid, protein, carbohydrate and nucleic acids, decrease in biomass and yield productivity, and the appearance of toxicity symptoms.^{25,26} Typical toxicity of As in plants is illustrated in Fig. 1. The oxidative stress is mitigated either by higher activities of the enzymes or exogenous uses of proline.^{27–29} This toxicity is responded to by plants *via* several mechanisms: hyperaccumulation, antioxidant defense system, and phyto-chelation.^{30,31} Arsenate reduction to As(III) and its subsequent sequestration into the vacuole in plant roots is considered a major As detoxification mechanism.^{32–34} In addition to As reductase enzymes, the enzymes from other systems also could reduce As(V), *e.g.* glyceraldehyde-3-phosphate dehydrogenase, and F1Fo ATP-synthase in the mitochondria. Moreover, instead of inorganic phosphate, these enzymes incorporate As(V) into the biological molecules and form arseno-esters.^{35–37}

Regarding root uptake from the soil, various factors control the dynamics of As in the rhizosphere, such as the formation of iron plaque, phosphate status, soil oxidation/reduction status, and inter-conversion between organic and inorganic As species.³⁵ Furthermore, the soil parent material and clay contents/type plays a vital role in the regulation of As in soil solution. The uptake ability of As by plants varies from species to species.

The speciation pattern of As also affects its accumulation by plants. Arsenate is a chemical analog to inorganic phosphate and is efficiently taken up by plant roots through inorganic phosphate transport. Arsenate is uploaded to the xylem vessels through an inorganic phosphate transport protein, but As non-hyperaccumulators generally retain the majority of As(V) in the plant's root. On the other hand, in rice plants, nodulin-26 like plasma membrane proteins (LSi1 and LSi2) are also responsible for As(III) uptake and transport.³⁸

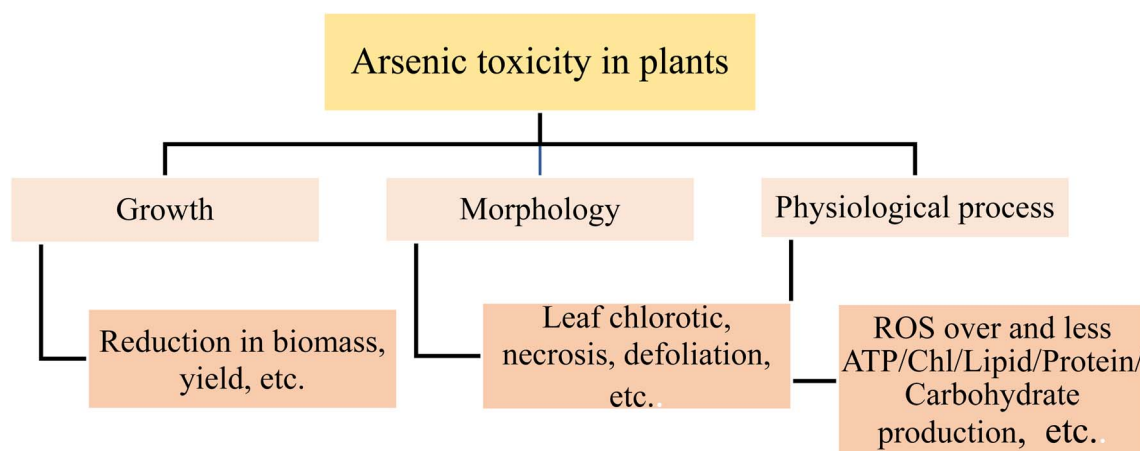


Fig. 1 Arsenic toxicity in plants.



Cereal grasses, bamboos, and natural grasses that belong to the Poaceae family are some of the main sources of food for both humans and animals.³⁹ For instance, rice (*Oryza sativa*), an aquatic grass, is considered the main food for $\approx 50\%$ of the population of the world,⁴⁰ and rice husk (seed coat) and straw (vegetative part) are used as fodder for livestock. Nonetheless, grasses can be heavily polluted with arsenic: the shoots and roots of red fescue (*Festuca rubra*), barnyard, and bermudagrass (*Cynodon dactylon*) were contained As up to 824 mg kg^{-1} .^{41–44} In the particular case of rice, it accumulated more As than other crops due to its uptake from both contaminated water and soil.⁴⁵ Moreover, studies on arsenic speciation in rice have shown that the major fraction corresponded to inorganic As.⁴⁶ Examples of arsenic contamination in different types of plants (grasses, herbs, shrubs, and trees)^{47–62} are presented in Table 1.

The Codex Alimentarius Commission⁷³ established a maximum limit of 0.2 mg kg^{-1} for inorganic As. However, overall, As levels in rice have been shown to vary widely from 0.020 – 2.05 mg kg^{-1} among various countries in Asia, Europe, and the USA. The highest level was reported in South Bangladesh. The As uptakes in rice depend on its concentration in water and soil, physicochemical factors of soil *i.e.* Fe, P, S, and Si concentrations, and environmental conditions controlling As availability and uptake in the soil–rhizosphere–plant system.⁷⁴ As contents up to 1.09 mg kg^{-1} have been detected in paddy rice and rice products: rice milk, rice bran, baby rice, rice crackers, brown rice syrup, cereal bars, and breakfast cereals. The high-yield rice varieties, such as Kalinga, IR-64, G. Gurmatia, Shyamla, Ek Hazar Das, and M2, were found to be more sensitive to As accumulation.^{47,51–54} Arsenic concentration increases in the sequence: rice grain < husk < straw \ll root.^{48–50} Similar arsenic accumulation patterns have been observed in wheat, pea, and bean grown in soil contained with As.^{75,76} Bamboo, an important plant in the tropical region, was found to accumulate As over the 0.03 – 0.09 mg kg^{-1} range.^{77,78} The fractions of MMA, DMA, and TMAO were in the 4.2 – 16.5 , 13.9 – 44.9 , and 11.8 – 18.4% intervals, respectively.

