Arsenic removal technologies for middle- and low-income countries to achieve the SDG-3 and SDG-6 targets: A review

Akhilesh Kumar Yadav [a], Harish Kumar Yadav [a,b], Aliya Naz [c,*], Monika Koul [d], Abhiroop Chowdhury [e], Shashank Shekhar [a]

[a] Department of Geology, University of Delhi, New Delhi 110007, India
[b] Eastern Coal Fields Limited, Asansol, West Bengal 700073, India
[c] Jindal School of Liberal Arts and Humanities, O.P. Jindal Global University, Sonipat, Haryana 131001, India
[d] Department of Botany, Hansraj College, University of Delhi, New Delhi 110007, India
[e] Jindal School of Environment and Sustainability, O.P. Jindal Global University, Sonipat, Haryana 131001, India

ARTICLE INFO

ABSTRACT

Contamination of arsenic (As) in groundwater has increased across the world with prominence in the middle- and low-income countries. The United Nations 'Sustainable Development Goals' (SDG's)- 'good health and well-being' (SDG 3) and 'safe and clean water and sanitation for all' (SDG 6), cannot be achieved without monitoring and remediating 'As' pollution in groundwater. Over 230 million people worldwide are affected due to arsenic-contaminated drinking water. More than 200 articles discussing the 'As' contamination, toxicity and cost effective technology were reviewed in this study focusing on economic status of the affected nation as per World bank report. Cost budget analysis suggested that chemical oxidation followed by precipitation (0. 043-0. 076 US $/m^3$), low cost adsorbent (0. 1 US$/m^3$), hybrid treatment technologies (0. 15-0. 17 US$/m^3$) and biological oxidation (0. 2 US$/m^3$) can be applied in low income countries through community based models to mitigate the health problem related to As contamination in order to achieve SDG 3 and SDG 6 targets. This study recommends further research on budget friendly 'As' remediation systems and policy level interventions in the affected nations to cater safe drinking water to all.

1. Introduction

Elevated concentrations of As in the groundwater is a serious concern in many parts of the world especially low and middle income countries such as India, Bangladesh, China, Cambodia, Nepal and, Vietnam (Smedley and Kinniburgh, 2002). Over 85% of world's population is dependent on the groundwater for their drinking water source (World Bank, 2012; Shaji et al., 2021). Arsenic is a geogenic pollutant, originating from the minerals in the rocks. The distribution of As is more prevalent in the areas of active plate tectonics, magmatism and associated hydrothermal activity. But 'As' pollution is not limited only to tectonically active areas. One of the examples is the sedimentary alluvial fan of lower Ganges- Brahmaputra- Meghna basin, the home of 400 million people. Here As is a geogenic pollutant found in the semi-confined/confined/ unconfined aquifer located between the Pleistocene terraces including the Barind (North Bengal), the partially weathered gray silts and clay floodplains and Chottanarpur formations in the West.

Over 230 million populations are suffering from As contamination in groundwater (Shaji et al., 2021). Among these, 78% of this exposure is reported in south Asian developing countries (Rajendran et al., 2021). Current literature indicates that the groundwater in India, Bangladesh, China, Cambodia, Nepal, Vietnam, Argentina, Bolivia, Chile, Mexico, and Brazil have been contaminated with As (Ravenscroft et al., 2011; Singh et al., 2015; Sarkar and Paul, 2016; Bindal and Singh, 2019). As per World Bank report, all these major effected nations belong to the category of lower and middle income countries (World Bank, 2020).

UN Sustainability Development Goals addresses the major issues of development and envision a green, sustainable future by 2030. Arsenic pollution and exposure to human population is one of the major hurdles to achieve the targets of 'Good health & wellbeing' (SDG-3) and its major target "reduce illnesses and deaths from hazardous chemicals and pollution (target 3. 9: SDG goals)". It is also vital to manage the As pollution to achieve SDG-6 (clean water and sanitation for all) and its

major target 6. 1: Safe and affordable drinking water. The dependency on groundwater is difficult to circumvent in middle-low income countries with high population density. Hence, viable As removal techniques are mandatory if policy makers and engineers can even try to achieve the SDG-6 targets by stipulated deadline of 2030.

Sources of As contamination are mainly sulfide minerals (chalcophilics) such as arsenopyrite (FeAsS), realgar (AsS), niccolite (NiAs), cobaltite (CoAsS), hydrothermal water, volcanic ash, and iron oxyhydroxide/oxide as weathering products ((Masuda, 2018); Reimann and Caritat, 2012; 2742 Uddin and Jeong, 2020). Geological processes such as hydrothermal activities, ore depositions and sediment weathering naturally contribute to As contamination in groundwater (Zkeri et al., 2018; Jeelani et al., 2020; Wei et al., 2021).

Commonly used As removal technologies are ion exchange, membrane filtration, reverse osmosis, adsorption and chemical and biological remediation. Most of these technologies are expensive, complex and not sustainable for long term application especially in low and middle income countries (Abejón et al., 2015). Such as chemical oxidation followed by precipitation and adsorption methods requires chemicals and generate As contaminated sludge which disposal adds up extra operational cost, in contrast ion exchange, reverse osmosis, membrane filtration produces less sludge but are expensive due to costly membrane, high electricity consumption and complex method and demands experts for proper maintenance. Biological methods of As removal is not very effective for high As contaminated water, although it is suitable for the water contaminated with low concentration of As. The search of the suitable As removal technology is still a major challenge among researchers, scientists, and policy makers (Amen et al., 2020).

Through this review, we present the sources, occurrence of As contamination in groundwater. We have elucidated how As chemistry affects contamination of groundwater resources. An appraisal of recent methods to remediate As from drinking water that are being used across the globe along with limitations associated with the technologies and challenges encountered are presented in detail. This review also presents a cost effective analysis to decide the best suited As removal technology for low and middle income countries in view of achieving SDG goal 3 and 6.

2. Toxicity of As

Arsenic enters in humans either through contaminated drinking 'As' laden water, or by consuming 'As' bio-accumulated food crops (Singh et al., 2015). Contamination of As has impacted human lives by getting bio accumulated, bio-transformed and bio magnified across the food chain ((Chakraborti et al., 2016a,b; Kumari et al., 2018). Arsenic causes oxidative stress by damaging redox-sensitive signaling molecules by metal induced signal transduction pathways leading to the activation of a transcription factor governing the expression of the genes involved in several diseases, including cancer (Mandal, 2017; Hasanuzzaman et al., 2018; Necula et al., 2021). Arsenic is responsible for a variety of complications in the human body such as the immune system, cardiovascular, brain, nervous, hepatic, reproductive and renal functions (Naujokas et al., 2013; Chakraborti et al., 2018) (Fig. 1). Chronic exposure of As can cause Parkinson's, melanosis, leucomelanosis, keratosis, gangrene, dermal irritation, and cancer (Panda, 2015; Dorsey, 2018). The elevated As can accumulate in the hair and nails (Gault et al., 2008; Francesconi, 2010; Wongsasuluk et al., 2021).

Arsenic impact the zinc finger DNA repair proteins- poly (ADP-ribose) polymerase-1 (PARP-1), playing a significant role in increasing chances of cell mutation which can eventually lead down to carcinogenesis (Zhou et al., 2021). Deposits of As in the dermal layers causing depletion of S-adenosylmethionine pool and causes hypermethylation of Arsenite methyltransferase, that can induce carcinogenesis in skin (Das et al., 2021).

Recent researches have highlighted that impact of As reduces the semen production capacity in males due to inhibition of androgen receptor and ERK/AKT/NF-kB signaling pathways crucial for spermatogenesis (Sengupta et al., 2013; Renu et al., 2018). Arsenic, a major Endocrine disrupting agent, impact the Glutathione reductase enzyme action in the Pentose Phosphate Pathways (PPP) and inhibits the cell
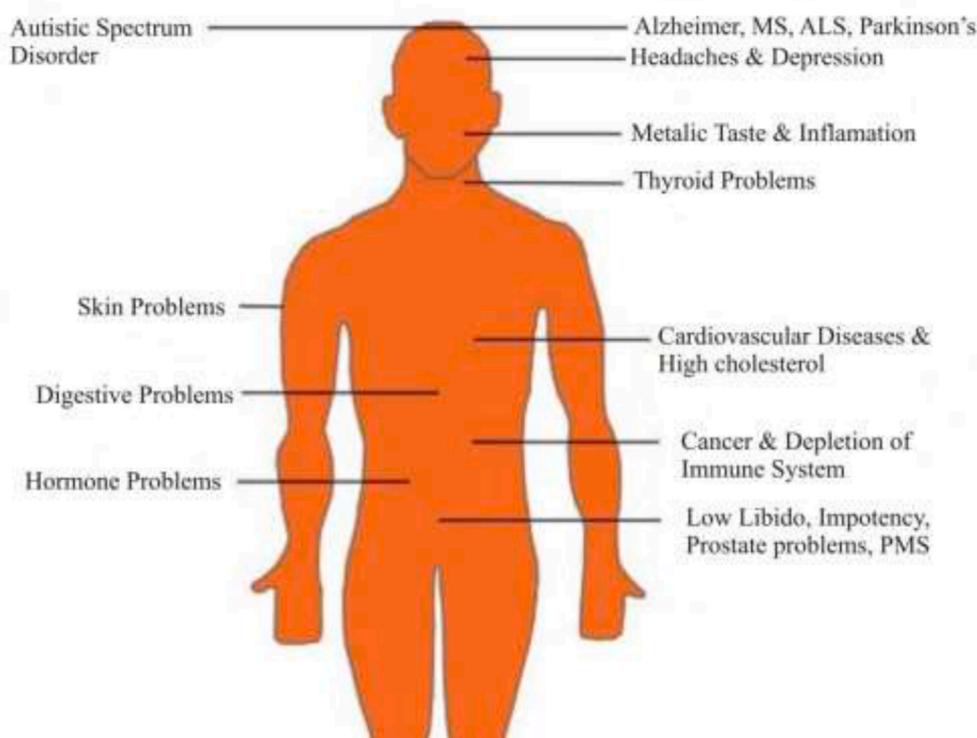

Fig. 1. Long term Arsenic exposure and their associated health impacts on human (modified from Panda 2015)

signaling molecules required for production of endocrine signals (Sabir et al., 2019). Arsenic can be a factor for progression of Parkinson's disease, as it induces imbalances in Ca^{2+} pathways during ATP synthesis mechanisms in a neuron due to over production inflammation inducing cytokines such as Interleukin- 1β (IL-1β), IL-6, Tumor Necrosis Factor - α (TNF-α) (Jomova et al., 2010). In cause-effect studies focusing on 'Parkinson's disease' indicates that As have propensity to mutate/ hinder transcription-translation from DJ-1 in the neuron cells by increase oxidative stress in the cell (Raj et al., 2021).

Consuming a high protein diet such as milk, fish, pulses and meat can prevent toxicity to some extent (Mondal et al., 2013). High income countries have resources and technologies to removal of As at source as well as the people can effort sufficient protein diet. Unfortunately marginalized people of low and middle income countries cannot afford the protein rich diet is at highest risk of As toxicity, which again hinder the goal SDG-3. To achieve SDG-3 goals, the removal of As at source through commercial and household level is the primary necessity.

WHO (World Health Organization) has constantly been tracking the As levels in the groundwater. With latest research inputs and increase in the incidence of the toxicity of As and its biomagnification WHO and statutory bodies of different countries have revised the guidelines for the permissible limits (Table. 1). These issues are majorly responsible for inability of nations across the world to effectively manage the problem of As-induced health hazard and without proper remediation technology innovations, it will be impossible to comply with the global SDG-3 targets.

3. Arsenic impacted countries according to economic status

About 90% of As comes from geogenic sources and most of the Asian countries are at high risk of As exposure (Shaji et al., 2021). The toxicity

Table 1
Chronology of alterations in acceptable/permissible limits for Arsenic concentration in Drinking water guidelines advocated by different national and international statutory bodies.

Standards	Year (Updated)	Standard limit (µg/l)	Remarks
WHO	1958	200	WHO International Drinking water Standard:
WHO	1963	50	WHO recommend lowering guide value from 200 to 50 µg/l
WHO	1993	10	WHO provisional guideline recommends lowering guide value to from 50 to 10 µg/l
European Standard for Drinking water	1998	10	Lowered the acceptable limit. EU. 1998
Standard for drinking water Quality: Ministry of Health of China (GB 5749-2006)	2006	50	This limit applicable for all drinking water supply sources of urban and rural areas of China
USEPA and National Research council	1974	50	Later the standard proposed to reduce the maximum contamination units from 50 to 10 µg/l in January 2006
US EPA: National Primary Drinking Water Regulations	2009	10	Public health goal is set for zero contamination of As in water
Indian Standard (IS: 10500)	2012	10	Acceptable limit is 10 µg/l, while the permissible is upto 50 µg/l
Australian Drinking Water Guidelines 6 2011	2017	10	These values are as per National Health and Medical Research Council (NHMRC) of Australian Government

of As through groundwater source is a challenge especially for the low and middle income countries due to limited resources and funds. Arsenic concentrations and sources reported in different countries are listed in the Table 2. Although some of the high income countries are reported upto 10000 µl of As, the exposed population are very less in comparison to Asian countries (Rahaman et al., 2021). As exposed population are highest from the Asian countries (> 200 million) followed by America (2.5 million), Europe (1. 2 million) Africa (0. 5 million), and Australia (0.001 million) (Kumar and Ghosh, 2021; Shaji et al., 2021). More than 30 Asian countries are reported high As concentration in groundwater out of which severely As impacted countries are Bangladesh, India, China, and Pakistan (Table 2).

On the basis of mortality rate, the highest As toxicity impacted country is Bangladesh where >40% of groundwater sources are As contaminated and about 21. 4% of all deaths occur because of high concentration of As (> 10 µg/l) in drinking water (WHO, 2018). About 1. 47 crore Indian are at high risk of As induced cancer out of which over 1 lakh deaths is also reported due to chronic exposure of As through water (Dutta et al., 2019). Agenda for Sustainable Development on holistic management of drinking water services and monitoring of drinking water quality by 2030, cannot be possible till the global profile of arsenic contamination not monitored and managed (Johnston, 2016). The regular monitoring of As contamination and proper management is necessary to achieve SDG 3 and SDG 6 goal.

4. Arsenic removal technologies

Extensive research on the As removal from water has been carried out across the world (Singh et al., 2021). Most of the studies have been carried out in the laboratories, while a few were performed in the field. However, many of these methods have shown success at pilot scale and do not work in field conditions (Vangronsveld et al., 2009; Baig et al., 2015; Kurz et al., 2020). For example, the membrane filtration method, although effective in As removal, is a costly and complex procedure. Ion exchange is very effective at small scale for As removal, however at large scale it is expensive and has high maintenance cost (Höll, 2010). Adsorption method is also expensive at pilot scale due to high cost of adsorbent, and it is difficult to separate As in presence of other competitive ions in water (Siddiqui and Chaudhry, 2017). Most of the expensive technology is well adopted by the high-income countries around the world; however, for the middle- and low-income countries it is not affordable. Coagulation with metal salts and lime followed by filtration is the widely used method and significantly economic and efficient for As removal from water (Ge et al., 2020). Microbes are used to remove As from water, however very few study highlighted the usage of microbes for As from contaminated water at pilot scale (Laroche et al., 2018).