About arsenic concentration in fruits, vegetables, and plant leaves, the values ranging from 0.01 to 0.10 , 1.06 – 1.43 , and 2.8 – 43.1 mg kg^{-1} , respectively, have been reported.^{59,63,65,71} Commonly consumed leafy and tuberous vegetables, as well as spices and coconut water, have also been identified as potential As intake sources.^{57,58,60–62,66–68,72} Tobacco leaves and weeds are also potential sources for As (0.538 – 3.5 mg kg^{-1}) intake.^{55,69}

Aquatic life. Arsenic is widespread in aquatic environments due to its natural and anthropogenic activities. It is a hazardous pollutant and its toxic effects on aquatic life are significantly dependent on various abiotic factors (*e.g.*, temperature, pH, Eh, organic matter content, phosphate concentration, suspended solids, and presence of other substances and toxicants), as well as on As speciation, and duration of exposure. Continuous exposure of freshwater organisms, including fish, to low concentrations of As ($10 \mu\text{g L}^{-1}$) results in bioaccumulation in the liver and kidney, inducing hyperglycemia, depletion of enzymatic activities, various acute and chronic toxicity, and immune system dysfunction.⁷⁹

Arsenic is found in estuarine and marine waters at concentrations in the 0.5 – $3 \mu\text{g L}^{-1}$ range with a mean value of $1.3 \mu\text{g}$

L^{-1} .⁸⁰ Marine organisms – including in macroalgae and invertebrates and fish – normally contain high organic As residues, such as arsenosugars and AsB.^{81,82} The inorganic As concentration is negligible, and methylated As compounds are identified in marine ecosystems from the enzymatic methylation of inorganic As.

Total and organic arsenic concentrations in representative marine organisms are presented in Table 2. It may be observed that arsenosugars are accumulated in marine algae and crustaceans at high concentrations of up to 100 mg kg^{-1} .^{83–85} AsB, an amino acid derivative, is predominant in most finfish and shellfish, zooplankton, and some algae, while arsenolipids are present in seaweeds.

In Canadian lake water, the zooplankton and phytoplankton organisms contained As concentrations of up to 340 and 894 mg kg^{-1} dry weight (DW), respectively. The main As compounds identified by HPLC-ICP-MS in all plankton were inorganic As (from 38% to 98% of total arsenic). No other As compounds were found in phytoplankton, but zooplankton organisms showed the presence of organoarsenic compounds accounting for up to 47% of the total As.⁸⁶ Total As observed in various fishes of New York and the Arabian Gulf ranged from 5 to 134 mg kg^{-1} .^{87,88}

Terrestrial animal. Terrestrial animals, *i.e.*, cows, buffalos, goats, sheeps, pigs, birds, rabbits, *etc.* are exposed to As generally *via* water and feed. They are used as food and frequently contaminated with As⁸⁹ as shown in Table 3. This contamination also affects products of animal origin (POAO): for instance, poultry egg yolk, albumen, and poultry products retain arsenic, reaching concentrations of up to 0.465 mg kg^{-1} , respectively.^{90,91} The levels of As in the liver, kidney, and meat of beef, mutton, caprine, and chicken varied from 0.01 to $0.34 \pm 0.23 \text{ mg kg}^{-1}$, and livers and kidneys were found to have the highest significant levels.⁹² The mean concentration of As in the meat was observed in the order: chicken > duck > beef > mutton.⁹³ The highest concentration of As was observed in chicken meat ($2.9 \pm 3.6 \text{ mg kg}^{-1}$) and the lowest was found in mutton ($1.3 \pm 1.2 \text{ mg kg}^{-1}$). Quite high concentrations of arsenic (40.80 – 52.44 mg kg^{-1}) in the meat samples from Pakistan were reported.⁹⁴

The amphibians are exposed to As *via* soil, food, and water as inorganic arsenic, and they bio-transformed in the less toxic organo arsenicals, *i.e.*, MMA, DMA, and TMAO. The total As concentration in frog legs observed was 1.6 – 4.4 mg kg^{-1} with a mean value of $2.7 \pm 1.1 \text{ mg kg}^{-1}$.⁹⁵ The methylated organo arsenicals contributed major fractions: MMA (< 6%), DMA(V) (up to 46%), and TMAO (< 10%). High As of up to 0.171 mg kg^{-1} (wet weight) in snake liver was observed.^{96,97} In the muscle of Green turtles and Hawksbill turtles, high total As of up to 69 mg kg^{-1} and 210 mg kg^{-1} , respectively, were reported but present mostly in the organic form 66 – 84% as AsB.⁹⁸

The ingestion of milk has been reported to be one of the most important pathways of exposure to As in humans.⁹⁹ Rapid increase in urbanization and industrialization caused contamination of milk with toxic elements.^{100,101} For the case of arsenic, taking milk samples from cows, buffalos, sheep, goats, and camels as an example is shown in Table 4. It is worth noting that