The methods based on reverse osmosis, ion exchange, adsorption through nanoparticles, membrane filtration, have shown significant efficiency in As removal from water, but are complex, require expertise and are economically not viable. Several Asian low- and middle-income countries are severely affected by geogenic pollution which requires easy and economically feasible options. Various As removal techniques and their advantages and disadvantages are depicted in Table 3. Various properties of this element and its valence states are exploited to devise an effective protocol to decontaminate the water.
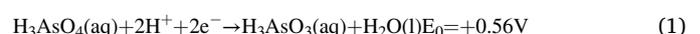
4.1. Removal of As by chemical oxidation

In groundwater and in anoxic conditions, As is predominant as arsenite [As (III)] at neutral pH (Smedley and Kinniburgh, 2002; Kanel et al., 2005; Drahota et al., 2009). According to Singh et al. (2015) it exists as oxyanion with a neutral charge, H_3AsO_3 which has a very low affinity towards mineral surfaces and thus remains in soluble form. In oxidizing environments, As exists in pentavalent state *i. e,* arsenate [As (V)] having negative charge, $H_2AsO_4^-$ or $HAsO_4^{2-}$ (Kang et al., 2000).

Table 2

Arsenic concentration (μg/l) in groundwater reported in the different countries according to their economy list (World Bank 2020).

Economy	Countries	Location	Arsenic Concentration	Sources	Refs.
High income countries	United State of America	Western USA (Alaska, Arizona, California, Hawaii, Idaho, Maine, Nevada, Oregon, and Washington)	1-48000 24,300	Older basin-fill sediments due to dissolution of sulphide and pyrite minerals	Welch et al., 1988 Shaji et al., 2021, Flanagan et al., 2015
	Chile	Northern and central parts of Chile	800-27000	Aquifer contaminated due to quaternary volcanogenic sediments	Dauphiné et al., 2011, Corradini, et al. 2018
	New Zealand	Waikato region	8. 0-9080. 0	Geothermal waters	Lord et al., 2012
	Mexico	Lagunera, Valle del Guadiana, valle da Zimapan	0-2400	Volcanic sediments	Shaji et al. 2021
	Finland	South-west Finland	0-2230	Weathering of minerals basically Arsinopyrite and As- sulphide	Kurttio et al. 1998; Pedretti et al. 2019
	Canada	Western Quebec	0. 2-326. 4	Bedrock weathering	Bondu et al. 2017
	Germany	Eastern and Southern Germony	0-550	As contamination through alluvial sandstone and sediments affects the shallow aquifer	Heinrichs and Udluft, 1999; Shaji et al. 2021
	France	Alpine/Mediterranean Var River watershed and partially remediated mining site in Southern France	0-263	As laced bedrock	Shaji et al., 2021, Barats et al, 2014
	Romania	Transylvania	1-176	As mineral rock weathering	Gurzau and Gurzau, 2001
	Japan	Fukuoka	0. 001-0. 293	Volcanic sediment, Holocene coastal sands	Kondo et al., 1999
		Southern Japan (Kyushu island)	25,700		Shaji et al., 2021; Even et al., 2017
Upper middle income countries	Brazil	Ribera Valley, Amapa State, Rio das Valihas, Minas, Gerais, Rondonia State, Amazon	100,000	Aquifer gets contaminated through As by sulphide and gold ore	Matschullat et al., 2000; Shaji et al., 2021
	Argentina	Eastern, North eastern North central Argentina	14,969	Tertiary quaternary volcanic deposits	Robles et al., 2016; Shaji et al., 2021
		Chaco-Pampean plain, Pampas, Cordoba	10–5300 100-3810		Nicolli et al., 2012 Nicolli et al., 1989
	Thailand	Nakhon Si Thammarat Province,	1. 25-5114	Shallow (alluvial) aquifer contaminated due to mining process	Williams et al., 1996
		Ronpibool,	1-5000	Water contaminated by tin mining waste	Choprapwon and Porapakkham, 2001
	China	Inner Mongolia, Xinjiang, PR China Shanxi, PR	1-2400 0. 05-850 0. 03-1. 41	As-Fe rock weathering, Holocene alluvial sediment	Guo et al. 2001 Yinlong, 2001 Yinlong, 2001
	Iran	North-west, North-east, South-east, and South-west of Iran, Rafsanjan plain	4-1061	Volcanic mountains and copper mines, weathering of sediments	Hamidian et al., 2019; Rahnamarad et al., 2020
	Mexico	Lagunera region	8-624	Volcanic sediments	De Razo et al., 1990
	Russia	Republic of Dagestan, Karelia,	1-500 2–89. 3	Geothermal waters Water of the flooded mine "Arsenic"	Abdulmutalimova et al., 2019 Cherkasova et al., 2021
	Peru	Locumba River; Western Amazonia	500-700	Unconfined aquifers composed of pure sand	Sancha and Castro, 2001
	Indonesia	West Java	10-350	River and Aquifer	Fauzi et al., 2017
	South Africa	Northern Cape Province	<20-252. 86	Sulphide minerals, goldmines	Abiye and Bhattacharya, 2019
	Brazil	Minas Gerais State	0. 5- 40. 1	Water contaminated by gold mining	Bidone et al., 2016
Lower middle income countries	India	Districts of East India including (West Bengal), Assam (Barak Valley)	3-3880	Arsenic-rich sediments; Rock-water interaction; via arsenic-contaminated alluvial aquifers; partially weathered gray silts and clay floodplains and chottanarpur structure; aquifer semi-confined between the Pleistocene terraces	Mandal et al., 1996; Shaji et al., 2021; Thambidurai et al, 2013, Mahanta et al, 2015
		Bihar, Jharkhand, Uttar Pradesh, (Upper and middle Ganga Plain) Punjab, (Northwest India)	10-3192		Saha et al. , 2010; Alam et al. , 2016; Hundal et al., 2007; Wu et al. , 2021
		North-eastern India including Bishnupur district, Manipur	50-986		Oinam et al. , 2011; Saurav et al., 2015
	Ghana	Southern and central Ghana	0-4500	Aquifer in confluence with As bearing rocks near gold mines	Buamah et al., 2008; Shaji et al., 2021
	Vietnam	Mekong delta	0-1470	Deep aquifer	Erban et al., 2013
		Hanoi	1-3050	Arsenic-rich sediments	Berg et al., 2001
	Cambodia	Mekong River floodplain	1-1340	Sediment aquifers	Buschmann et al., 2007
	Nepal	Nawalparasi district	10-1338	Aquifer contaminated with As due to oxidation-reduction process of iron oxides and pyrite	Yadav et al., 2014
	Bangladesh	Chapai Nawabganj district of Bangladesh	2. 34 -586. 96	Holocene alluvial sediments, organic matter, reducing, salinity, As rich minerals	Islam et al., 2019
	Pakistan	Vehari	0. 4- 132 1. 0-105. 3	Arid and semiarid region contaminated with As; Quaternary sediments	Shahid et al, 2018 Shah et al., 2020
	Sri Lanka	Mannar island	0. 60-34. 0	Reductive dissolution of Fe-Mn oxides and oxy-hydroxides coated on sandy aquifer materials	Bandara et al., 2018

Oxidation leads to conversion of soluble Arsenite to partially soluble Arsenate and subsequently precipitation of Arsenate (Jain and Ali, 2000; Bolan et al., 2014). The redox system of As (III) and As(V) and can be stated as follows:

$$H_3AsO_4(aq)+2H^++2e^-\rightarrow H_3AsO_3(aq)+H_2O(l)E_0=+0.56V \quad (1)$$

The standard oxidizing potential for As (III) to As(V) is less than the

Table 3

The latest techniques available for the removal of arsenic from arsenic- contaminated waters.

Water treatment Techniques	Various processes used	Merits	Demarits	References
Chemical oxidation and precipitation	Oxidation through manganese dioxide, chlorine, permanganate, ozone, and ferrate	Chemical are easily available, low cost with simple operation	Slow process, sedimentation and filtration is required, produce high volume of liquid waste which increase the operational cost	Zakhar et al., 2018
Coagulation and flocculation	Aluminum, Iron, titanium chloride, zirconium chloride based coagulants	Materials easily available, process is not complex, not required skilled technician	Produce large volume of As bearing sludge, which required proper disposal and this adds up cost	Höll, 2010
Electrocoagulation	Iron electrode	100% removal is possible at laboratory scale	Sludge management needed	Kabir and Chowdhury, 2017
Biological treatment	Biological oxidation of As (III), arsenic removal through microbes, microalgae and fungi	Generated sludge can be used for waste water treatments, Cost effective	Treated water needs tertiary treatment before supply	Ghosh et al., 2019
Adsorption	Aluminum based sorbents, activated carbon, iron based sorbents, clays and soils,, zeolites and other miscellaneous adsorbents	Comparatively high removal efficiency	Suspended salts affects arsenic removal efficiency; The adsorption efficiency highly dependent on the water quality	Luong et al., 2018
Membrane filtration	Membrane distillation, microfiltration, nanofiltration, ultrafiltration	Best available technology for water treatment to remove arsenic, High removal efficiency	Wastage of huge amount of water with toxic waste water	Dutta et al., 2012
Nanoparticles	Iron, titanium and zirconium based nanoparticles	Simple handling, less working area required for treatment processes	For better efficiency it is required to connect photochemical process	Siddiqui et al., 2019
Ion exchange	Using different ion exchange membranes	High efficiency and commercially available	Not suitable for high TDS water. Pretretation required. Costly and regeneration of membrane is difficult	Mohanty, 2017

oxidizing potential of Ferric [Fe(II)] to Ferrous [Fe(III)]. However, the oxidation rate of arsenite is relatively much less than Fe (II) and hence arsenite can sometimes exist in a meta-stable state even in oxidizing environments (Ahmad et al., 2018).

The popular oxidizing materials for oxidizing arsenite to arsenate are chlorine, chlorine dioxide, chloramine, ferrate, hydrogen peroxide, manganese oxide, ozone, and permanganate (Kim and Nriagu, 2000; Manning et al., 2002a, b; Lee et al., 2003; Ghurye et al., 2004 Dodd et al., 2006; Sorlini and Gialdini, 2010). Fig 2 shows the role of $KMnO_4$ and $FeCl_3$ in oxidation of arsenite by the advanced oxidation-coprecipitation-filtration (AOCF) method.
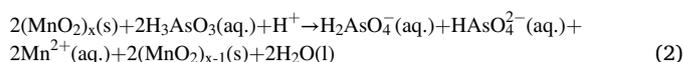
4.1.1. Chemical oxidation using manganese dioxide

Manganese dioxide is a strong oxidant in an environment which can reduce the mobility of As, Fe, Co, Cr, and organic matter (Oscarson et al., 1980; Crowther et al., 1983; Eary and Rai, 1987; Li et al., 2010). Feng et al (2006) synthesized three Mn oxide minerals namely, birnessite,

cryptomelane, and hausmannite which generally occur in soil and sediments. Depending on their respective crystal structure, composition and surface properties, they have different abilities for As (III) oxidation. Cryptomelane has a tunnel structure, while birnessite has layered structure, and hausmannite shows a lower oxide structure. The highest ability of As(III) oxidation has been exhibited by cryptomelane followed by birnessite and hausmannite respectively (Feng et al., 2006).

The oxidative reaction of As (III) with cryptomelane (or birnessite) is as follows:

(1). At lower pH condition:

$$2(MnO_2)_x(s)+2H_3AsO_3(aq.)+H^+ \rightarrow H_2AsO_4^-(aq.)+HAsO_4^{2-}(aq.)+2Mn^{2+}(aq.)+2(MnO_2)_{x-1}(s)+2H_2O(l) \tag{2}$$

(2). At higher pH condition:

$$2(MnO_2)_x(s)+2H_3AsO_3(aq.)\rightarrow H_2AsO_4^-(aq.)+HAsO_4^{2-}(aq.)+3H^+(aq.)+2(MnO_2)_{x-1}.MnO(s) \tag{3}$$
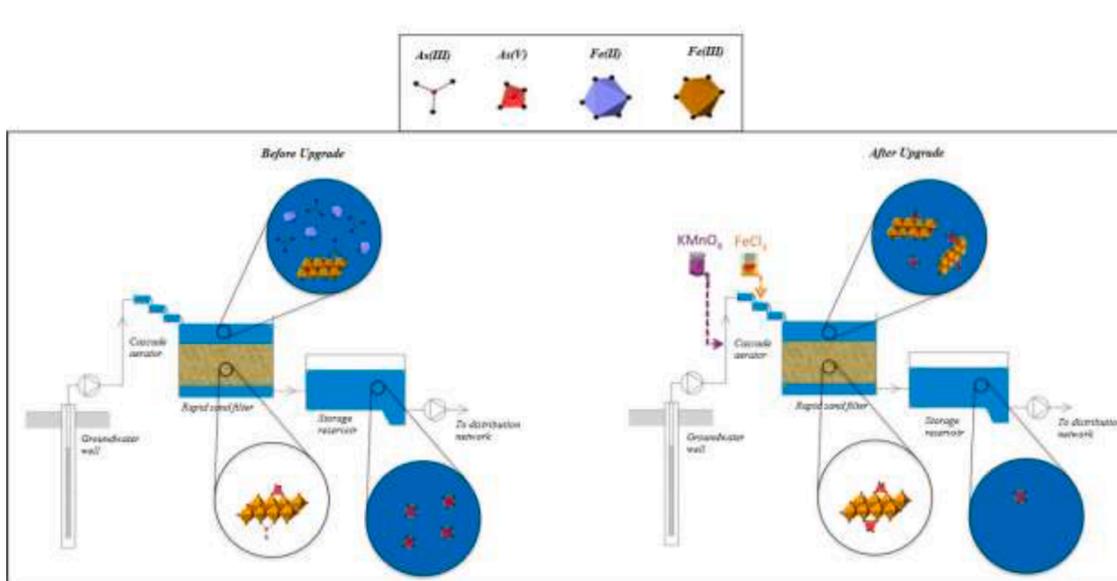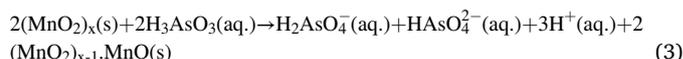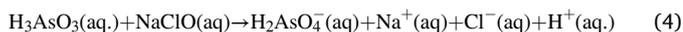

Fig. 2. Principle of advanced oxidation-coprecipitation-filtration (AOCF) for As decontamination (modified from Ahmad et al. 2018).

In the above equations $(MnO_2)_x$ is denoted for Mn oxides *i. e,* cryptomelane and birnessite. With an initial increase in pH value, the amount of As(III) oxidized was first decreasing. But as the pH was continuously increasing, the oxidation amount of As(III) by Mn oxide has increased remarkably.

Manning et al. (2002a) experimented As removal through birnessite. For this process a conventional stirring technique and an extending X-ray adsorption fine structure spectroscopy (EXAFS) both have been used. The stirred reaction experiment showed, the oxidation of As(III) was taking place before the adsorption of Arsenate on MnO_2 solid phase. EXAFS study confirmed As(V)- MnO_2 complex as a 'bridged complex' formed at MnO_2 crystal corners as well as on the interlayer parts (Mohan and Pittman Jr, 2007; Su and Puls, 2008).

4.1.2. Chemical oxidation using chlorine-based oxidants

Free available chlorine (FAC) can oxidize As (III) under all the tested conditions (Sorlini and Gialdini, 2010). The oxidation reaction between As (III) and FAC is as follows:

$$H_3AsO_3(aq.)+NaClO(aq)\rightarrow H_2AsO_4^-(aq.)+Na^+(aq)+Cl^-(aq)+H^+(aq.) \quad (4)$$

In the above reaction, oxidation of 1 mole of As (III) requires 1 mole of NaClO (hypochlorite), which is equivalent to 2 moles of Cl_2 (Clifford and Ghurye, 2001). Experiments performed by Dodd et al. (2006) described that only 0. 1 mg/l of Cl_2 dose as FAC is adequate for the depletion of As (III) in a real water samples spiking 50 µg/l As(III) level to <1 µg/l of As(III) within 10 s.

Chlorine dioxide (ClO_2) was also used for the oxidation of As (III), but it was not very effective (Clifford and Ghurye, 2001). This study suggested that only 20 to 30% of oxidation took place in the 3-fold stoichiometric dose of ClO_2, and after that oxidation nearly stopped. However, with an increase in pH, the oxidation reaches from 30% to 50% (Sorlini and Gialdini, 2010). It appeared that the initial Arsenite concentration does not increase oxidation efficiency significantly, as the researchers got similar results at 300 mg/l of As (III). The reaction for oxidizing As (III) using ClO_2:
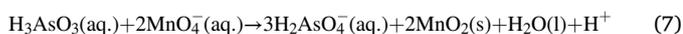
$$H_3AsO_3(aq.)+2ClO_2(g)+H_2O(l)\rightarrow H_2AsO_4^-(aq.)+2ClO_2^-(aq.)+3H^+ \quad (5)$$

Ghurye and Clifford (2004)) attempted an experiment using a pre-formed NH_2Cl. It was observed that there was no As (III) oxidation taking place. But the *in-situ* formed NH_2Cl oxidized As (III) to about 40%.

$$H_3AsO_3(aq.)+NH_2Cl(s)+H_2O(l)\rightarrow HAsO_4^-(aq.)+NH_4^+(aq.)+Cl^-(aq.)+2H^+ \quad (6)$$

Iron with concentration of 0. 3-3 mg/l, and manganese with 0. 2 mg/l, had shown very little effect on As(III) oxidation process (Bundschuh et al., 2021). But sulfides (1-2 mg/l) slowed down the process to a greater extent. In presence of sulfide, the oxidant dose used was 3-10 times the stoichiometric requirement to oxidize As(III) (Clifford and Ghurye, 2001)
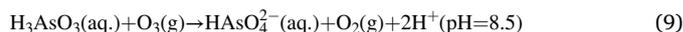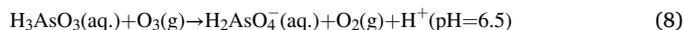
4.1.3. Chemical oxidation using potassium permanganate

Sorlini and Gialdini (2010) carried out an experiment on the As oxidation through potassium permanganate. Their research suggested Potassium Permanganate can oxidize As(III) up to 95 to 98% at the initial 50 mg/l of Arsenite. However, the increased doses of $KMnO_4$ enhanced the oxidation efficiency of Arsenite up to 100%. This oxidant worked well at the initial 300 mg/l of As(III) concentration, but this required increasing the oxidant dose to get higher efficiency. However, there was no change in oxidation yield when the pH changed. The reaction is as follows:

$$H_3AsO_3(aq.)+2MnO_4^-(aq.)\rightarrow 3H_2AsO_4^-(aq.)+2MnO_2(s)+H_2O(l)+H^+ \quad (7)$$
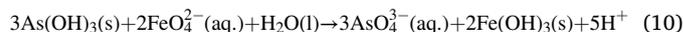
4.1.4. Chemical oxidation using ozone

Ozone acts as a rapid oxidant. It took only 15 s to oxidize > 95% of arsenite. However, the oxidation rate suddenly reduced due to the presence of total organic matter and sulfate (Ghurye et al., 2004a; Khuntia et al., 2014). It is also suggested that the higher dose of O_3 is needed to oxidize As(III) in groundwater which is already enriched in total organic carbon. The following reaction takes place between O_3 and As(III):

$$H_3AsO_3(aq.)+O_3(g)\rightarrow H_2AsO_4^-(aq.)+O_2(g)+H^+(pH=6.5) \quad (8)$$

$$H_3AsO_3(aq.)+O_3(g)\rightarrow HAsO_4^{2-}(aq.)+O_2(g)+2H^+(pH=8.5) \quad (9)$$

With the help of pure oxygen (O_2) and air as oxidants, about 57% and 54% of As(III) was oxidized respectively in the near neutral pH range (Kim and Nriagu, 2000).

4.1.5. Chemical oxidation using ferrate

Potassium ferrate [Fe(VI)] is highly stable, environment friendly, and has a very high oxidizing power. The bi-product of the oxidant is Fe (III), which is non-toxic in nature (Sharma, 2002). The oxidation of arsenite using ferrate with a stoichiometric ratio of 3:2 [As(III):Fe(VI)] has also proven as an efficient method (Wang et al., 2021). Researchers also stated that the concentration of 'As' was lowered to <50 µg/l from initial concentration of 517 µg/l'As', using just 2 mg/l of Fe(VI) (Lee et al., 2003). However, in order to get better results the pH of the water should be 4 and time for optimum reaction is 5 min. The reaction is given below (after Singh et al. 2015).

$$3As(OH)_3(s)+2FeO_4^{2-}(aq.)+H_2O(l)\rightarrow 3AsO_4^{3-}(aq.)+2Fe(OH)_3(s)+5H^+ \quad (10)$$

Oxidation with potassium permanganate, ozone and ferrate has shown high efficiency for As removal in comparison to oxidation with chlorinated compounds. The chemical oxidation and precipitation is the most convenient, feasible and effective method. However, the biggest disadvantage is the disposal of As contaminated low dense sludge volume. The disposal of liquid waste makes this process costly (Kabir and Chowdhury, 2017). This process needs chemicals and required quite trained operators. Precision is most important to achieve maximum removal efficiency.

4.2. Coagulation and flocculation

Coagulation and flocculation basically depend upon the co-precipitation of both inorganic oxides of other metals and the insoluble arsenates (Mohindru et al., 2017). The process involves the addition of metal-based coagulants such as ferric chloride, ferric sulfate and alum to the contaminated water (Sancha, 2006; Rathi and Kumar, 2021). For maximum As removal efficiency, the coagulant is mixed homogeneously throughout the aqueous medium. The metal-based coagulant e. g. $FeCl_3$ hydrolyzes itself in water and forms positively-charged ferric hydroxide $Fe(OH)_3$ (Wang et al., 2021). As(III) is pretreated with some oxidant to convert into As(V), it is a necessary step in the elimination of As from contaminated water. As(V) is an anion and it is attracted to the positively charged $Fe(OH)_3$ flocs (Fig. 3). In the whole process of coagulation and flocculation, pH, As speciation, coagulant dose, and the agitation speed are the major parameters (Sancha, 2006).

Aluminum sulfate (alum) is the most widely used coagulant for water treatment in United States of America (Hering and Elimelech, 1997) and in the developing nations. Addition of coagulants increases the As(V) removal. The coagulants accelerate the elimination of Arsenate from the aqueous solution by transforming it into insoluble products (Wickramasinghe et al., 2004. The more 'alum' dose is used, the more aluminum oxide is formed, which provides a greater surface area for the adsorption of As(V) (Baskan and Pala, 2010). This work suggested 100% removal of arsenate at initial As concentration of 500 and 1000 µg/l, at the
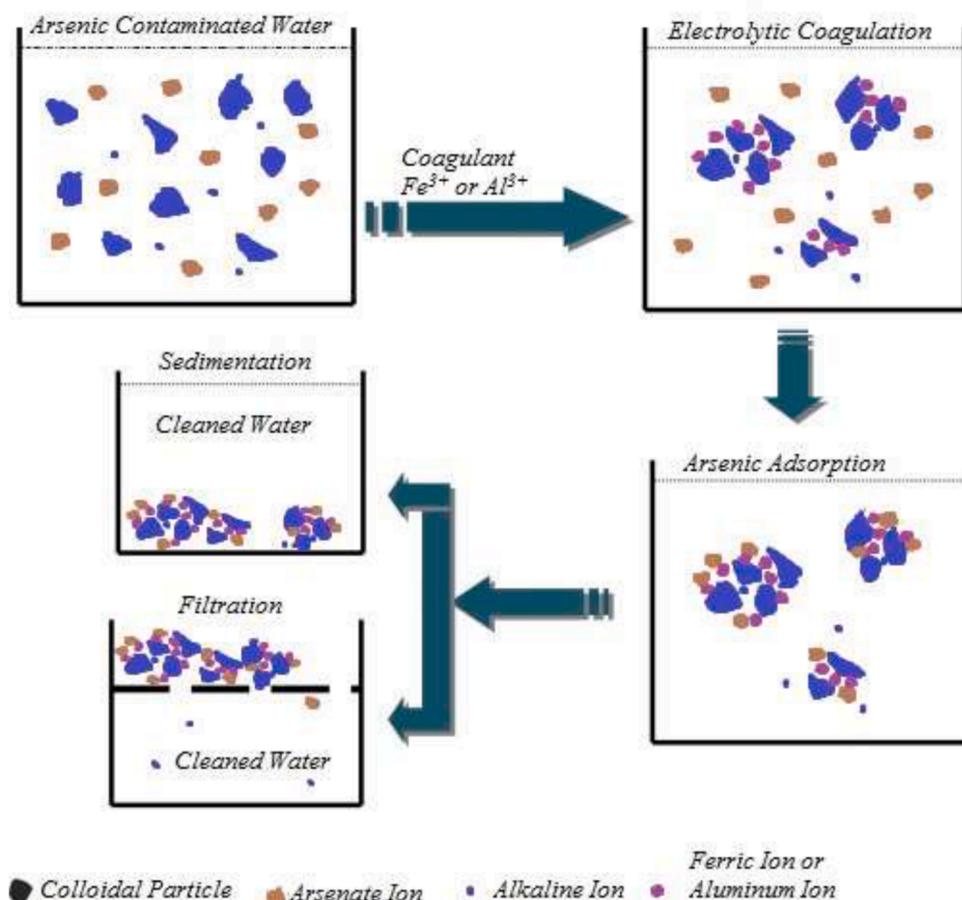
Fig. 3. Arsenic removal mechanism through coagulation and flocculation technique (modified from Song and Gallegos-Garcia 2014.
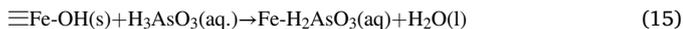
coagulant doses of 42 to 56 mg/l, respectively. However Matsui et al. (2017) reported 30 mg/l of alum can show the maximum efficiency to precipitate arsenate at a pH value of 7-8 (Habuda-Stanić and Nujić, 2015).

Another coagulant iron salt ($FeCl_3$) also studied and found effective in order to remove As from contaminated water (Ghosh et al, 2003). It was detected that both arsenite and arsenate were eliminated from aqueous media with a $FeCl_3$ of 40 mg/l within a pH range of 6–7. 5. But with the increasing pH value, As(V) removal efficiency reduced very sharply. However, the presence of anions like Cl^- and NO_3^- did not significantly affect the coagulation process but the removal efficiency was remarkably low due to SO_4^- ions. The co-precipitation reaction for different inorganic As species are as follows (Ghosh et al, 2003):

I. As(V) separation-

$$\equiv Fe\text{-}OH(s) + H_2AsO_4(aq.) \rightarrow Fe\text{-}H_2AsO_4(aq.) + H_2O(l) \qquad (14)$$

II. As(III) separation-

$$\equiv Fe\text{-}OH(s) + H_3AsO_3(aq.) \rightarrow Fe\text{-}H_2AsO_3(aq) + H_2O(l) \qquad (15)$$

where $\overline{\equiv}Fe\text{-}OH$ represents nucleation of precipitation on the solid surface.

Based on the surface complexion model, adsorption and coagulation were compared as it is evident that adsorption is an important mechanism that governs the removal of As during coagulation (Ghosh et al., 2003; Jain and Singh, 2012). However, the removal efficiency of $FeCl_3$ decreased in the presence of total organic carbon at pH 8-9 (Henke, 2009). Direct filtration technique after the coagulation achieved more than 95% removal efficiency at pH 7 and $FeCl_3$ dosage of 2 mg/l. Groundwater samples from US and Bangladesh were evaluated for coagulation and filtration by using $FeCl_3$ and $(Fe_2(SO_4)_3)$

(Wickramasinghe et al., 2004).

Sancha (2000) investigated the As removal efficiency of Titanium chloride ($TiCl_3$) as a coagulant. It was reported that both As(III) and As (V) removal were greatly dependent on pH i. e, with the increasing pH As(V) removal efficiency lowered. However, the maximum removal efficiencies of As(V) and As(III) were not more than 49% and 42%, respectively at optimum dosage and pH conditions (Mohindru et al., 2017).

Coagulation and flocculation process ideal for the water rich in Fe and Mg. This process needs very nominal capital investment (Baigorria et al., 2021). This method can be installed at larger scale –community level to supply As free water. Although it remove As upto 95% from contaminated water, alike chemical oxidation and precipitation this process produces As contaminated sludge and disposal of toxic sludge increase the running cost.

4.3. Electrocoagulation

Electrocoagulation is an alternative to the conventional coagulation and filtration techniques. Electrochemical reactions that occur in cathode and anode also include *in-situ* generation of coagulants or flocs (Santos et al., 2015; Ali et al., 2013; Weerasundara et al., 2021). When electrocoagulation was compared to chemical coagulation using $FeCl_3$, it was clear that electrocoagulation had better As removal efficiency (Lakshmanan et al., 2010). This technique could overcome the drawbacks of the conventional As removal methods such as low As removal efficiency, time consuming, high operating cost and toxic sludge production (Khandegar and Saroha, 2013; Sahu et al., 2014; Song et al., 2017; Demirbas et al., 2019; Alka et al., 2021).

Metal electrodes mainly of iron or aluminum which are involved in

electrochemical reactions and metallic cations like Fe(II), Fe(III), or Al (III) are generated due to the oxidation reaction on anode. Initially, monomeric Fe or Al ions form $FeOH^+$, $FeOH^{2+}$, $Fe(OH)_2^+$, $AlOH^{2+}$, $Al(OH)_2^+$ and polymeric Fe or Al ions form $Fe(H_2O)_5OH^{2+}$, $Fe(H_2O)_4(OH)_2^+$, $Fe(H_2O)_8(OH)_2^{4+}$, $Al_6(OH)_{15}^{4+}$, $Al_7(OH)_{17}^{4+}$, $Al^{13}(OH)_{34}^{5+}$. These ions subsequently form a series of iron or aluminum hydroxides/oxyhydroxides such as $Fe(OH)_2$, $Fe(OH)_3$, $Al(OH)_3$, with large surface area to adsorb the dissolved contaminants (Kobya et al., 2003). pH acts as an important factor influencing the achievement of the electro-coagulation process. However, the pH depends on the type of electrode used and also on the initial pH. Aluminum electrodes with initial pH <8 give higher final pH in contrast initial pH >8 pH reduces the final pH. In iron electrodes the final pH is always higher than the initial pH. Kobya et al. (2011) performed an experiment to find out the pH at which maximum As removal efficiency can be achieved in electrocoagulation techniques. The optimal As removal efficiency 99% with iron electrode was achieved at a pH of 6. 5 and with aluminium electrode (37%), the pH was 7 (Kumar et al., 2004).

Presence of phosphate as a competing ion inhibits the removal of As during electrocoagulation process (Wan et al., 2011; Song et al., 2014). It was also reported that the presence of phosphorus slows down Fe (II) oxidation to Fe(III) which leads to the reduction in the formation of complexes. When the effect of silica on As removal was evaluated by Wan et al. (2011), it was suggested that there is no significant effect of dissolved silica on As removal efficiency up to 20 mg/l in electro-coagulation process. But Vasudevan et al. (2010) had previously suggested that silica concentrations from 0 to 15 mg/l in the aqueous solution reduced As(V) removal efficiency.

Electrocoagulation process provides 99% As removal efficiency depending on the electrode used and other parameters such as initial As concentration, pH and presence of other ions in water. The disposal of the sludge generated by the process is one of the disadvantages of this technology. Studies of Babu et al. (2021), suggested the management of As-Fe laded sludge generated by electrocoagulation process. This process needs continuous electricity which also adds up additional running cost, and thus not very effective method to install in rural areas of most low income countries.