Review

Table 1 Arsenic reported in different plants

Location	Sample ^a	As concentration ^b (mg kg ⁻¹)	Source	Ref.
Kaudikasa, Rajnandgaon, India	Rice(20)/husk(20)/straw(20)/root (20)	0.17–0.72 (0.47 ± 0.07)/0.40–1.58(0.83 ± 0.15)/2.5–5.9(4.2 ± 0.5)/204–354 (276 ± 21)	Atmospheric deposition and soil	47
Bangladesh	Grain/husk/traw	(0.5 ± 0.02)/(1.6 ± 0.20)/(2.37 ± 0.44)	Irrigation water	48
Bangladesh	Grain/husk/straw(17)	0.08–0.45(0.23 ± 0.08)/0.14–1.87(0.75 ± 0.38)/0.46–9.50 (2.89 ± 2.01)	Soil and irrigation water	49
Bangladesh	Grain/husk/straw/root(20)	0.19–1.17/0.45–3.42/0.64–16.3/18 – 478	Irrigation water	50
Republic of Kazakhstan	Rice (95)	0.25–0.45(0.36 ± 0.02)	Soil	51
Bangkok, Thailand	Rice (31)	0.084–0.27 (0.17 ± 0.009)	Environmental contamination	52
Malaysia	Rice (22)	(0.091 ± 0.001)	Environmental contamination	53
Brazil	Rice (<i>Oryza sativa</i> L.)(27)	0.003–1.3	Pesticides	54
Raipur, India	Weeds(3)	1.0–3.5	Atmospheric deposition	55
Ambagrh Tehsil, Rajnandgaon, India	Plant leaves(45) ^c	6.2/5.6/12/3.1/8.2/7.1/3.9/4.6/9.3/5.7/3.9/7.1/13/1.7/3.7/2.2/5.9/0.8/27/1.3/0.7/3.2/9.1/1.9/2.2/3.3/4.1/6.2/9.5/1.4/6.4/5.2/7.1/7.4/1.8/0.3/8.1/3.8/3.3/4.7/0.8/6.2/17/4.6	Atmospheric deposition and soil	56
West Bengal, India	Pea/lentil/mustard seed/potato/cauliflower/onion bulb/brinjal/spinach/bitter guard/garlic/radish/green chili/arum/amarnath/papaya/cabbage/lady's finger/pumpkin/beans/tomato/lemon	0.0003–1.02/0.141/0.096/0.198/0.654/0.293/0.162/0.279/0.257/0.021/0.126/0.344/0.085/0.407/0.372/0.258/0.209/0.301/0.184/0.090/0.084/0.012/0.209/0.301/0.184/0.090/0.084/0.012	Soil and water	57
Korba, India	Leafy vegetables(6)	0.56–2.05 (1.55 ± 0.19)	Atmospheric deposition and soil	58
Korba, India	Tree leaves(6)	2.8–43.1 (10.38)	Atmospheric deposition and soil	59
West Bengal, India	Coriander leaf/stem/root (5)	0.54–0.80 (0.69)/0.44–61 (12.60)/0.99–2.01 (1.45)	Groundwater	60
West Bengal, India	Cumin/turmeric powder/arum leaf/papaya	0.04786–0.20975/0.29733–0.2809/0.331–0.341/0.1965–0.373	Irrigation water	61
West Bengal, India	Potato/onion/cauliflower/carrot/tomato	0.24–0.30/0.10–0.29/0.19–0.20/0.24–0.29/0.15–0.18	Contaminated water	62
Bangladesh	Vegetables/crops(7)	0.96–1.43 (1.7 ± 0.16)	Industrial effluents	63
Nepal	Onion leaves/onion bulb/cauli flower/rice/brinjal/potato (6)	<0.01–0.55 (0.27)	Irrigation water	64
Nigeria	Guava/apple/pineapple/orange/pawpaw (5)	20–96.84(53.79)	Environmental contamination	65
Serbia	Black pepper powder(2)/ginger powder(2)	0.33–0.51(0.42 ± 0.02)/0.11–0.18(0.145 ± 0.008)	Environmental contamination	66
South Africa	<i>C. Albugy</i> , <i>B. oleracea</i> , <i>S. nigrum</i> , <i>B. rapa</i> (4)	1.5–1.9 (1.7 ± 0.2)	Industrial and commercial activities	67
Thailand	<i>Zingiberaceous rhizomes</i> (6)	0.0425–0.1451	Soil	68
Global	Bertel leaves/slaked lime/zarda (flavored tobacco) betel quids(4)	0.406/4.56/0.285/0.035	Environmental contamination	69
Global	Tobaco(8)	0.144–3.9149 (1.4586)	Environmental contamination	70
Hainan Island, China	Mango	0.0006–0.05 (0.0086)	Soil	71
Bangladesh	Coconut water(28)	0.005–0.170 (0.070)	Soil pollution	72

^a The number of samples is given in brackets. ^b The number in brackets following a concentration range is the mean value, while the number after “±” is the standard deviation. ^c The samples are as following: *Cynodon dactylon* (grass)/*Oryza sativa* (rice)/*Amaranthus spinosus* L./*Amaranthus tricolor* L./*Coriandrum sativum*/Foeniculum vulgare/Capsicum annum/Solanum melongena/Solanum lycopersicon/Dioscorea bulbifera/Amorphophallus paeoniifolius/Acacia concinna/Momordica charantia/Cucurbita maxima/Trigonella foenum-graecum/Vigna radiate/Cajanus cajan/Vigna sinensis/Vigna unguiculata/Lablab purpureus/Tamarindus indica/Vachellia nilotica/Musa paradisiaca/Zingiber officinale L./Curcuma longa/Ficus racemose L./Artocarpus heterophyllus/Ziziphus mauritiana/Ficus religiosa/Carica papaya/Moringa oleifera/Tectona grandis/Ocimum tenuiflorum/Mentha spicata/Hibiscus sabdariffa/Abelmoschus esculentus/Citrus limon/Aegle marmelos/Psidium guvava/Syzygium cumini/Madhuca longifolia/Schleichera trijuga/Diospyros melanoxylon/Mangifera indica/Shorea robusta.



Table 2 Arsenic content in marine organisms

Location	Sample	Concentration ^a (mg kg ⁻¹)	Ref.
USA	Seafood	20–100 (arsenosugar, 80%; organolipids, arsenic hydrocarbons and arsenic glycopospholipids, 0.6–6.7%)	82
Greek coastal areas	Shrimp	11.8–62.6 (AB, 8.6–58.8)	83
Poland	Hijiki algal species	102.7	84
Gulf of Trieste, Italy	Benthic (<i>Pteromylaeus bovinus</i> , <i>Myliobatis aquila</i>) and pelagic rays (<i>Pteroplatytrygon violacea</i>)	32.4–362	85
Canada	Phytoplankton	154–894 (iAs, 38–98%)	86
Canada	Zooplankton	7–340 (sulfate arseno-sugar, 47%)	86
NY, USA	Shrimp (<i>Acetes</i> sp.)	5–30 (AB, <95%)	87
Arabian gulf	Shellfish and finfish	11–134 (iAs, 0.03%; AB, 81%)	88

^a The concentration is given for AsT, with additional information for specific species in the brackets.