4.4. As removal through low cost adsorbents

Adsorption technology has been used worldwide due to its high removal efficiency, sludge free and easy operation and handling. Hence, this technique is widely used for the treatment of different pollutants from the contaminated water (Naz and Chowdhury, 2021). Adsorption process is affected by various parameters such as temperature, pH, nature of adsorbate and adsorbent, contact time, concentration of pollutants and, presence of other competitive ions (Chiban et al., 2016). Variety of adsorbent material have been studied on the As removal from drinking water such as aluminium based sorbents, iron oxides, activated carbon, clays and soils, zeolites, flyash, bismuth impregnated biochar, portland cement biochar and chiston crosslinked with transition metals (Aredes et al., 2013; Chutia et al., 2009; Chowdhury et al., 2021; Anjum et al., 2011; Zhu et al., 2016; Han et al., 2019; Kabir and Chowdhury, 2017; Alkurdi et al., 2019; Pincus et al., 2021). Nowadays, plant based adsorbents become more popular due to their cost effectiveness. Study suggested that about 70% removal of As(III) arsenic was achieved at pH 2. 0 by chars (obtained by rapid pyrolysis of oak bark as a byproduct of bio-oil production) (Mohan et al., 2007). However, the cost effectiveness of the adsorption technology is highly dependent on the cost of adsorbent material. As per literature, low cost adsorbent media, such as 5. 7 US$/kg for activated alumina, 6. 05 US$/kg for granular ferric hydroxide, and 11. 55 US$/kg for bayoxid, are significantly effective in the removal of As from water (Callegari et al., 2018). Thus the cost of adsorption can be reduced by selecting adsorbent and regeneration materials.

Adsorption is one of the cost effective process for the As removal

from contaminated water. It provides > 95% As removal efficiency (Baigorria et al., 2021). The installation is simple at reasonable operation cost. This process also does not required trained operators. Less chemical used in this process, except sometimes pH needs to be maintaining for achieving high removal efficiencies. The ions present in the water can compete with As and thus process become complex. The regeneration is difficult and bacteriological contamination may occur during the adsorption process.

4.5. Ion exchange

Ion exchange is a physicochemical process in which the ions of the solid phase are exchanged with the equal number of ions from the contaminated water (Sarkar and Paul, 2016). In this technique, synthetic resins are used as solid phase for absorbing the arsenic ions very efficiently. Balaji and Matsunaga (2002) evaluated the adsorption performance of As(III) and As(V) using TiO_2-loaded Amberlite XAD-7 resin. It was prepared by impregnating $Ti(OC_2H_4)_4$ followed by hydrolysis using ammonium hydroxide. Results showed strong adsorption of As(V) from a pH range of 1–5 and of As(III) from pH 5-10. Adsorption capacities for As(V) was 0. 063 mmol/g at pH 4 and for As(III) it was 0. 13 mmol/g at pH 7. Cations such as Na (I), Cd(II), Pb(II) did not show significant effect on arsenic adsorption. Anion exchanger (AE) was prepared using coconut coir pith (CP) for removal of As(V) from aqueous solutions (Anirudhan and Unnithan, 2007). A maximum of 99. 2% As(V) removal was achieved at pH 7. 0 for an initial As(V) concentration of 1 ppm with 2 g/l adsorbent dose.

Ion exchange is one of the promising As removal technology. With advancement of science the process become high in demand in high income countries. This process provides > 99% of removal of As from the contaminated water. Most of the time this process does not require pH adjustment except very few cases such as while using activated alumina pH adjustment necessary to achieve highest efficiency (Clifford and Ghurye, 2002). The process is frequent although complex and needs expensive ion exchange resins which may be main reason why it is not popular among low income countries. Regeneration creates a sludge disposal problem, and frequent regeneration of exhausted resins is required. This technique applicable only for low 'total dissolved solids' thus pretreatment require which adds up extra cost (Zakhar et al., 2018). This process requires careful continuous monitoring, thus required trained workers to operate the treatment plant. The installation cost is also very high if it is installed at community level basis.

4.6. Removal of As through biological methods

Nowadays biological remediation techniques are being used more often in developing countries for arsenic removal (Yamauchi and Takata, 2019; Naz et al., 2013, 2021). The role of microorganisms in removing As concentration has been investigated for decades (Banerjee et al., 2013). Biological remediation includes phytoremediation and bio-adsorption using plants, microbes respectively (Stefanescu et al., 2017; Ilieva et al., 2020). Nigam et al. (2013) investigated the bio-sorption ability of *Hydrilla verticillata* for uptake of As from water under various parameters like pH, temperature, contact time, sorbent dose and initial As concentration. The results showed maximum As adsorption of 96. 35% with the adsorbent dosage of 0. 5g per 100 ml of water at initial As concentration of 100 μg/l for contact time of an hour and at a pH 6 (Nigam et al., 2013; Mehdi et al., 2021). Hassan et al. (2009) used both biological and physicochemical treatment methods for As removal.

Arsenic bioremediation depends on the microbial activity to remove, demobilize or adsorbing As from aqueous solutions different biochemical process such as oxidation, biomethylation, complexation and coprecipitation process (Wang and Zhao, 2009; Bahar et al., 2013). Fig 4 depicts activities of microorganisms causing vaporization, precipitation, dissolution, deposition, and redox reactions.
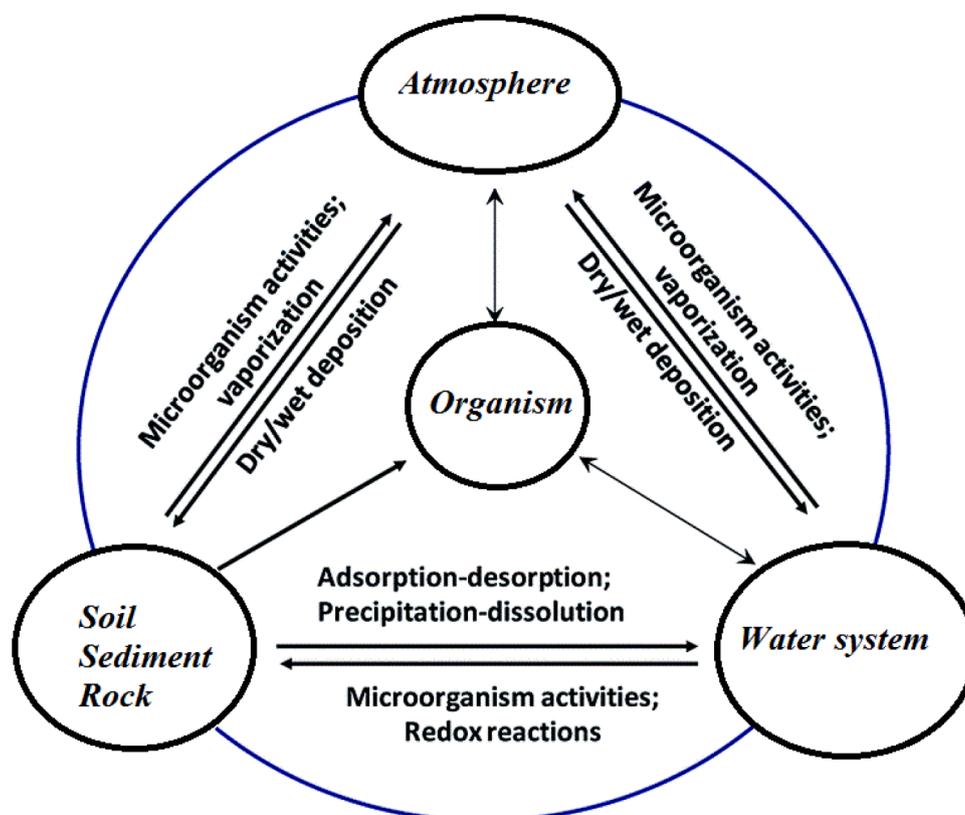
Fig. 4. Mechanism of bioremediation of Arsenic from aqueous solution through micro-organism (modified from Hao et al. 2018).

4.6.1. As(III) oxidation through bacteria

Most of the As oxidizing bacteria are isolated from the extreme environments which have high amounts of As (Bachate et al., 2012). This shows that there is a wide distribution of As(III)-oxidizers in the environment (Bahar et al., 2012). The most efficient heterotroph As(III) oxidizer which could oxidize 500 μM of As(III) within a contact time of 12 h with initial cell density of 1.5×10^7 cell/mL at pH 5-7 was *Stenotrophomonus* sp. strain MM-7 (Bahar et al., 2012). On the other hand, a chemolithotrophic As(III) oxidizing bacteria *Agrobacterium/Rhizobium* designated as NT-26 was isolated from a gold mine from Australia (Santini et al., 2000; Ito et al., 2012). NT-26 can grow in a minimal salt medium containing As(III) as an electron donor with doubling growth time as 7. 6 h. Species like *Sulfolobus acidocaldarius, Theiomonas arsenivorans* are able to oxidize As(III) at low pH i. e, ($\leq$ 6) (Dastidar and Wang, 2009). But the optimum oxidation of As(III) took place in pH range of 5–7 (Battaglia-Brunet et al., 2011; Mehdi et al., 2021).

Leiva et al. (2014) also suggested the higher efficiency of oxidation by biogeochemical processes in their findings. This method has a high potential of replacing conventional treatment methods of As contaminated water in Asian countries. In a recent study conducted in Italy by Zecchin et al. (2021) it was found out that aquifers contaminated with As had lots of bacterial communities that survived in the polluted waters and these communities have enormous potential to remediate the polluted water. However, studies are at the preliminary stage. Dabrowska et al. (2021) used mushroom waste served as the substrate for the microbial consortia that played a role in remediation of As. Microbial fuel cell found very effective in As removal, it is also effective for removal of organic matter and heavy metals (Tabassum et al. 2021). Since chemicals are not added to the groundwater, it is quite economical and environmentally sound (Katsoyiannis and Zouboulis, 2004a, 2004b; Katsoyiannis et al., 2008). Novel and innovative protocols exploiting the further potential of microbes and other biological organisms using biotechnological and nanotechnology approaches are being developed in various research labs.

4.6.2. Removal of As by microalgae and fungi

Algae display a two-step process in water purification. First step involves the adsorption of metal ions on the cell surface and the second, metal ions perforate into the cells through the cell wall (Bahar et al., 2013; Mehdi et al., 2021). Whereas Fungi help in decontaminating the water by: (i) biosorption of As on fungal surface, (ii) accumulation of As in intracellular spaces and (iii) bio volatilization through some metabolites. Approximately 70% removal of As(III) took place by a common green algae *S. abundans* when the initial As(III) concentration was 5 mg/l (Jahan et al., 2006). However the maximum uptake of As was observed by *Microcystis aeruginosa* when exposed to As(III) and As(V) within 15 days of exposure (Wang et al., 2013). Study suggested that, a wild-type strain *Aspergillus niger* (fungi) was much more tolerant to As (V) than other fungal strains (Mukherjee et al., 2010). At 25 mg/l As(V) concentration, growth of *A. niger* increased but they could survive only up to 100 mg/l of As(V) as per Bahar et al., 2013. Detoxification of As through volatilization by methylation has also been studied (Irshad et al., 2021; Tripathi et al. 2020; Verma et al., 2019). However, no study has reported the exact mechanisms behind As detoxification with help of fungi (Irshad et al., 2021).

The biological treatment systems provides significant As removal. The process is less complex and required very less maintenance, does not require much trained operators and suitable for rural areas (Hayat et al., 2017; Zhai et al., 2020). The major disadvantage is it is a slow process of As decontamination from water and suitable for only low As contaminated water. The drinking water treated through microbes, microalgae and fungi needs tertiary treatment before supply. The As removal efficiency is not predictable as this process is highly dependent on the environmental variables such as temperature, and humidity (Lièvremont et al., 2009).

5. Discussion

Although many techniques have been developed in the last few years

that show promising results, the sustainability and cost effectiveness of methods is an important issue (Alkurdi et al., 2019). The laboratory protocols show various limitations when applied on the field. The same method applied in different laboratory gives different results, as As removal is highly dependent on the operation, scale of the treatment plants, various parameters, available ions in the water and initial As concentrations. Thus it is difficult to decontaminate the water using similar techniques as the physiographic, climatic, and environmental conditions vary with time and space.

Adopting the hybrid approach such as microbial fuel cell fixing followed by oxidation of As through Fe and Mn oxide can lead to the As removal techniques through an efficient, effective, economic. Research methods using hybrid approaches are now proving popular for the decontaminating As in drinking water. Studies of Maity et al. (2021) also suggested that the hybrid (chemical/adsorption and biological treatment) can be the best As removal techniques in context of cost effectiveness, efficiency and sustainable As remediation strategy. Study of Katsoyiannis et al., 2014 also suggested that hybrid methods such as preoxidation with biological method followed by GFH/adsorption and ozone oxidation followed by chemical precipitation are cost effective and more feasible in comparison to most of the methods (Table 4).

Process complexity, hazardous materials handling, and waste disposal considerations can also have a major influence on the choice of a process. The application of low cost As treatment process can be an effective tool to save millions from As toxicity in middle and low income countries. The cost benefit analysis suggested that chemical coagulation (0. 043 US$/$m^3$) (except sludge disposal cost), adsorption by low cost adsorbents – laterite clay (0. 10 US$/$m^3$), adsorption with Fe oxide coated sand filtration (0. 11 US$/$m^3$), ion exchange (0. 12 US$/$m^3$) and hybrid methods (0. 15-0. 17 US$/$m^3$) were most economical in comparison to other reported technologies (Table 4).

Cost of maintenance is a recurring cost that does make As removal methods less popular in developing countries. Due to complexity and cost barriers, most of the As removal technology may not yield fruitful result, but coupled with social interventions, the targets can be achieved. Thus community participation plays an important role to make the As remediation process sustainable. Therefore, it is important to bring local communities together to achieve the sustainable goals of good health and clean water these are SDG-3 and SDG 6 respectively.

6. Arsenic removal *Vs* SDG 3 and SDG 6 goals

Till date there has been approximately 140 thousand articles are published on As, As contamination, As toxicity, and As removal technologies. But till date the situation of millions of people impacted by As is remain unchanged. Now, the question arises-What is the feasible method to remove As with a practical and social objective of alleviating people suffering due to exposure to this metalloid. UN SDGs have already being formulated by international agency to transition the world to a greener environment friendly future to key goals of SDGs (Total 17 goals) is SDG 3 (Health and Well-being) and SDG-6 (Clean water and Sanitation). The global target is to achieve this by 2030. But with 500 million people, mostly residing in low/middle income countries impacted by As is a barrier to achieve this goals. Hence, this review focuses on the cost effectiveness of prevalent As removal technologies with an overall focus on its practical usability in low/middle income countries.

As per the recent researches, low and middle income nations are mostly affected by As pollution. Unlike other water borne pollutants, being a metaloid, As is difficult to be removed from the aquifer without effective treatment. These treatment methods add cost allocations for the policy makers, making them unpopular. Another option will be to supply drinking water in the Arsenic polluted regions to limit human exposure to geogenic As. Works of Hernandez et al. (2019) suggested the requirement and process for the policy level interventions to install a community based As removal plants for the As impacted rural region.

Works of Roy et al. (2015), highlights the effectiveness of community based water treatment systems in the villages of Malatipur, Barshimul, Sirkapara, Gujastirampur in the Arsenic impacted district of Murshidabad, West Bengal, India. According to Kinniburgh and Smedley (2001), *In situ* a pilot scale chemical and bacterial oxidation based As treatment plant were installed has worked well. 'Danida arsenic mitigation pilot project' was one of the well-known community level water treatment units for the removal of As from contaminated aquifers in Bangladesh (Jain and Singh, 2012). This method is not efficient for removing high concentrations of As but is capable of reducing the As concentration to permissible levels in Bangladesh. Two primary advantages of using *in-situ* oxidation techniques are: (i) low cost of installation and no serious sludge-related disposal issue (ii) small-scale facility needed (Paul et al., 2010). Van Halem et al. (2010) observed that the freshly oxidized adsorbed iron was available for co-adsorption of As indicating that the As adsorption is dependent on the amount of adsorbed iron that is oxidized (Luong et al., 2018).

The policy level intervention can focus on community based awareness and aim to improve their access to clean drinking water and sanitation (SDG-6). Identifying polluted ground water zones (wells) and disusing them in favor of non-polluted aquifer can be another alternative for communities dependent on ground water for their primary water needs (Chen et al., 2007). 'Willingness to pay' by effected population for clean drinking water is another criterion that need to be evaluated by policy makers while formulating As removal systems suited for community. For example, people may be willing to pay for availing services pertaining to daily need but may find 'paying for water' unacceptable even if it impacts their health and wellbeing (Orgill et al., 2013). Hence, with research focus continuing on developing As removal technologies, there need to be coordinated policy level interventions with community participation to manage the issue in the larger scale.

7. Conclusions and recommendations

Lower- and middle-income countries impacted by geogenic As pollution in the groundwater need economic and feasible 'As' remediation technologies. Technologies developed follows As-removal efficient is mainly dependent on environmental variables, installation and running cpst, installation charges. The existing technologies need to be efficient, environmentally friendly and cost effective to target achieving the goals of SDG 3 and SDG 6 in low/middle income countries. Most of the Asian countries falling under the low and middle income range are worst affected with elevated As concentration in drinking water. Success stories of arsenic removal at community based units' needs to be studied and implemented in different parts of the globe facing similar issues. Innovating 'easy to use', efficient hybrid technologies with low maintenance cost, low electricity demand, low waste generation is the only way forward in achieving the overall target of delivering 'clean and safe drinking water' to all in order to protect the 'health and wellbeing' of impacted populations. Regular monitoring, community awareness, community participation, research on cost effective As-removal models coupled with policy level intervention to ensure clean water supply to all, should be focused in all As-impacted nations.

Ethical approval

All authors are informed of the ethical guidelines of the journal and we declare that we have complied with them.

Table 4
Cost benefit analysis of popular As remediation process.

Popular process	Treatment Methods	Running cost (US$/m³)	Remarks	
Adsorption	Adsorption on iron oxide coated sand	0. 73	Loss of medium capacity, fouling by inorganic and organics matter and orifice clogging	Chappell et al., 2001; Joshi and Chaundhuri, 1996; Ahmed, 2006
	Sorptive filtration using gravel bed containing iron sludge	>0. 71	Presence of divalent cations (Ni²⁺, Co²⁺, Mg²⁺) enhances the adsorption. As sludge management is difficult.	Ali et al. 2001; Kabir and Chowdhury, 2017.
	Ferrous based red mud sludge (FRS)	Material cost 88–118 US$/ton	Without chemical addition or special care. But sometimes bacteriological contamination may occur	Li et al., 2010
	BUET activated alumina	0. 74–1. 19	Compacted activated alumina column adsorbs arsenic on surface of alumina grains. Not suitable for commercial scale as As contaminated sludge disposal is difficult	Chappell et al. 2001; Ahmed 2001
	Filtration with zero-valent iron (ZVI)	1. 2	90% arsenic removal possible from phosphate and silicate rich water. Regular backwashing of sand filter is required.	Hug and Leupin, 2003
	Fill and draw units	1. 015	Manually mixing of water with oxidant and coagulant at 60 rpm speed for 30 s and overnight sedimentation. Controlled mixing and tank gradient aids floc formation and enhance the removal rate. Not capable to reduce below specific level	Ahmed, 2001, 2006
	Read-F arsenic removal unit	2	Iron removal by sand filter to avoid clogging of resin bed.High selectivity for both As(III) and As(V) under wide range of conditions	Ahmed. 2006; Hanchett et al., 2011
	Laterite as a low-cost adsorbent in a sustainable decentralized filtration system	0. 10	Low cost absorbent. Significantly good efficiency	Nguyen et al., 2020
	Adsorption with iron oxide coated sand filteration	0. 11	Cost effective technology for low concentration of As in water. This process effectively removed methane, ammonia, iron and manganese along with As	Petrusevski et al., 2007
Ion exchange	An integrated ion-exchange membrane process coupled with Fe co-precipitation	0. 12 (as per rough estimation as per laboratory condition)	The major costs in membrane processes are due to the cost of membranes and due to the need of their replacement	Lopes et al., 2020
Reverse osmosis	Reverse osmosis unit	0. 52 (Community level unit for inhabitants 20000, while cost increased 0. 45-0. 88 US$/m³ for population 5000-50000)	High pressure, high pH and low temperature favoured a more efficient removal of arsenic, whereas an increase in ionic strength reduced the removal of arsenate. Dependency on the skilled personnel. Pretreatment required as preexisting ions interfere the filtration process. Adjusting the pH of raw water can increase the media capacity and lowers the operating costs; however, pH control equipment increasesinvestment costs and the overall operational complex	Abejón et al., 2015
Chemical coagulation and chemical reduction	In situ oxidation of iron and arsenic in the aquifer	0. 076 (except the sludge disposal cost)	It allows formation of iron hydroxide coating on sand grains around the strainer of the well. Recollected water from the aquifer shows around 50–70% reduction of arsenic. Bacteriological contamination may result in some cases	Ahmed, 2006
	The granular ferric hydroxide	0. 043 (except the sludge disposal cost)	Chemical processes include oxidation and precipitation, where each process is carried out in separate operational units and thus increased capital cost associated with the necessary chemicals and equipment	Driehaus, 2002
	Iron-based subsurface arsenic removal (SAR)	0. 06–0. 07	Pilot scale study proved efficient for removal of Arsenic from water in Vietnam	Kurz et al., 2020
Electrocoagulation	Electrocoagulation of As	0. 22–0. 31	This process needs continuous supply of electricity, which is associated with additional initial cost and technical issues. Disposal of toxic sludge is also adds up cost in these processes	Addy, 2010, Addy et al, 2011; Kabir and Chowdhury, 2017
Biological remediation	Biological removal and fixation of As		A stable arsenite oxidation efficiency of 99% was achieved, while the removal of total arsenic was 93%. The drawback of biological methods lies firstly, in the predominance of the most toxic As (III), which requires a prior step of oxidation it may be biological oxidation through microbes, algae and fungi. However water contaminated with low concentration of As can be easily detoxify with help of biological treatments	Vega-Hernandez et al., 2021
	Microbial fuel cell	0. 2 (58 USD per Gallon)	This fuel cell was effective for the removal of both inorganic organic contaminates. This technology is mostly suitable for industrial waste.	Tabassum et al. 2021
Hybrid methods		0. 17 ± 0. 02		Katsoyiannis et al., 2015

Table 4 (*continued*)

Popular process	Treatment Methods	Running cost (US$/m^3)	Remarks	
	Pre-oxidation with biological method followed by GFH/ adsorption		The cost of adsorbents count is around 0. 09 ± 0. 02 €/m3,which is more than 50% of the total operating cost	
	Ozone oxidation followed by Chemical precipitation	0. 15 ± 0. 02	Operational cost including handling of backwash water including thickening and dewatering of the sludge	Katsoyiannis et al., 2015

Consent to participate

All authors have participated in the design, planning and writing and validation of results of this work.

Consent for publication

All authors agree to the publication of this research according to the guidelines of the journal.

Availability of data and materials

All data used in this manuscript are available in references.

CRediT authorship contribution statement

Akhilesh Kumar Yadav: Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **Harish Kumar Yadav:** Data curation, Writing – original draft. **Aliya Naz:** Methodology, Investigation, Data curation, Writing – review & editing, Visualization. **Monika Koul:** Writing – review & editing, Visualization. **Abhiroop Chowdhury:** Conceptualization, Writing – review & editing. **Shashank Shekhar:** Validation, Resources, Supervision.

Declaration of Competing Interest

Authors declare that they do not have any conflict of interest.

Acknowledgments

References

Abdulmutalimova, T.O., Revich, B.A., Ramazanov, O.M., 2019. Arsenic contamination in drinking water from groundwater sources and health risk assessment in the Republic of Dagestan, Russia. In: Environmental Arsenic in a Changing World: Proceedings of the 7th International Congress and Exhibition on Arsenic in the Environment (AS 2018). CRC Press, Beijing, PR China, p. 375.

Abejón, A., Garea, A., Irabien, A., 2015. Arsenic removal from drinking water by reverse osmosis: minimization of costs and energy consumption. Sep. Purif. Technol. 144, 46–53.

Abiye, T.A., Bhattacharya, P., 2019. Arsenic concentration in groundwater: archetypal study from South Africa. Groundw. Sustain. Dev. 9, 100246 https://doi.org/ 10.1016/j.gsd.2019.100246.

Addy, S.E., 2010. Electrochemical arsenic removal (ECAR) for rural Bangladesh—Merging technology with sustainable implementation. Lawrence Berkeley National Laboratory.

Addy, S.E.A., Gadgil, A.J., van Genuchten, C.M. and Li, L., 2011. Locally affordable arsenic remediation for rural South Asia using electrocoagulation. In Proceedings of the 35th WEDC International Conference, Loughborough, UK.

Ahmad, A., Cornelissen, E., van de Wetering, S., van Dijk, T., van Genuchten, C., Bundschuh, J., van der Wal, A., Bhattacharya, P., 2018. Arsenite removal in groundwater treatment plants by sequential Permanganate–Ferric treatment. J. Water Process Eng. 26, 221–229. https://doi.org/10.1016/j.jwpe.2018.10.014.

Ahmed, A., 2006. Arsenic mitigation technologies in South and East Asia. 44.

Ahmed, M.F. (2001, May). An overview of arsenic removal technologies in Bangladesh and India. In Proceedings of the BUET-UNU International Workshop on Technologies for Arsenic Removal from Drinking Water, Dhaka (pp. 5-7).

Alam, M., Shaikh, W.A., Chakraborty, S., Avishek, K., Bhattacharya, T., 2016. Groundwater arsenic contamination and potential health risk assessment of Gangetic Plains of Jharkhand, India. Expo. Health 8 (1), 125–142. https://doi.org/10.1007/ s12403-015-0188-0.

Ali, MA, Badruzzaman, ABM, Jalil, MA, Hossain, MD, Hussainuzzaman, MM, Badruzzaman, M, Akter, N(2001). Development of low-cost technologies for removal of arsenic from groundwater. Technologies for Arsenic Removal from Drinking Water. Edited by: M. Feroze Ahmed, M. Ashraf Ali and Zafar Adeel. Bangladesh University of Engineering and Technology, Dhaka-The United Nations University, Tokyo, 99-120.

Ali, I., Asim, M., Khan, T.A., 2013. Arsenite removal from water by electro-coagulation on zinc–zinc and copper–copper electrodes. Int. J. Environ. Sci. Technol. 10 (2), 377–384. https://doi.org/10.1007/s13762-012-0113-z.

Alka, S., Shahir, S., Ibrahim, N., Ndejiko, M.J., Vo, D.V.N., Abd Manan, F., 2021. Arsenic removal technologies and future trends: a mini review. J. Clean. Prod. 278, 123805 https://doi.org/10.1016/jjclepro2020123805.

Alkurdi, S.S., Herath, I., Bundschuh, J., Al-Juboori, R.A., Vithanage, M., Mohan, D., 2019. Biochar versus bone char for a sustainable inorganic arsenic mitigation in water: what needs to be done in future research? Environ. Int. 127, 52–69.

Amen, R., Bashir, H., Bibi, I., Shaheen, S.M., Niazi, N.K., Shahid, M., Rinklebe, J., 2020. A critical review on arsenic removal from water using biochar-based sorbents: the significance of modification and redox reactions. Chem. Eng. J. 396, 125195.

Anirudhan, T.S., Unnithan, M.R., 2007. Arsenic (V) removal from aqueous solutions using an anion exchanger derived from coconut coir pith and its recovery. Chemosphere 66 (1), 60–66.

Anjum, A., Lokeswari, P., Kaur, M., Datta, M., 2011. Removal of As (III) from aqueous solutions using montmorillonite. J. Anal. Sci. Methods Instrum. 1 (2), 25.

Aredes, S, Klein, B, Pawlik, M, 2013. The removal of arsenic from water using natural iron oxide minerals. J. Cleaner Prod. 60, 71–76.

Babu, DS, Vijay, K, Nidheesh, PV, Kumar, MS, 2021. Performance of continuous aerated iron electrocoagulation process for arsenite removal from simulated groundwater and management of arsenic-iron sludge. Sustain. Energy Technol. Assess. 47, 101476.

Bachate, SP, Khapare, RM, Kodam, KM, 2012. Oxidation of arsenite by two β-proteobacteria isolated from soil. Appl. Microbiol. Biotechnol. 93 (5), 2135–2145. https://doi.org/10.1007/s00253-011-3606-7.

Bahar, M, Megharaj, M, Naidu, R, 2012. Arsenic bioremediation potential of a new arsenite-oxidizing bacterium Stenotrophomonas sp. MM-7 isolated from soil. Biodegradation 23 (6), 803–812. https://doi.org/10.1007/s10532-012-9567-4.

Bahar, MM, Megharaj, M, Naidu, R, 2013. Bioremediation of arsenic-contaminated water: recent advances and future prospects. Water Air Soil Pollut. 224 (12), 1–20. https://doi.org/10.1007/s11270-013-1722-y.

Baig, SA, Sheng, T, Hu, Y, Xu, J, Xu, X, 2015. Arsenic removal from natural water using low cost granulated adsorbents: a review. Clean–Soil, Air, Water 43 (1), 13–26. https://doi.org/10.1002/clen201200466.

Baigorria, E, Cano, L, Alvarez, VA, 2021. Nanoclays as eco-friendly adsorbents of arsenic for water purification. Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications, pp. 455–470.

Balaji, T, Matsunaga, H, 2002. Adsorption characteristics of As (III) and As (V) with titanium dioxide loaded Amberlite XAD-7 resin. Anal. Sci. 18 (12), 1345–1349.

Bandara, UGC, Diyabalanage, S, Hanke, C, van Geldern, R, Barth, JA, Chandrajith, R, 2018. Arsenic-rich shallow groundwater in sandy aquifer systems buffered by rising carbonate waters: a geochemical case study from Mannar Island, Sri Lanka. Sci. Total Environ. 633, 1352–1359. https://doi.org/10.1016/jscitotenv201803226.

Banerjee, S, Majumdar, J, Samal, AC, Bhattachariya, P, Santra, SC, 2013. Biotransformation and bioaccumulation of arsenic by Brevibacillus brevis isolated from arsenic contaminated region of West Bengal. IOSR J Environ. Sci. Toxicol. Food Technol. 3 (1), 1–10.

Barats, A, Féraud, G, Potot, C, Philippini, V, Travi, Y, Durrieu, G, Dubar, M, Simler, R, 2014. Naturally dissolved arsenic concentrations in the Alpine/Mediterranean Var River watershed (France). Sci. Total Environ. 473, 422–436.

Baskan, MB, Pala, A, 2010. A statistical experiment design approach for arsenic removal by coagulation process using aluminum sulfate. Desalination 254 (1-3), 42–48. https://doi.org/10.1016/jdesal200912016.

Battaglia-Brunet, F, Crouzet, C, Breeze, D, Tris, H, Morin, D, 2011. Decreased leachability of arsenic linked to biological oxidation of As (III) in solid wastes from bioleaching liquors. Hydrometallurgy 107 (1-2), 34–39. https://doi.org/10.1016/ jhydromet201012019.