Table 3 Arsenic contamination in animal samples

Location	Sample ^a	Concentration ^b (mg kg ⁻¹)	Source	Ref.
West Bengal, India	Chicken egg albumen (22)/chicken egg yolk (22)	0.028–0.062/0.048–0.111	Water and feed	90
West Bengal, India	Chicken and duck feathers (30)/chicken and duck litters (30)/chicken whole egg (30)/duck whole egg (30)	(0.385 ± 0.125)/(0.535 ± 0.101)/(0.222 ± 0.120)/(0.155 ± 0.231)	Ground water	91
Nigeria	Beef liver/mutton liver/caprine liver/chicken liver/beef kidney/mutton kidney/aprine kidney/chicken kidney	(0.08 ± 0.01)/(0.34 ± 0.23)(0.15 ± 0.06)/(0.03 ± 0.01)/(0.14 ± 0.01)/(0.18 ± 0.06)/(0.05 ± 0.22)/(0.11 ± 0.01)	Environment	92
Bangladesh	Chicken/duck/beef/mutton (100)	0.08–3.3<(2.9 ± 3.6)/(2.4 ± 1.0)/(1.4 ± 0.90)/(1.3 ± 1.2)>	Environment	93
Pakistan	Mutton/chicken	42.4/44.09	Environment	94
Canada	Frog leg	1.6–4.4 (2.7 ± 1.1)	Food and environment	95
USA ^c	Pine snake: liver(17)/kidney(15)/muscle(20)/skin(20)/heart(15)/blood(29)	(0.156 ± 0.0273)/(0.167 ± 0.0532)/(0.125 ± 0.0313)/(0.0914 ± 0.0217)/(0.145 ± 0.0473)/(0.0070 ± 0.0033)	Food	96
USA ^c	Water snake from East Fork Poplar Creek: blood(20)/kidney(20)/liver(20)/muscle(20)/skin(20)/whole body(20)	0.0028–0.027(0.0101 ± 0.0013)/0.0068–0.167(0.0513 ± 0.0103)/0.000424–1.151(0.171 ± 0.058)/0.0072–0.112(0.0379 ± 0.0084)/0.014–0.084(0.0369 ± 0.0044)/(0.129 ± 0.021)	Food	97
	Water snake from Little River: blood(27)/kidney(27)/liver(27)/muscle(27)/skin(27)/whole body(27)	0.0011–0.076(0.0184 ± 0.0030)/0.001–0.400(0.0669 ± 0.0166)/0.00098–0.178(0.0369 ± 0.0071)/0.0015–0.190(0.0328 ± 0.0087)/0.00015–0.140(0.0323 ± 0.0069)/(0.071 ± 0.008)		
Japan	Green turtles: intestine(2)/kidney(6)/liver(5)/lung(2)/muscle(5)/spleen(2)/tomach(1) Hawksbill turtles: eyeball(1)/heart(1)/kidney(6)/liver(10)/lung(1)/muscle(9)/spleen(1)/stomach(1)	6.6/(17 ± 14)/(4.9 ± 3.3)/7.9/(69 ± 52)/7.6/6.148/28/(45 ± 38)/(25 ± 32)/33/(210 ± 140)/24/22	Food	98

^a If available, the number of samples is given in brackets. ^b The number in brackets is the mean value, while the number after “±” is the standard deviation. Angle brackets following a concentration range indicate the details for different sample types. ^c Results are given based on wet weight.

a positive correlation (0.926–0.974) between the As concentration in milk samples of cattle and that in the corresponding drinking water of farms/flocks has been confirmed in the literature.¹⁰² It should also be clarified that organic species, such as AsB and dimethylarsinate constitute most of the water-soluble arsenic present in milk.¹⁰³ The As content in the human and animal milk samples ranged from 2.36 to 10.75 and from 4.93 to 72.0 μg L⁻¹, respectively.^{90,103–106} At least 5-fold more As in the animal milk was detected due to feeding of As contaminated foods and water.

Mosses and lichens. Mosses and lichens are non-vascular plants that clean polluted air and water by absorbing

contaminants. The accumulation of As is carried out by the ion exchange process by the formation of complexes between the metal ions and the organic functional groups, *i.e.*, phosphodiester, carboxyl, phosphoryl, polyphenols, sulfhydryl, and amine groups of surface cells. The adsorbed metal on the moss surface is uptaken by specific membrane transport proteins or *via* channels present in the cell membrane.¹⁰⁷ Arsenical Compound Resistance (ACR3) gene is found in a wide range of organisms including bacteria, fungi, mosses, and gymnosperms, and extruded As from the cell cytoplasm thus lowering the intracellular concentration.¹⁰⁸



Table 4 Arsenic contamination in milk

Location	Milk type ^a	Concentration ^b (μg L ⁻¹)	Source	Ref.
West Bengal	Cattle (30)	(13 ± 2)–(72 ± 12)	Water and food	90
Iran	Human (20)	(7.73 ± 4.01)–(10.75 ± 7.62)	Water and food	101
Pakistan	Cow/buffalo/sheep/goat/camel (3)	15.1–18.4/2.6–7.7/25.7–33.2/10.5–37.3/6.6–13.7	Water and food	103
Lebanon	Human milk (74)	(2.36 ± 1.95)	Food and smoking	104
Turkey	Human/cow (35)	(4.219 ± 0.079)/(4.932 ± 0.38)	Environment	105
Bangladesh	Cow milk (240)	(26.2 ± 2.8)	Water/paddy/straw	106

^a The number of samples is given in brackets. ^b The number in brackets is the mean value, while the number after “±” is the standard deviation.

Mosses such as *Fabriona ciliaris*, *Leskea angustata*, *Pleurozium schreberi*, *Scleropodium purum*, *Hylocomium splendens*, *lagicthecium denticulatum*, *Bryum argenteum*, *Sphagnum* sp., *Hypnum cupressiforme*, *Thuidium tamariscinum*, *Brachytechium salebrosum*, *Brachytechium rutabulum*, *Polytrichum formosum*, and *Sphagnum girgensohnii* have been used for mapping metal pollution from localized atmospheric sources due to the accumulation by passive transport.¹⁰⁹ Moreover, mosses can clean polluted water by absorbing contaminants. Compounds such as glutathione, phytochelatins, metallothionins, and secondary metabolites play an important role in As detoxification and their enhanced tolerance.¹¹⁰

Representative reports on the accumulation of As in mosses, lichens, ferns, algae, and macrophytes are summarized in Table 5.^{111–141}

As is shown in Table 5, Epilithic and *Scopelophila cataractae* mosses were able to accumulate As in concentrations of up to 1300 mg kg⁻¹.^{111,112} The dominant As species in the mosses were inorganic forms (87%), with low concentrations of organic forms, viz. MMA (11.8%) and DMA (6.0%).¹¹²

Lichens are also widely used as environmental indicators or bio-indicators. For instance, *Asplenium nidus*, *Polypodium aureum*, *Polystichum tsus-simense*, *Pteris cretica*, *Pteris longifolia*, and *Pteris umbrosa* have been assayed for biomonitoring of heavy metal air pollution.^{142,143} Their secondary metabolites (e.g., usnic acid, norstictic acid, and psoromic acid) play an important role in binding the metal ions.¹⁴⁴ As shown in Table 5, accumulation of As in the range of 0.46–51.95 mg kg⁻¹ have been reported with different lichens (*Equisetum pratense*, *Pyxine cocoes*, *Pyxine cocoes*, *Phaeophyscia hispidula*, as well as foliose, leprose, squamulose and crustose lichens).^{113–116} Inorganic forms of As (arsenite and arsenate) were present in significant amounts in most of the lichen samples.¹⁴⁵

Ferns. Ferns (oldest groups of plants) phyto-remediate both As(III) and As(V) via roots and store it in cellular vacuoles of fronds as arsenite. Transporter proteins (ATPases) mediate the metal uptake across the plasma membrane in the fern.¹⁴⁶ Accumulation of As takes place in the cytosol via the phosphate cycle and is stored mostly as As(III) complex with thiol group compounds. The stress developed is detoxified by the use of glutathione, superoxide dismutase, and catalase for the scavenging various reactive oxygen species.

The accumulation potentiality of ferns such as *Pteris vittata*, *Pityrogramma calomelanos*, *P. cretica*, *P. longifolia*, *P. umbrosa*, *P. argyrea*, *P. quadriaurita*, *P. ryiunkensis* and *P. biaurita*, *Adiantum*

radiata, *Chielanthes sinuta*, and *Polystichum acrostichoides* is summarized in Table 5. They are very promising hyper-accumulators for As extraction, given that concentrations of up to 11 110 mg kg⁻¹ have been reported.^{112,117–120,123–125,147–149}

Algae. Algae (photosynthetic organisms) play an important role in the cycling of arsenic. The accumulation of As in algae occurs via the biosorption process.¹⁵⁰ Several phytoplankton and cyanobacteria have been observed to be resistant to high As exposure. Detoxification of As in microalgae is carried out through adsorption on the cell surface and intracellular metabolism of As, including a redox reaction, complexation with carboxyl, hydroxyl, sulfate, sulfhydryl (thiol), phosphate, amino, amide, imine compounds and sequestration into vacuoles, methylation and further transformation to less toxic organic forms such as arsenosugars or arsenolipids, and excretion from cells.¹²¹ The most common forms of As in seaweeds are arsenosugars, some of which are considered to be innocuous: AsB, arsenocholine, and TMAO.¹⁵¹

Some species of microalgae (*Chlamydomonas* spp., *Chlorella vulgaris*, *Scenedesmus* spp., *Synechocystis* spp., etc.) hold the potential for remediation of inorganic arsenic.¹²¹ Contents reported in the literature on algae food products; rhodophyta, phaeophyta, and chlorophyta; *Chlorella vulgaris*; *Chara* spp., *Lyngbya* spp., *Nitella* spp., *Pithophora* spp., *Hydrodictyon* spp., *Spirogyra* spp. and *Cladophora* spp. are presented in Table 5. Concentrations over a wide varying range have been registered, from 2.3 to 50 000 mg kg⁻¹ DW.^{125–127,129,130} The inorganic As³⁺/As⁵⁺ forms were the major species, while glycerol-arsenosugar (gly-sug), DMA, and methylarsonic acid (MAA) were only present as minor constituents.¹²⁷

Macrophytes. A number of aquatic plant species: macrophytes, such as *Azolla* spp., *Callitriche hamulate*, *Callitriche stagnalis*, *Ceratophyllum demersum*, *Hydrilla verticillata*, *Limncharis flava*, *Oenanthe crocata*, *Persicaria amphibia*, *Ranunculus peltatus*, *Ranunculus trichophyllus*, *Typha angustifolia*, etc. have been studied for the remediation of toxic contaminants.¹⁵² Several metal chelators and enzymes are involved in the uptake, transportation, sequestration, and modification of arsenic for its storage into vacuoles.¹⁵³

The accumulation of As from contaminated environments in various macrophytes is summarized in Table 5. For instance, the rootless duckweed *Wolffia globosa* accumulated a relatively high concentration of As (>1000 mg kg⁻¹ DW) in the frond.¹⁵⁴ Arsenic concentrations of over the 104–2346 mg kg⁻¹ have been reported for *Callitriche* spp., *Ranunculus* spp., *Lemna minor*,



Table 5 Accumulation of As with mosses, fern, algae and macrophyte

Location	Sample ^a	Concentration ^b (mg kg ⁻¹)	Source	Ref.
South China	Mosses	0.67–9.6 (2.4 ± 1.7)	Industrial emission	111
Japan	<i>Scopelophila cataractae</i>	1300	Mine tailing	112
Dhar, MP, India	Foliose lichens/leprose lichens/squamulose/crustose	10.98–51.95/28.63–51.20/(0.46 ± 0.03)/(20.99 ± 0.58)	Industrial activities	113
Katni, MP, India	<i>Pyxine cocoes</i> (7)	0–33.4 (11.58)	Mining and industrial activities	114
Rewa, MP, India	<i>Phaeophyscia hispidula</i> (8)	0–19.6 (8.53)	Vehicular emission	
West Bengal, India	Foliose lichen <i>Pyxine cocoes</i> (Sw.) Nyl	(48.1 ± 2.1)	Contaminated environment	115
Austria	<i>Vaccinium vitis idaea</i> and <i>Equisetum pratense</i> (2)	0.27–8.45	Arsenic smelter	116
England	<i>Pteris cretica chilsi</i> / <i>Pteris cretica crista</i> / <i>Pteris cretica mayii</i> / <i>Pteris cretica parkerii</i> / <i>Pteris cretica rowerii</i> / <i>Pteris longifolia</i> (6)	1358/1506/1239/2493/1425/2361	Simulation experiment	117
South China	<i>Pteris cretica</i> (fronds)/ <i>Pteris cretica</i> (brake)	3–704/149–694	Arsenic mine	118
South China	<i>P. vittata</i> (78)/ <i>P. cretica</i> (13)/ <i>P. multifida</i> (3)	4.54–3599/28.7–757/11.2–341	Industrial emission	119
Yunnan, Southwestern China	<i>Pteris vittata</i> L. fronds	7215–11 110	Contaminated soil	120
South China	<i>P. multifida</i> and <i>P. oshimensis</i>	1262–47 235	Arsenic mine	121
South China	<i>A. capillus-veneris</i>	Up to 500	Simulation experiment	122
South China	<i>Pteris fauriei</i>	337	Industrial emissions	123
South China	<i>Pteris</i> roots(5)/ <i>Pteris</i> fronds(5)/ <i>Adiantum</i> roots(5)/ <i>Adiantum</i> frond(5)/ <i>Marsilea</i> roots(5)/ <i>Marsilea</i> frond(5)/ <i>Ceratopteris</i> roots(5)/ <i>Ceratopteris</i> frond(5)	1.492–125.316/0.37–43.63/0.477–31.157/0.413–26.965/1.214–104.812/0.531–45.85/0.2578–37.3885/0.076–11.08	Contaminated soil	124
South China	<i>Pteris vittata</i> (brake fern)	3280–4980	Contaminated soil	125
Raipur, India	<i>Chara</i> spp./ <i>Lyngbya</i> spp./ <i>Nitella</i> spp./ <i>Pithophora</i> spp./ <i>Hydrodictyon</i> spp./ <i>Spirogyra</i> spp.	8/10/20/10/9/9	River water	126
Loa River Basin, Chile	<i>Cladophora</i> sp. and <i>Chara</i> sp. and aquatic plants: <i>Azolla</i> sp., <i>Myriophyllum aquaticum</i> , <i>Phylloscirpus</i> cf. <i>desserticola</i> , <i>Potamogeton pectinatus</i> , <i>Ruppia filifolia</i> and <i>Zannichellia palustris</i> (5)	182–11100/20–48	Contaminated water	127
China	Sea weed (Rhodophyta)/Phaeophyta/Chlorophyta (92)	>100/20–50/10–15	Sea water	128
Spain	Algae (18) food product	AsT: 2.3–141, iAs: 0.15–88	Industrial activities	129
Bangladesh	Green algae (<i>Pithophora</i>)	1400.4	Simulation experiment	130
Japan	<i>Chlorella vulgaris</i>	50 000	Simulation experiment	131
China	<i>Hydrilla verticillata</i> (L.f.) Royle (shoot)	>700	Simulation experiment	132
China	<i>Ceratophyllum demersum</i> L. (shoot)	862–963	Simulation experiment	133
Iraq	<i>Wolffia globosa</i> , <i>Ceratophyllum demersum</i> and <i>Ceratophyllum demersum</i>	1000/284/963	Simulation experiment	134
China	<i>T. angustifolia</i>	150	Simulation experiment	135
Japan	<i>Ceratophyllum demersum</i> L.	227.5	Simulation experiment	136
Kinghorn Loch, UK	<i>Persicaria amphibia</i> (L.) Gray (leaves, stems and roots)	(40 ± 65.3)	Red mud sludge	137
Thailand	<i>Limnocharis flava</i> (plant)	(0.78 ± 0.31)	Municipal landfill	138
Raipur, India	<i>Azolla pinnata</i> , <i>Pistia stratiotes</i> , <i>Salvinia molesta</i> , <i>Nelumbo nucifera</i> , <i>Trapa natans</i> , <i>Persicaria punctate</i> , and <i>Persicaria maculosa</i>	1.0–8.0	River water	139