Berg, M, Tran, HC, Nguyen, TC, Pham, HV, Schertenleib, R, Giger, W, 2001. Arsenic contamination of groundwater and drinking water in Vietnam: a human health threat. Environ. Sci. Technol. 35 (13), 2621–2626. https://doi.org/10.1021/ es010027y.

Bidone, E, Castilhos, Z, Cesar, R, Santos, MC, Sierpe, R, Ferreira, M, 2016. Hydrogeochemistry of arsenic pollution in watersheds influenced by gold mining

activities in Paracatu (Minas Gerais State, Brazil). Environ. Sci. Pollut. Res. 23 (9), 8546–8555. https://doi.org/10.1007/s11356-016-6089-3.

Bindal, S, Singh, CK, 2019. Predicting groundwater arsenic contamination: Regions at risk in highest populated state of India. Water Res. 159, 65–76.

Bolan, N, Kunhikrishnan, A, Thangarajan, R, Kumpiene, J, Park, J, Makino, T, Kirkham, MB, Scheckel, K, 2014. Remediation of heavy metal (loid) s contaminated soils–to mobilize or to immobilize? J. Hazard. Mater. 266, 141–166. https://doi.org/10.1016/jjhazmat201312018.

Bondu, R, Cloutier, V, Rosa, E, Benzaazoua, M, 2017. Mobility and speciation of geogenic arsenic in bedrock groundwater from the Canadian Shield in western Quebec, Canada. Sci. Total Environ. 574, 509–519. https://doi.org/10.1016/jscitotenv201608210.

Buamah, R, Petrusevski, B, Schippers, JC, 2008. Presence of arsenic, iron and manganese in groundwater within the gold-belt zone of Ghana. J. Water Supply: Res. Technol.—AQUA 57 (7), 519–529.

Bundschuh, J, Schneider, J, Alam, MA, Niazi, NK, Herath, I, Parvez, F, Tomaszewska, B, Guilherme, LRG, Maity, JP, López, DL, Cirelli, AF, 2021. Seven potential sources of arsenic pollution in Latin America and their environmental and health impacts. Sci. Total Environ. 780, 146274 https://doi.org/10.1016/jscitotenv2021146274.

Buschmann, J, Berg, M, Stengel, C, Sampson, ML, 2007. Arsenic and manganese contamination of drinking water resources in Cambodia: coincidence of risk areas with low relief topography. Environ. Sci. Technol. 41 (7), 2146–2152. https://doi.org/10.1021/es062056k.

Callegari, A, Ferronato, N, Rada, EC, Capodaglio, AG, Torretta, V, 2018. Assessment of arsenic removal efficiency by an iron oxide-coated sand filter process. Environ. Sci. Pollut.Res. 25 (26), 26135–26143.

Chakraborti, D, Rahman, MM, Ahamed, S, Dutta, RN, Pati, S, Mukherjee, SC, 2016a. Arsenic contamination of groundwater and its induced health effects in Shahpur block, Bhojpur district, Bihar state, India: risk evaluation. Environ. Sci. Pollut.Res. 23 (10), 9492–9504. https://doi.org/10.1007/s11356-016-6149-8.

Chakraborti, D, Rahman, MM, Ahamed, S, Dutta, RN, Pati, S, Mukherjee, SC, 2016b. Arsenic groundwater contamination and its health effects in Patna district (capital of Bihar) in the middle Ganga plain, India. Chemosphere 152, 520–529. https://doi.org/10.1016/jchemosphere201602119.

Chakraborti, D, Singh, SK, Rahman, MM, Dutta, RN, Mukherjee, SC, Pati, S, Kar, PB, 2018. Groundwater arsenic contamination in the Ganga River Basin: a future health danger. Int. J. Environ. Res. Public Health 15 (2), 180. https://doi.org/10.3390/ijerph15020180.

Chappell, WR, Abernathy, CO, Calderon, RL, 2001. Arsenic Exposure and Health Effects IV. Null Genotypes of Glutathione s-Transferasem1, t1 and p1, and Risk of Carotid Atherosclerosis Among Residentsin the Lanyang Basin of Taiwan. Elsevier Science, p. 492. Elsevier.

Chen, Y, van Geen, A, Graziano, JH, Pfaff, A, Madajewicz, M, Parvez, F, Ahsan, H, 2007. Reduction in Urinary Arsenic Levels in Response to Arsenic Mitigation Efforts in Araihazar, 115. Environmental Health Perspectives, Bangladesh, pp. 917–923.

Cherkasova, EV, Konyshev, AA, Soldatova, EA, Sidkina, ES, Mironenko, MV, 2021. Metal speciation in water of the flooded mine "arsenic"(Karelia, Russia): Equilibrium-Kinetic modeling with a focus on the influence of humic substances. Aquat. Geochem. 27 (2), 141–158. https://doi.org/10.1007/s10498-021-09393-3.

Chiban, M, Carja, G, Lehutu, G, Sinan, F, 2016. Equilibrium and thermodynamic studies for the removal of As (V) ions from aqueous solution using dried plants as adsorbents. Arabian J. Chem. 9, S988–S999.

Choprapwon, C, Porapakkham, Y, 2001. Occurrence of cancer in arsenic contaminated area, ronpibool district, nakorn srithmmarat province, Thailand. Arsenic Expo. Health Effects 201–206. Elsevier.

Chowdhury, A, Naz, A, Chowdhury, A, 2021. Waste to resource: applicability of fly ash as landfill geoliner to control ground water pollution. Mater. Today: Proc. 60, 8–13. https://doi.org/10.1016/jmatpr202110367.

Chutia, P, Kato, S, Kojima, T, Satokawa, S, 2009. Arsenic adsorption from aqueous solution on synthetic zeolites. J. Hazard. Mater. 162 (1), 440–447.

Clifford, DA, Ghurye, GL, 2002. Metal-oxide adsorption, ion exchange, and coagulation-microfiltration for arsenic removal from water. Environ. Chem. Arsenic 217–245.

Clifford, D, Ghurye, G, 2001. Arsenic III to Arsenic V. Water Qual. Prod. 28.

Corradini, F, Correa, A, Moyano, MS, Sepúlveda, P, Quiroz, C, 2018. Nitrate, arsenic, cadmium, and lead concentrations in leafy vegetables: expected average values for productive regions of Chile. Arch. Agron. Soil Sci. 64 (3), 299–317.

Crowther, DL, Dillard, JG, Murray, JW, 1983. The mechanisms of Co (II) oxidation on synthetic birnessite. Geochim. Cosmochim. Acta 47 (8), 1399–1403. https://doi.org/10.1016/0016-7037(83)90298-3.

Dabrowska, M, Debiec-Andrzejewska, K, Andrunik, M, Bajda, T, Drewniak, L, 2021. The biotransformation of arsenic by spent mushroom compost–An effective bioremediation agent. Ecotoxicol. Environ. Saf. 213, 112054 https://doi.org/10.1016/jecoenv2021112064.

Das, A, Sanyal, T, Bhattacharjee, P, 2021. Depletion of S-adenosylmethionine pool and promoter hypermethylation of Arsenite methyltransferase in arsenic-induced skin lesion individuals: A case-control study from West Bengal, India. Environ. Res. 198, 111184.

Dastidar, A, Wang, YT, 2009. Arsenite oxidation by batch cultures of Thiomonas arsenivorans strain b6. J. Environ. Eng. 135 (8), 708–715. https://doi.org/10.1061/(ASCE)EE1943-78700000020.

Dauphiné, DC, Ferreccio, C, Guntur, S, Yuan, Y, Hammond, SK, Balmes, J, Smith, AH, Steinmaus, C, 2011. Lung function in adults following in utero and childhood exposure to arsenic in drinking water: preliminary findings. Int. Arch. Occup. Environ. Health 84 (6), 591–600. https://doi.org/10.1007/s00420-010-0591-6.

Del Razo, LM, Arellano, MA, Cebrian, ME, 1990. The oxidation states of arsenic in well-water from a chronic arsenicism area of northern Mexico. Environ. Pollut. 64 (2), 143–153. https://doi.org/10.1016/0269-7491(90)90111-O.

Demirbas, E, Kobya, M, Oncel, MS, Şık, E, Goren, AY, 2019. Arsenite removal from groundwater in a batch electrocoagulation process: Optimization through response surface methodology. Sep. Sci. Technol. 54 (5), 775–785. https://doi.org/10.1080/0149639520181521834.

Dodd, MC, Vu, ND, Ammann, A, Le, VC, Kissner, R, Pham, HV, Cao, TH, Berg, M, Von Gunten, U, 2006. Kinetics and mechanistic aspects of As (III) oxidation by aqueous chlorine, chloramines, and ozone: relevance to drinking water treatment. Environ. Sci. Technol. 40 (10), 3285–3292. https://doi.org/10.1021/es0524999.

Dorsey, E, Sherer, T, Okun, MS, Bloem, BR, 2018. The emerging evidence of the Parkinson pandemic. J. Parkinson's Dis. 8 (s1), S3–S8.

Drahota, P, Rohovec, J, Filippi, M, Mihaljevič, M, Rychlovský, P, Červený, V, Pertold, Z, 2009. Mineralogical and geochemical controls of arsenic speciation and mobility under different redox conditions in soil, sediment and water at the Mokrsko-West gold deposit, Czech Republic. Sci. Total Environ. 407 (10), 3372–3384. https://doi.org/10.1016/jscitotenv200901009.

Driehaus, W, 2002. Arsenic removal-experience with the GEH® process in Germany. Water Sci. Technol.: Water Supply 2 (2), 275–280.

Dutta, T, Bhattacherjee, C, Bhattacherjee, S, 2012. Removal of arsenic using membrane technology–a review. International Journal of Engineering Research and Technology 1, 1–23.

Dutta, TK, Satapathy, D, Manda, DK, Chatterjee, A, 2019. Sources and impact of arsenic on livestock in India and its amelioration through dietary strategy. Indian J. Dairy Sci. 72 (1).

Eary, LE, Rai, D, 1987. Kinetics of chromium (III) oxidation to chromium (VI) by reaction with manganese dioxide. Environ. Sci. Technol. 21 (12), 1187–1193.

Erban, LE, Gorelick, SM, Zebker, HA, Fendorf, S, 2013. Release of arsenic to deep groundwater in the Mekong Delta, Vietnam, linked to pumping-induced land subsidence. Proc. Natl. Acad. Sci. 110 (34), 13751–13756. https://doi.org/10.1073/pnas1300503110.

Even, E, Masuda, H, Shibata, T, Nojima, A, Sakamoto, Y, Murasaki, Y, Chiba, H, 2017. Geochemical distribution and fate of arsenic in water and sediments of rivers from the Hokusetsu area, Japan. J. Hydrol.: Reg. Stud. 9, 34–47.

Fauzi, RR, Sumiya, K, Matsumoto, M, Yamaoka, S, Muslim, D, Kondo, S, 2017. River and groundwater quality assessment for domestic clean water in Cimanintin area, West Java, Indonesia. In *Proceedings of the 2nd Join Conference of Utsunomiya University and Universitas Padjadjaran* (pp. 206-212).

Feng, XH, Zu, YQ, Tan, WF, Liu, F, 2006. Arsenite oxidation by three types of manganese oxides. J. Environ. Sci. 18 (2), 292–298.

Flanagan, SV, Marvinney, RG, Zheng, Y, 2015. Influences on domestic well water testing behaviour in a Central Maine area with frequent groundwater arsenic occurrence. Sci. Total Environ. 505, 1274–1281.

Francesconi, KA, 2010. Arsenic species in seafood: origin and human health implications. Pure Appl. Chem. 82 (2), 373–381. https://doi.org/10.1351/PAC-CON-09-07-01.

Gault, AG, Rowland, HA, Charnock, JM, Wogelius, RA, Gomez-Morilla, I, Vong, S, Polya, DA, 2008. Arsenic in hair and nails of individuals exposed to arsenic-rich groundwaters in Kandal province, Cambodia. Sci. Total Environ. 393 (1), 168–176.

Ge, J, Guha, B, Lippincott, L, Cach, S, Wei, J, Su, TL, Meng, X, 2020. Challenges of arsenic removal from municipal wastewater by coagulation with ferric chloride and alum. Sci. Total Environ. 725, 138351.

Ghosh, B, Das, MC, Gangopadhyay, AK, Das, TB, Singh, K, Lal, S, Mitra, S, Ansari, SH, Goswami, TK, Chakraborty, SK, Banerjee, NN, 2003. Removal of arsenic from water by coagulation treatment using iron and magnesium salt. http://nopr. niscair. res.in/handle/123456789/22705.

Ghosh, S, Debsarkar, A, Dutta, A, 2019. Technology alternatives for decontamination of arsenic-rich groundwater—A critical review. Environ. Technol. Innov. 13, 277–303.

Ghurye, G, Clifford, D, 2004. As (III) oxidation using chemical and solid-phase oxidants. J.-Am. Water Works Assoc. 96 (1), 84–96. https://doi.org/10.1002/j1551-88332004tb10536x.

Ghurye, G, Clifford, D, Tripp, A, 2004. Iron coagulation and direct microfiltration to remove arsenic from groundwater. J. Am. Water Works Assoc. 96 (4), 143–152. https://doi.org/10.1002/j1551-88332004tb10605x.

Guo, HR, Yu, HS, Hu, H, Monson, RR, 2001. Arsenic in drinking water and skin cancers: cell-type specificity (Taiwan, ROC). Cancer Causes Control. 12 (10), 909–916.

Gurzau, ES, Gurzau, AE, 2001. Arsenic in Drinking Water from Groundwater in Transylvania, Romania: An Overview. Elsevier, Oxford, pp. 181–184.

Habuda-Stanić, M, Nujić, M, 2015. Arsenic removal by nanoparticles: a review. Environ. Sci. Pollut.Res. 22 (11), 8094–8123. https://doi.org/10.1007/s11356-015-4307-z.

Hamidian, AH, Razeghi, N, Zhang, Y, Yang, M, 2019. Spatial distribution of arsenic in groundwater of Iran, a review. J. Geochem. Explor. 201, 88–98. https://doi.org/10.1016/jgexplo201903014.

Han, C, Yang, T, Liu, H, Yang, L, Luo, Y, 2019. Characterizations and mechanisms for synthesis of chitosan-coated Na–X zeolite from fly ash and As (V) adsorption study. Environ. Sci. Pollut.Res. 26 (10), 10106–10116.

Hanchett, S, Johnston, R, Khan, MH, 2011. Arsenic removal filters in Bangladesh. In: UNC Water and Health Conference.

Hao, L, Liu, M, Wang, N, Li, G, 2018. A critical review on arsenic removal from water using iron-based adsorbents. RSC Adv. 8 (69), 39545–39560. https://doi.org/10.1039/C8RA08512A.

Hasanuzzaman, M, Nahar, K, Fujita, Meds, 2018. Mechanisms of Arsenic Toxicity And Tolerance In Plants. Springer.

Hassan, KM, Fukuhara, T, Hai, FI, Bari, QH, Islam, KMS, 2009. Development of a bio-physicochemical technique for arsenic removal from groundwater. Desalination 249 (1), 224–229. https://doi.org/10.1016/jdesal200808015.

Hayat, K, Menhas, S, Bundschuh, J, Chaudhary, HJ, 2017. Microbial biotechnology as an emerging industrial wastewater treatment process for arsenic mitigation: a critical review. J. Cleaner Prod. 151, 427–438.

Heinrichs, G, Udluft, P, 1999. Natural arsenic in Triassic rocks: a source of drinking-water contamination in Bavaria. Germany. Hydrogeol. J. 7 (5), 468–476.