Table 5 (Contd.)

Location	Sample ^a	Concentration ^b (mg kg ⁻¹)	Source	Ref.
Bolivia	Totora plant (root)/Totora plant shoot and Periphyton	30.8–65.0/0.4–1.5/1452–2647	Contaminated lake water	140
Portugal	<i>Callitriche lusitânica/Callitriche brutia/L. minor/A. caroliniana/R. trichophyllus/Callitriche stagnalis/Fontinalis antipyretica</i>	2346/523/430/397/354/354/346	Contaminated water	141

^a If available, the number of samples is given in brackets. ^b The number in brackets is the mean value, while the number after “±” is the standard deviation.

Oenanthe crocata, *Azolla caroliniana* and *Fontinalis antipyretica*.^{141,155} Simulation experiments for As accumulation conducted with *Hydrilla verticillata*, *Ceratophyllum demersum*, *Azolla* spp., and *Typha angustifolia* achieved contents of up to 5000 mg kg⁻¹.^{130–136} Much lower values were found for other macrophytes, such as *Limncharis flava*; *Azolla pinnata*, *Pistia stratiotes*, *Salvinia molesta*, *Nelumbo nucifera*, *Trapa natans*, *Persicaria punctata*, *Persicaria maculosa*, *Persicaria amphibia*, and totora plant, which bioaccumulated up to 87.2 mg kg⁻¹ from the contaminated water.^{137–140}

Remediation

Arsenic contamination of the environment is a widespread problem in many areas due to serious health risks. Conventional techniques, including oxidation, coagulation–flocculation, and membrane techniques, are frequently used for arsenic removal from water.¹⁴ In order to oxidize As(III) into As(V), oxidants such as O₂, O₃, Cl₂, Cl₂O, ClO, H₂O₂, ClNH₂, KMnO₄; photocatalytic oxidation (UV/H₂O₂); or chemoautotrophic arsenite-oxidizing bacteria (CAOs) may be used.¹⁵⁶ The combination of FeCl₃, Fe₂(SO₄)₃, ZrCl₄, ZrOCl₂, TiCl₃, TiCl₄, Al₂(SO₄)₃, etc. with an anionic flocculant is widely employed for coagulation of As in wastewater and sludge. Various membrane filtration techniques, *i.e.*, microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, are used for As(V) removal. Concerning arsenic-contaminated soil, remediation technologies include chemical methods (soil washing and immobilization), physical methods (soil replacement, soil cover, turnover and attenuation, and electro-kinetic remediation), biological methods (phytoextraction and bioremediation) and combined methods, which are discussed in detail in a recent review by Wan *et al.* 2019.¹⁵⁷ In connection with As(V) sorption, many different materials have been assayed, including biochar, activated carbon, coal, red mud, fly ash, chicken feathers, kaolinite, montmorillonite, goethite, zeolites, activated alumina, titanium dioxide, iron hydroxide, zero-valent iron, chitosan, and cation-exchange resins.^{14,158} The maximum adsorption achieved with pine wood was up to 124 mg g⁻¹.¹⁵⁸ High removal efficiencies have also been reported for carbon nanotubes and nanoparticles of Fe₂O₃, Fe₃O₄, ZrO₂, CeO₂, hydrous titanium dioxide, Ti-BYC, etc.^{159–162} as well as for metal–organic frameworks (MOFs), which feature high porosity and surface areas.¹⁵⁷ Adsorption capacities of up to 120 mg g⁻¹ (As V by FeO nanoparticle), 122.3 mg g⁻¹ (As III by nano-structured Fe–Cu binary

oxides), 296.23 mg g⁻¹ (As III by nanoscale Fe–Mn binary oxides loaded on zeolite), and 201.10 mg g⁻¹ (As V by nanoscale Fe–Mn binary oxides loaded on zeolite) have been reported, respectively.

The adsorption method is simple with high removal efficiency but others are inadequate due to interferences of other ions or high rejection water.¹⁶³ The physical methods based on mixing polluted and nonpolluted soils, washing with various acids, and immobilization of As over solid matrices are tedious.¹⁶⁴ The chemical methods in which As is adsorbed over metal oxides including nanosized particles (*i.e.*, metal oxides, mixed metal oxides, hydroxide-based nanoparticles, magnetic nanoparticles, composite nanoparticles, photocatalytic nanoparticles, etc.), and formation of insoluble stable phase *viz.* FeAsO₄ and FeAsO₄·2H₂O are inadequate due to either lower efficiency or being expensive.¹⁶⁵ Electro-remediation and membrane technologies are effective methods for arsenic remediation but to apply in the field is expensive and tedious.^{15,166}

Bioremediation and phytoremediation approaches based on the reduction of As with bacteria (*Pseudomonas*, *Psychrobacter*, *Citrobacter*, *Bacillus*, *Bosea*, *Vibrio*, and *Enterobacter*), oxidation with (*archaeobacterium Sulfolobus acidocaldarius* strain BC, *Alcaligenes faecalis*, *Shewanella algae*, β-proteobacteria strain UPLAs1, *Alcaligenes faecalis*, *Comamonas terrae* sp.) and methylation with (*Escherichia coli*, *Salmonella*, *Vibrio*, *Yersinia*, *Haemophilus*, and *Brucella*), and bioaccumulation of As with free-floating and aquatic rooted plants *viz.* water hyacinth, *Agrostis* sp., *Pteris vittata*, *Pteris cretica*, etc. are widely accepted methods.^{167,168} Some plants, *e.g.* *Baccharis neglecta*, *Scirpus holoschoenus*, *Atriplex lentiformis*, *Rhododendron tomentosum*, *Lupinus albus*, *Retama sphaerocarpa*, *Ulex europaeus*, *Griselinia littoralis*, *Eucalyptus cladocalyx*, *Leptospermum scoparium*, *Fuchsia excorticata*, *Anthoxanthum odoratum*, *Agrostis capillaries*, *Veronica beccabunga*, *Salix atrocinerea*, *Viola allchariensis*, *Viola arsenica*, and *Viola macedonia* belonging to families Asteraceae, Cyperaceae, Chenopodiaceae, Ericaceae, Fabaceae, Griselinaceae, Myrtaceae, Onagraceae, Poaceae, Scrophulariaceae, Salicaceae and Violaceae were reported for phytostabilization of As in the roots.¹⁶⁹ However, other plants *e.g.* *Piracicaba*, *Braz Calotropis procera* L., *Leersia Oryzoides*, *Pteris* (8223 ± 791 mg kg⁻¹), and *Eichhornia* (4517 ± 402 mg kg⁻¹) have been claimed for phytoextraction of As with translocation of maximum content in the upper part of plants.^{170–174} Most of them are



hyperaccumulators as they accumulate As in shoots beyond a certain threshold limit, in which the BF (bioaccumulation factor, soil to plant metal transfer) and TF (translocation factor, root to shoot metal transfer) should be more than one (>1).

The phyto-remediation technology involves phyto-stabilization (elimination of bioavailability of metal in soil), rhizodegradation (degradation of contaminant under plant root sphere), rhizo-filtration (removal of metals from water), phyto-degradation (breakdown of contaminant), and phytovolatilization (uptake of contaminant by plant roots and its conversion to a volatile form) mechanisms.¹⁷⁵ The root plants exudate allelopathic compounds, terpenoids, flavonoids, amino acids, sugars, bicarbonates, organic and inorganic acids, protons, and sugars to stabilize, demobilize and bind the contaminants in the soil matrix.¹⁷⁶ Various factors, *i.e.*, plant-produced chelating agents, induced pH changes, and redox reactions, are responsible to solubilize and accumulate the metal. A range of transport mechanisms or specialized proteins embedded in the plant cell plasma membrane involved in metal uptake and translocation include sequestration inside root cells, transport *via* the symplast across the endodermis into the stele, and membrane transport-protein-mediated release into the xylem. Arsenic phytoremediation from soil or water can take place *via* various mechanisms, *e.g.*, phytoextraction (removal of metals from soil matrix) phytostabilization, rhizofiltration (absorption of contaminants present in the rhizosphere into plant root system), and phytovolatilization, as shown in Fig. 2.

Phytoremediation is a simple, convenient, and cost-effective technique to clean air, water, soil, and sediment, and discussed their potentiality with various plants, *e.g.*, mosses and lichens, ferns, algae, and macrophytes in detail.

Removal efficiencies of As reported with representative techniques are summarized in Table 6.^{177–184} It can be seen from Table 6 that over 90% of As(v) can be effectively removed with adsorption, coagulation, ion exchange, and membrane

methods (including NF and RO). By contrast, the removal efficiencies of As(III) are technique dependent and are apparently lower than those of As(v), which can be attributed to the possibility of As(III) existing as uncharged species (H_3AsO_3^0).¹⁷⁷ Regarding that, inorganic As(III) is approximately 10-fold more toxic than As(v), improvement of removal efficiency of As(III) is required.

Fortunately, membrane distillation had been reported with sufficient removal efficiencies (close to 100%) for As(III) and As(v).^{180–182} Membrane distillation could play a role in helping the water industry meet the United Nations' Sustainable Development Goals (SDGs).¹⁸³

Disposal of contaminated biomass

Contaminated biomass from phytoextraction processes is a serious threat to both the environment and human health. Several methods have been proposed for the disposal of heavy metal-contaminated biomass, including composting, compaction, incineration, ashing, pyrolysis, direct disposal, and liquid extraction.¹⁸⁴ It should be noted that incineration – the most frequent option – is deemed as an unsafe process due to the emission of arsenic. A safer method for disposal was reported by Carrier *et al.* 2011,¹⁸⁵ based on sub and supercritical water treatments of the contaminated biomass to leach out the maximum arsenic in the liquid phase. Hydrous iron oxides were then used as a sorbent for the recovery of arsenic from the aqueous phase. Recently, the flash pyrolysis biochar method has been recommended for the immobilization and disposal of contaminated biomass.^{186,187} Pyrolysis is a concept that describes the thermal breakdown of organic compounds in an oxygen-free condition at temperatures ranging from 250 to 900 °C.¹⁸⁸ This is a different method of transforming biomass waste into valuation products such as biochar, syngas, and bio-oil. Pyrolysis may be classified into three broad categories based on the operating conditions (heating rate, temperature,