Henke, KR, 2009. Waste treatment and remediation technologies for arsenic. Arsenic: Environ. Chem. Health Threats Waste Treat. 351–430. https://doi.org/10.1002/9780470741122ch7.

Hering, JG, Chen, PY, Wilkie, JA, Elimelech, M, 1997. Arsenic removal from drinking water during coagulation. J. Environ. Eng. 123 (8), 800–807. https://doi.org/10.1061/(ASCE)0733-9372(1997)123:8(800).

Hernandez, D, Boden, K, Paul, P, Bandaru, S, Mypati, S, Roy, A, Amrose, S, Roy, J, Gadgil, A, 2019. Strategies for successful field deployment in a resource-poor region: Arsenic remediation technology for drinking water. Dev. Eng. 4, 100045 https://doi.org/10.1016/jdeveng2019100045.

Höll, WH, 2010. Mechanisms of arsenic removal from water. Environ. Geochem. Health 32 (4), 287–290. https://doi.org/10.1007/s10653-010-9307-9.

Hug, S.J., Leupin, O., 2003. Iron-catalyzed oxidation of arsenic(III) by oxygen and by hydrogen peroxide: pH-dependent formation of oxidants in the Fenton reaction. Environ Sci Technol 37, 2734–2742.

Hundal, HS, Kumar, R, Singh, K, Singh, D, 2007. Occurrence and geochemistry of arsenic in groundwater of Punjab, Northwest India. Commun. Soil Sci. Plant Anal. 38, 2257–2277. https://doi.org/10.1080/00103620701588312, 17-18.

Ilieva, DM, Argirova, M, Angelova, LY, Gradinaru, RV, Drochioiu, G, Surleva, AR, 2020. Application of chemical and biological tests for estimation of current state of a tailing dump and surrounding soil from the region of Tarniţa, Suceava, Romania. Environ. Sci. Pollut.Res. 27 (2), 1386–1396.

Irshad, S, Xie, Z, Mehmood, S, Nawaz, A, Ditta, A, Mahmood, Q, 2021. Insights into conventional and recent technologies for arsenic bioremediation: a systematic review. Environ. Sci. Pollut.Res. 28 (15), 18870–18892.

Islam, M, Reza, AHM, Sattar, GS, Ahsan, M, Akbor, M, Siddique, M, Bakar, A, 2019. Distribution of arsenic in core sediments and groundwater in the Chapai Nawabganj district, Bangladesh. Arabian J. Geosci. 12 (3), 1–19.

Ito, A, Miura, JI, Ishikawa, N, Umita, T, 2012. Biological oxidation of arsenite in synthetic groundwater using immobilised bacteria. Water Res. 46 (15), 4825–4831. https://doi.org/10.1016/jwatres201206013.

Jahan, K, Mosto, P, Mattson, C, Frey, E, Derchak, L, 2006. Microbial removal of arsenic. Water Air Soil Pollut. Focus 6 (1), 71–82. https://doi.org/10.1007/s11267-005-9014-1.

Jain, CK, Ali, I, 2000. Arsenic: occurrence, toxicity and speciation techniques. Water Res. 34 (17), 4304–4312. https://doi.org/10.1016/S0043-1354(00)00182-2.

Jain, CK, Singh, RD, 2012. Technological options for the removal of arsenic with special reference to South East Asia. J. Environ. Manage. 107, 1–18. https://doi.org/10.1016/jjenvman201204016.

Jeelani, G, Lone, SA, Nisa, AU, Mukherjee, A, Deshpande, RD, 2020. Sources and processes of groundwater arsenic mobilization in upper Jhelum basin, western Himalayas. J. Hydrol. 591, 125292.

Johnston, RB, 2016. Arsenic and the 2030 Agenda for sustainable development. In: Arsen Res Glob Sustain-Proc 6th Int Congr Arsen Environ AS, pp. 12–14. *2016*.

Jomova, K, Vondrakova, D, Lawson, M, Valko, M, 2010. Metals, oxidative stress and neurodegenerative disorders. Mol. Cell. Biochem 345, 91–104, 1–2.

Joshi, A, Chaudhuri, M, 1996. Removal of arsenic from ground water by iron oxide-coated sand. J. Environ. Eng. 122 (8), 769–771.

Kabir, F, Chowdhury, S, 2017. Arsenic removal methods for drinking water in the developing countries: technological developments and research needs. Environ. Sci. Pollut.Res. 24 (31), 24102–24120.

Kanel, SR, Manning, B, Charlet, L, Choi, H, 2005. Removal of arsenic (III) from groundwater by nanoscale zero-valent iron. Environ. Sci. Technol. 39 (5), 1291–1298. https://doi.org/10.1021/es048991u.

Kang, M, Kawasaki, M, Tamada, S, Kamei, T, Magara, Y, 2000. Effect of pH on the removal of arsenic and antimony using reverse osmosis membranes. Desalination 131 (1-3), 293–298. https://doi.org/10.1016/S0011-9164(00)90027-4.

Katsoyiannis, IA, Mitrakas, M, Zouboulis, AI, 2015. Arsenic occurrence in Europe: emphasis in Greece and description of the applied full-scale treatment plants. Desalin. Water Treat. 54 (8), 2100–2107.

Katsoyiannis, IA, Zikoudi, A, Hug, SJ, 2008. Arsenic removal from groundwaters containing iron, ammonium, manganese and phosphate: A case study from a treatment unit in northern Greece. Desalination 224 (1-3), 330–339. https://doi.org/10.1016/jdesal200706014.

Katsoyiannis, IA, Zouboulis, AI, 2004a. Application of biological processes for the removal of arsenic from groundwaters. Water Res. 38 (1), 17–26. https://doi.org/10.1016/jwatres200309011.

Katsoyiannis, IA, Zouboulis, AI, 2004b. Biological treatment of Mn (II) and Fe (II) containing groundwater: kinetic considerations and product characterization. Water Res. 38 (7), 1922–1932. https://doi.org/10.1016/jwatres200401014.

Khandegar, V, Saroha, AK, 2013. Electrocoagulation for the treatment of textile industry effluent–a review. J. Environ. Manage. 128, 949–963. https://doi.org/10.1016/jjenvman201306043.

Khuntia, S, Majumder, SK, Ghosh, P, 2014. Oxidation of As (III) to As (V) using ozone microbubbles. Chemosphere 97, 120–124.

Kim, MJ, Nriagu, J, 2000. Oxidation of arsenite in groundwater using ozone and oxygen. Sci. Total Environ. 247 (1), 71–79. https://doi.org/10.1016/S0048-9697(99)00470-2.

Kinniburgh, DG, Smedley, P. Arsenic contamination of groundwater in Bangladesh. http://nora.nerc.ac.uk/id/eprint/11986.

Kobya, M, Can, OT, Bayramoglu, M, 2003. Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes. J. Hazard. Mater. 100 (1-3), 163–178. https://doi.org/10.1016/S0304-3894(03)00102-X.

Kobya, M, Demirbas, E, Bayramoglu, M, Sensoy, MT, 2011. Optimization of electrocoagulation process for the treatment of metal cutting wastewaters with response surface methodology. Water Air Soil Pollut. 215 (1), 399–410. https://doi.org/10.1007/s11270-010-0486-x.

Kondo, H, Ishiguro, Y, Ohno, K, Nagase, M, Toba, M, Takagi, M, 1999. Naturally occurring arsenic in the groundwaters in the southern region of Fukuoka Prefecture, Japan. Water Res. 33 (8), 1967–1972. https://doi.org/10.1016/S0043-1354(98)00377-7.

Kumar, A, Ghosh, AK, 2021. Assessment of arsenic contamination in groundwater and affected population of Bihar. Arsenic Toxicity: Challenges and Solutions. Springer, Singapore, pp. 165–191.

Kumar, PR, Chaudhari, S, Khilar, KC, Mahajan, SP, 2004. Removal of arsenic from water by electrocoagulation. Chemosphere 55 (9), 1245–1252. https://doi.org/10.1016/jchemosphere200312025.

Kumari, P, Chowdhury, A, Maiti, SK, 2018. Assessment of heavy metal in the water, sediment, and two edible fish species of Jamshedpur Urban Agglomeration, India with special emphasis on human health risk. Hum. Ecol. Risk Assess. Int. J. 24 (6), 1477–1500.

Kurttio, P, Komulainen, H, Hakala, E, Kahelin, H, Pekkanen, J, 1998. Urinary excretion of arsenic species after exposure to arsenic present in drinking water. Arch. Environ. Contam. Toxicol. 34 (3), 297–305.

Kurz, EEC, Luong, VT, Hellriegel, U, Leidinger, F, Luu, TL, Bundschuh, J, Hoinkis, J., 2020. Iron-based subsurface arsenic removal (SAR): Results of a long-term pilot-scale test in Vietnam. Water Res. 181, 115929.

Lakshmanan, D, Clifford, DA, Samanta, G, 2010. Comparative study of arsenic removal by iron using electrocoagulation and chemical coagulation. Water Res. 44 (19), 5641–5652. https://doi.org/10.1016/jwatres201006018.

Laroche, E, Casiot, C, Fernandez-Rojo, L, Desoeuvre, A, Tardy, V, Bruneel, O, Héry, M, 2018. Dynamics of bacterial communities mediating the treatment of an As-rich acid mine drainage in a field pilot. Front. Microbiol. 9, 3169.

Lee, Y, Um, IH, Yoon, J, 2003. Arsenic (III) oxidation by iron (VI)(ferrate) and subsequent removal of arsenic (V) by iron (III) coagulation. Environ. Sci. Technol. 37 (24), 5750–5756. https://doi.org/10.1021/es034203+.

Leiva, ED, dP Rámila, C, Vargas, IT, Escauriaza, CR, Bonilla, CA, Pizarro, GE, Regan, JM, Pasten, PA, 2014. Natural attenuation process via microbial oxidation of arsenic in a high Andean watershed. Sci. Total Environ. 466, 490–502. https://doi.org/10.1016/jscitotenv201307009.

Li, XJ, Liu, CS, Li, FB, Li, YT, Zhang, LJ, Liu, CP, Zhou, YZ, 2010. The oxidative transformation of sodium arsenite at the interface of α-MnO2 and water. J. Hazard. Mater. 173 (1-3), 675–681. https://doi.org/10.1016/jjhazmat200908139.

Lièvremont, D, Bertin, PN, Lett, MC, 2009. Arsenic in contaminated waters: biogeochemical cycle, microbial metabolism and biotreatment processes. Biochimie 91 (10), 1229–1237.

Lopes, MP, Galinha, CF, Crespo, JG, Velizarov, S, 2020. Optimisation of arsenate removal from water by an integrated ion-exchange membrane process coupled with Fe co-precipitation. Sep. Purif. Technol. 246, 116894.

Lord, G, Kim, N, Ward, NI, 2012. Arsenic speciation of geothermal waters in New Zealand. J. Environ. Monit. 14 (12), 3192–3201. https://doi.org/10.1039/C2EM30486D.

Luong, VT, Kurz, EEC, Hellriegel, U, Luu, TL, Hoinkis, J, Bundschuh, J, 2018. Iron-based subsurface arsenic removal technologies by aeration: A review of the current state and future prospects. Water Res. 133, 110–122. https://doi.org/10.1016/jwatres201801007.

Mahanta, C, Enmark, G, Nordborg, D, Sracek, O, Nath, B, Nickson, RT, Herbert, R, Jacks, G, Mukherjee, A, Ramanathan, AL, Choudhury, R, 2015. Hydrogeochemical controls on mobilization of arsenic in groundwater of a part of Brahmaputra river floodplain, India. J. Hydrol. Reg. Stud. 4, 154–171. https://doi.org/10.1016/jejrh201503002.

Maity, JP, Chen, CY, Bhattacharya, P, Sharma, RK, Ahmad, A, Patnaik, S, Bundschuh, J, 2021. Advanced application of nano-technological and biological processes as well as mitigation options for arsenic removal. J. Hazard. Mater. 405, 123885.

Mandal, BK, Chowdhury, TR, Samanta, G, Basu, GK, Chowdhury, PP, Chanda, CR, Lodh, D, Karan, NK, Dhar, RK, Tamili, DK, Das, D, 1996. Arsenic in groundwater in seven districts of West Bengal, India–the biggest arsenic calamity in the world. Curr. Sci. 976–986.

Mandal, P, 2017. Molecular insight of arsenic-induced carcinogenesis and its prevention. Naunyn Schmiedeberg's Arch. Pharmacol. 390 (5), 443–455.

Manning, BA, Fendorf, SE, Bostick, B, Suarez, DL, 2002a. Arsenic (III) oxidation and arsenic (V) adsorption reactions on synthetic birnessite. Environ. Sci. Technol. 36 (5), 976–981. https://doi.org/10.1021/es0110170.

Manning, BA, Hunt, ML, Amrhein, C, Yarmoff, JA, 2002b. Arsenic (III) and arsenic (V) reactions with zerovalent iron corrosion products. Environ. Sci. Technol. 36 (24), 5455–5461. https://doi.org/10.1021/es0206846.

Masuda, H, 2018. Arsenic cycling in the Earth's crust and hydrosphere: interaction between naturally occurring arsenic and human activities. Prog. Earth Planet. Sci. 5 (1), 1–11. https://doi.org/10.1186/s40645-018-0224-3.

Matschullat, J, 2000. Arsenic in the geosphere—a review. Sci. Total Environ. 249 (1-3), 297–312.

Matsui, Y, Shirasaki, N, Yamaguchi, T, Kondo, K, Machida, K, Fukuura, T, Matsushita, T, 2017. Characteristics and components of poly-aluminum chloride coagulants that enhance arsenate removal by coagulation: detailed analysis of aluminum species. Water Res. 118, 177–186. https://doi.org/10.1016/jwatres201704037.

Mehdi, SEH, Amen, R, Ali, A, Anjum, H, Mahmood, A, Mubashir, M, Mukhtar, A, Ullah, S, Al-Sehemi, AG, Ibrahim, M, Khan, MS, 2021. Sources, chemistry, bioremediation and social aspects of arsenic-contaminated waters: a review. Environ. Chem. Lett. 19 (5), 3859–3886. https://doi.org/10.1007/s10311-021-01254-3.

Mohan, D, Pittman Jr, CU, 2007. Arsenic removal from water/wastewater using adsorbents—a critical review. J. Hazard. Mater. 142 (1-2), 1–53. https://doi.org/10.1016/jjhazmat200701006.

Mohanty, D, 2017. Conventional as well as emerging arsenic removal technologies—a critical review. Water Air Soil Pollut. 228 (10), 1–21.

Mohindru, JJ, Garg, UK, Gupta, R, 2017. Coagulation-flocculation technologies for arsenic removal–a review. Asian J. Res. Chem. 10 (3), 405–413. https://doi.org/10.5958/0974-41502017000694.

Mondal, S, Mukherjee, S, Chaudhuri, K, Kabir, SN, Kumar Mukhopadhyay, P, 2013. Prevention of arsenic-mediated reproductive toxicity in adult female rats by high protein diet. Pharm. Biol. 51 (11), 1363–1371.

Mukherjee, A, Das, D, Mondal, SK, Biswas, R, Das, TK, Boujedaini, N, Khuda-Bukhsh, AR, 2010. Tolerance of arsenate-induced stress in Aspergillus niger, a possible candidate for bioremediation. Ecotoxicol. Environ. Saf 73 (2), 172–182. https://doi.org/10.1016/jecoenv200909015.

Naujokas, MF, Anderson, B, Ahsan, H, Aposhian, HV, Graziano, JH, Thompson, C, Suk, WA, 2013. The broad scope of health effects from chronic arsenic exposure: update on a worldwide public health problem. Environ. Health Perspect. 121 (3), 295–302. https://doi.org/10.1289/ehp1205875.