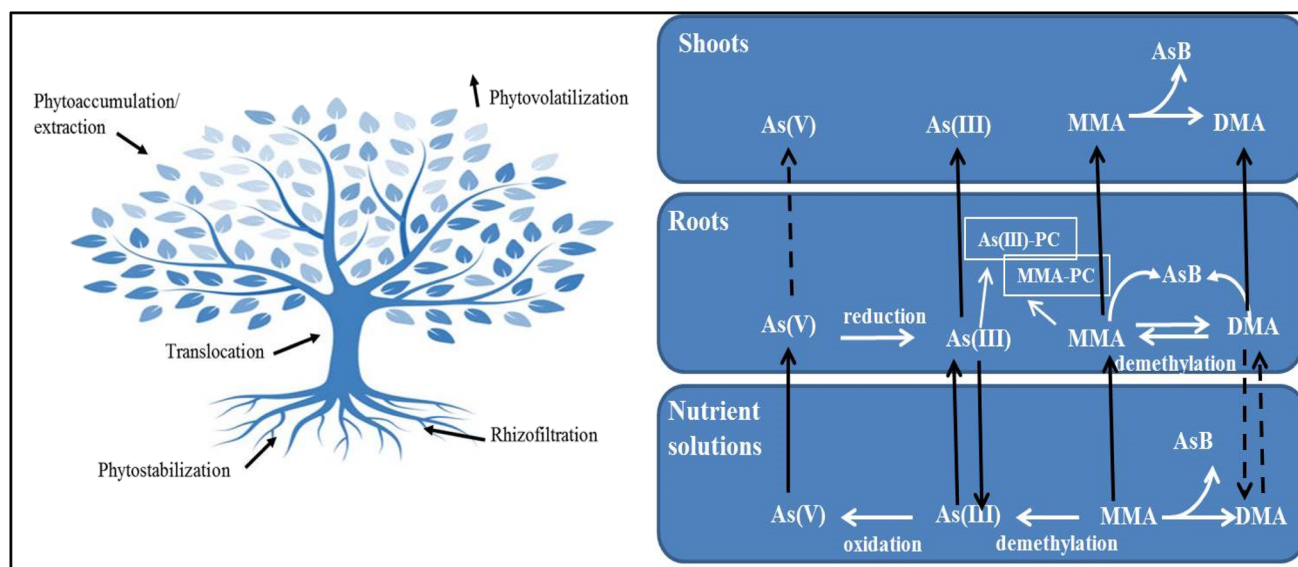


Fig. 2 As transportation mechanisms.



Table 6 Removal efficiencies of different arsenic removal techniques

Removal technology	Initial concentration (mg kg ⁻¹)	Removal efficiency for As(III)	Removal efficiency for As(V)	Reference
Adsorption by porous adsorbent (iron oxide coated sands, green sands, activated carbon, nano-adsorbents, <i>etc.</i>)	0.1	30–90%, <30% is also reviewed	>90%	177 and 178
Coagulation with alumina	NA ^a	<30%	>90%	178
Coagulation with iron salt	0.2	60–90%	>90%	178
Ion exchange resins	0.2	<30%	>90%	178
Membrane methods (NF and RO)	0.005	Up to 55%	>90%	179
Membrane distillation	5	Close to 100%	NA ^a	180
Membrane distillation	0.3 to 0.6	Over 99.9%	Over 99.9%	181
Membrane distillation	Up to 5	98.2%	98.8%	182

^a Not available.

residence time, and pressure): (i) slow pyrolysis with a temperature of 300 °C,¹⁸⁹ (ii) intermediate pyrolysis at temperatures ranging from 300 to 500 °C,¹⁹⁰ and (iii) fast pyrolysis with a heating temperature of over 500 °C.¹⁹¹

Fast pyrolysis is considered a rapid thermochemical process capable of liquefying carbon-based materials to a high-energy liquid bio-oil.¹⁹¹ Fast pyrolysis conditions are defined by the following characteristics: (i) rapid heating of biomass particles (>100 °C min⁻¹)¹⁹² (ii) short heating time of structural and pyrolysis fumes (0.5–2 s) at elevated temperatures¹⁹³ and (iii) moderate pyrolysis treatment temperatures (400–600 °C).¹⁹⁴ A critical distinguishing feature of fast pyrolysis development is the requirement to minimize fume residence time in the hot zone to obtain high-quality bio-oil.¹⁸⁸ Fast pyrolysis yields more bio-oil by ensuring that vapors are quickly extinguished or cooled.¹⁹⁵ The properties of biochar are essentially determined by the feedstocks, temperature, particle size, and heating rate, which directly affect the quality of biochar.¹⁹⁶ Meanwhile, the yield of biochar is influenced by the type and conditions of pyrolysis. Biochar has the potential to be a considerable resource for the elimination of harmful contaminants by bonding with functional groups, *e.g.*, hydroxyl and carboxyl groups, on the surface of biochar. The efficiency of biochar varies according to the type of biomass and pyrolysis operations. As a result, biochar appears to be a promising method of pollution removal but needs future development for perfect performance.

Conclusions

Arsenic contamination is a serious issue on a global scale for animal and human health as well as agriculture. Research on As origin, toxicities, mobility, distribution patterns, bio-accumulation, and remediation, the scientific understanding of this metalloid is still evolving, and the study of its interactions should help in the development of methods of safe clean-up and exposure prevention all the way down to the trophic level of plants. In this review, data on natural and anthropogenic

sources and the interaction of As with biota in different parts of the World have been presented, together with their main biogeochemical relations. Given that remediation technologies based on conventional physicochemical methods are financially infeasible in developing countries, natural adsorbents (in particular, waste materials/by-products and microalgal and fungal biomass) can be put forward as particularly promising solutions in terms of sustainability and cost-effectiveness. In the panorama presented herein, the latest state of the art on methods of bioaccumulation measurement and remediation that encompass the use of physicochemical and biological processes, *i.e.*, microbes, mosses, lichens, ferns, algae, and macrophytes have been analyzed. Since these bioremediation approaches for the clean-up of this contaminant are still at the initial experimental stages, some have not been recognized at full scale. Nonetheless, extensive research on these primitive plants as bio-accumulators can be instrumental in controlling arsenic exposure and rehabilitation and may result in major progress with a view to solving the problem on a worldwide scale. Further research on As contamination in major crops and animal foods, disposal of contaminated biomass, and installation of arsenic removal systems for contaminated water to minimize its adverse effect spectrum are required.

Data availability

All data are available in this review paper, and further information could be obtained from the corresponding author (<https://docs.google.com/document/d/1kz2tTt-zfVyxRTJbbxKtPA-S7LSxPosA/edit?usp=sharing&ouid=102850718200296775047&rtpof=true&sd=true>).

Author contributions

Khageshwar Singh Patel: conceptualization, data curation, investigation, methodology, validation, visualization, writing – original draft. Piyush Kant Pandey and Warren T. Corns: investigation, visualization, validation, editing. Pablo Martín-



Ramos: data curation, graphic drafting, editing original draft. Simge Varol: software, graphics drafting, editing – original draft. Prosun Bhattacharya: review and editing. Yanbei Zhu: review, editing, submission, and revision.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

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