Naz, A, Chowdhury, A, 2021. Pollutant extraction from water and soil using Montmorillonite clay-polymer composite: a rapid review. Mater. Today: Proc. 60, 1–7. https://doi.org/10.1016/jmatpr202110366.

Naz, A, Gupta, SK, 2013. Remediation of low level Hexavalent Chromium from water by activated sludge process: a review. Strategic Technol. Complex Environ. 1. Issues-A Sustain Approach.

Naz, A, Chowdhury, A, Mishra, BK, 2021. An insight into microbial remediation of hexavalent chromium from contaminated water. Contaminants in Drinking and Wastewater Sources. Springer, Singapore, pp. 209–224.

Necula, R, Zaharia, M, Butnariu, A, Zamfirache, MM, Surleva, A, Ciobanu, CI, Drochioiu, G, 2021. Heavy metals and arsenic in an abandoned barite mining area: ecological risk assessment using biomarkers. Environ. Forensics 1–12.

Nguyen, TH, Tran, HN, Vu, HA, Trinh, MV, Nguyen, TV, Loganathan, P, Nguyen, THH, 2020. Laterite as a low-cost adsorbent in a sustainable decentralized filtration system to remove arsenic from groundwater in Vietnam. Sci. Total Environ. 699, 134267.

Nicolli, HB, Bundschuh, J, Blanco, MDC, Tujchneider, OC, Panarello, HO, Dapeña, C, Rusansky, JE, 2012. Arsenic and associated trace-elements in groundwater from the Chaco-Pampean plain, Argentina: results from 100 years of research. Sci. Total Environ. 429, 36–56. https://doi.org/10.1016/jscitotenv201204048.

Nicolli, HB, Suriano, JM, Gomez Peral, MA, Ferpozzi, LH, Baleani, OA, 1989. Groundwater contamination with arsenic and other trace elements in an area of the Pampa, Province of Córdoba, Argentina. Environ. Geol. Water Sci. 14 (1), 3–16.

Nigam, S, Gopal, K, Vankar, PS, 2013. Biosorption of arsenic in drinking water by submerged plant: Hydrilla verticilata. Environ. Sci. Pollut.Res. 20 (6), 4000–4008. https://doi.org/10.1007/s11356-012-1342-x.

Oinam, JD, Ramanathan, AL, Linda, A, Singh, G, 2011. A study of arsenic, iron and other dissolved ion variations in the groundwater of Bishnupur District, Manipur, India. Environ. Earth Sci. 62 (6), 1183–1195. https://doi.org/10.1007/s12665-010-0607-2.

Orgill, J, Shaheed, A, Brown, J, Jeuland, M, 2013. Water quality perceptions and willingness to pay for clean water in peri-urban Cambodian communities. J. Water Health 11 (3), 489–506.

Oscarson, DW, Huang, PM, Liaw, WK, 1980. The oxidation of arsenite by aquatic sediments (Vol. 9, No. 4. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 700–703. https://doi.org/10.2134/jeq198000472425000900040032x.

Panda, BK, 2015. A brief review on the scenario of ground water pollution by arsenic in West Bengal. Int. J. Ecosyst. 5, 75–85. https://doi.org/10.5923/cije20150111.

Paul, AP, Maurer, DK, Stollenwerk, KG, Welch, AH, 2010. In-Situ Arsenic Remediation in Carson Valley, Douglas County, West-Central Nevada. US Department of the Interior, US Geological Survey.

Pedretti, D, Luoma, S, Ruskeeniemi, T, Backman, B, 2019. A geologically-based approach to map arsenic risk in crystalline aquifers: Analysis of the Tampere region, Finland. Geosci. Front. 10 (5), 1731–1741.

Petrusevski, B, Van der Meer, W, Baker, J, Kruis, F, Sharma, SK, Schippers, JC, 2007. Innovative approach for treatment of arsenic contaminated groundwater in Central Europe. Water Sci. Technol. Water Supply 7 (3), 131–138.

Pincus, LN, Petrović, PV, Gonzalez, IS, Stavitski, E, Fishman, ZS, Rudel, HE, Zimmerman, JB, 2021. Selective adsorption of arsenic over phosphate by transition metal cross-linked chitosan. Chem. Eng. J. 412, 128582.

Rahaman, MS, Rahman, MM, Mise, N, Sikder, MT, Ichihara, G, Uddin, MK, Ichihara, S, 2021. Environmental arsenic exposure and its contribution to human diseases, toxicity mechanism and management. Environ. Pollut. 289, 117940.

Rahnamarad, J, Derakhshani, R, Abbasnejad, A, 2020. Data on arsenic contamination in groundwater of Rafsanjan plain, Iran. Data Brief 31, 105772.

Raj, K, Kaur, P, Gupta, GD, Singh, S, 2021. Metals associated neurodegeneration in Parkinson's disease: Insight to physiological, pathological mechanisms and management. Neurosci. Lett. 753, 135873.

Rajendran, RM, Garg, S, Bajpai, S, 2021. Economic feasibility of arsenic removal using nanofiltration membrane: A mini review. Chem. Pap. 75 (9), 4431–4444.

Rathi, BS, Kumar, PS, 2021. A review on sources, identification and treatment strategies for the removal of toxic Arsenic from water system. J. Hazard. Mater. 418, 126299 https://doi.org/10.1016/jjhazmat2021126299.

Ravenscroft, P, Brammer, H, Richards, K, 2011. Arsenic Pollution: A Global Synthesis (Vol. 94). John Wiley & Sons.

Reimann, C, De Caritat, P, 2012. Chemical Elements in the Environment: Factsheets for the Geochemist and Environmental Scientist. Springer Science & Business Media.

Renu, K, Madhyastha, H, Madhyastha, R, Maruyama, M, Vinayagam, S, Gopalakrishnan, AV, 2018. Review on molecular and biochemical insights of arsenic-mediated male reproductive toxicity. Life Sci. 212, 37–58.

Robles, AD, Polizzi, P, Romero, MB, Boudet, LNC, Medici, S, Costas, A, Gerpe, M, 2016. Geochemical mobility of arsenic in the surficial waters from Argentina. Environ. Earth Sci. 75 (23), 1479.

Roy, PK, Majumder, A, Banerjee, G, Roy, MB, Pal, S, Mazumdar, A, 2015. Removal of arsenic from drinking water using dual treatment process. Clean Technol. Environ. Policy 17 (4), 1065–1076.

Sabir, S, Akash, MSH, Fiayyaz, F, Saleem, U, Mehmood, MH, Rehman, K, 2019. Role of cadmium and arsenic as endocrine disruptors in the metabolism of carbohydrates: inserting the association into perspectives. Biomed. Pharmacother. 114, 108802.

Saha, D, Sarangam, SS, Dwivedi, SN, Bhartariya, KG, 2010. Evaluation of hydrogeochemical processes in arsenic-contaminated alluvial aquifers in parts of Mid-Ganga Basin, Bihar, Eastern India. Environ. Earth Sci. 61 (4), 799–811. https://doi.org/10.1007/s12665-009-0392-y.

Sahu, O, Mazumdar, B, Chaudhari, PK, 2014. Treatment of wastewater by electrocoagulation: a review. Environ. Sci. Pollut.Res. 21 (4), 2397–2413. https://doi.org/10.1007/s11356-013-2208-6.

Sancha, AM, 2000. Removal of arsenic from drinking water supplies: Chile experience. Water Supply 18 (1), 621–625.

Sancha, AM, 2006. Review of coagulation technology for removal of arsenic: case of Chile. J. Health Popul. Nutr. 24 (3), 267. https://www.ncbi.nlm.nih.gov/pubmed/17366767.

Sancha, AM, Castro, ML, 2001. Arsenic in Latin America: Occurrence, Exposure, Health Effects and Remediation. Arsenic Exposure and Health Effects IV. Elsevier, Amsterdam, pp. 87–96.

Santini, JM, Sly, LI, Schnagl, RD, Macy, JM, 2000. A new chemolithoautotrophic arsenite-oxidizing bacterium isolated from a gold mine: phylogenetic, physiological, and preliminary biochemical studies. Appl. Environ. Microbiol. 66 (1), 92–97. https://doi.org/10.1128/AEM96192-972000.

Santos, S, Ungureanu, G, Boaventura, R, Botelho, C, 2015. Selenium contaminated waters: an overview of analytical methods, treatment options and recent advances in sorption methods. Sci. Total Environ. 521, 246–260. https://doi.org/10.1016/jscitotenv201503107.

Sarkar, A, Paul, B, 2016. The global menace of arsenic and its conventional remediation-A critical review. Chemosphere 158, 37–49. https://doi.org/10.1016/jchemosphere201605043.

Saurav, D, Sudipta, BS, Jyoti, LP, Madhumita, B, Yadav, RNS, Mridul, C, 2015. Groundwater arsenic contamination in north eastern states of India. J. Environ. Res. Dev. 9 (3), 621.

Sengupta, M, Deb, I, Sharma, GD, Kar, KK, 2013. Human sperm and other seminal constituents in male infertile patients from arsenic and cadmium rich areas of southern Assam. Syst. Biol. Reprod. Med. 59, 199–209. https://doi.org/10.3109/193963682013783143.

Shah, AH, Shahid, M, Khalid, S, Shabbir, Z, Bakhat, HF, Murtaza, B, Farooq, A, Akram, M, Shah, GM, Nasim, W, Niazi, NK, 2020. Assessment of arsenic exposure by drinking well water and associated carcinogenic risk in peri-urban areas of Vehari, Pakistan. Environ. Geochem. Health 42 (1), 121–133. https://doi.org/10.1007/s10653-019-00306-6.

Shahid, M, Khalid, M, Dumat, C, Khalid, S, Niazi, NK, Imran, M, Bibi, I, Ahmad, I, Hammad, HM, Tabassum, RA, 2018. Arsenic Level and Risk Assessment of Groundwater in Vehari, Punjab Province, 10. Exposure and Health, Pakistan, pp. 229–239. https://doi.org/10.1007/s12403-017-0257-7.

Shaji, E, Santosh, M, Sarath, KV, Prakash, P, Deepchand, V, Divya, BV, 2021. Arsenic contamination of groundwater: a global synopsis with focus on the Indian Peninsula. Geosci. Front. 12 (3), 101079.

Sharma, VK, 2002. Potassium ferrate (VI): an environmentally friendly oxidant. Adv. Environ. Res. 6 (2), 143–156. https://doi.org/10.1016/S1093-0191(01)00119-8.

Siddiqui, SI, Chaudhry, SA, 2017. Iron oxide and its modified forms as an adsorbent for arsenic removal: a comprehensive recent advancement. Process Saf. Environ. Prot. 111, 592–626.

Siddiqui, SI, Naushad, M, Chaudhry, SA, 2019. Promising prospects of nanomaterials for arsenic water remediation: a comprehensive review. Process Saf. Environ. Prot. 126, 60–97.

Singh, P, Borthakur, A, Singh, R, Bhadouria, R, Singh, VK, Devi, P, 2021. A critical review on the research trends and emerging technologies for arsenic decontamination from water. Groundwater Sustain. Dev. 14, 100607 https://doi.org/10.1016/jgsd2021100607.

Singh, R, Singh, S, Parihar, P, Singh, VP, Prasad, SM, 2015. Arsenic contamination, consequences and remediation techniques: a review. Ecotoxicol. Environ. Saf. 112, 247–270. https://doi.org/10.1016/jecoenv201410009.

Smedley, PL, Kinniburgh, DG, 2002. A review of the source, behaviour and distribution of arsenic in natural waters. Appl. Geochem. 17 (5), 517–568. https://doi.org/10.1016/S0883-2927(02)00018-5.

Song, P, Yang, Z, Xu, H, Huang, J, Yang, X, Wang, L, 2014. Investigation of influencing factors and mechanism of antimony and arsenic removal by electrocoagulation using Fe–Al electrodes. Ind. Eng. Chem. Res. 53 (33), 12911–12919. https://doi.org/10.1021/ie501727a.

Song, P, Yang, Z, Zeng, G, Yang, X, Xu, H, Wang, L, Xu, R, Xiong, W, Ahmad, K, 2017. Electrocoagulation treatment of arsenic in wastewaters: a comprehensive review. Chem. Eng. J. 317, 707–725. https://doi.org/10.1016/jcej201702086.

Song, S, Gallegos-Garcia, M, 2014. Arsenic removal from water by the coagulation process. The Role of Colloidal Systems in Environmental Protection. Elsevier, pp. 261–277. https://doi.org/10.1016/B978-0-444-63283-800011-9.

Sorlini, S, Gialdini, F, 2010. Conventional oxidation treatments for the removal of arsenic with chlorine dioxide, hypochlorite, potassium permanganate and monochloramine. Water Res. 44 (19), 5653–5659. https://doi.org/10.1016/jwatres201006032.

Stefanescu, R, Butnariu, AE, Zamfirache, MM, Surleva, A, Ciobanui, CI, Pintilie, O, Drochioiu, G, 2017. Yeast-based microbiological decontamination of heavy metals contaminated soils of Tarnita. Carpath. J. Earth Environ. Sci. 12 (1), 153–159.

Su, C, Puls, RW, 2008. Arsenate and arsenite sorption on magnetite: relations to groundwater arsenic treatment using zerovalent iron and natural attenuation. Water Air Soil Pollut. 193 (1), 65–78. https://doi.org/10.1007/s11270-008-9668-1.

Tabassum, N, Islam, N, Ahmed, S, 2021. Progress in microbial fuel cells for sustainable management of industrial effluents. Process Biochem. 106, 20–41.

Thambidurai, P, Chandrashekhar, AK, Chandrasekharam, D, 2013. Geochemical signature of arsenic-contaminated groundwater in Barak Valley (Assam) and surrounding areas, northeastern India. Proc. Earth Planet. Sci 7, 834–837. https://doi.org/10.1016/jproeps201303086.

Tripathi, P, Khare, P, Barnawal, D, Shanker, K, Srivastava, PK, Tripathi, RD, Kalra, A, 2020. Bioremediation of arsenic by soil methylating fungi: role of Humicola sp. strain 2WS1 in amelioration of arsenic phytotoxicity in Bacopa monnieri L. Sci. Total Environ. 716, 136758.

Uddin, M, Jeong, YK, 2020. Efficiently performing periodic elements with modern adsorption technologies for arsenic removal. Environ. Sci. Pollut.Res. 27 (32), 39888–39912.

Van Halem, D, Olivero, S, de Vet, WWJM, Verberk, JQJC, Amy, GL, van Dijk, JC, 2010. Subsurface iron and arsenic removal for shallow tube well drinking water supply in rural Bangladesh. Water Res. 44 (19), 5761–5769. https://doi.org/10.1016/jwatres201005049.

Vangronsveld, J, Herzig, R, Weyens, N, Boulet, J, Adriaensen, K, Ruttens, A, Thewys, T, Vassilev, A, Meers, E, Nehnevajova, E, van der Lelie, D, 2009. Phytoremediation of contaminated soils and groundwater: lessons from the field. Environ. Sci. Pollut.Res. 16 (7), 765–794. https://doi.org/10.1007/s11356-009-0213-6.

Vasudevan, S, Lakshmi, J, Packiyam, M, 2010. Electrocoagulation studies on removal of cadmium using magnesium electrode. J. Appl. Electrochem. 40 (11), 2023–2032. https://doi.org/10.1007/s10800-010-0182-y.

Vega-Hernandez, S, Sanchéz-Andrea, I, Weijma, J, Buisman, CJ, 2021. An integrated green methodology for the continuous biological removal and fixation of arsenic from acid wastewater through the GAC-catalyzed As (III) oxidation. Chem. Eng. J. 421, 127758.

Verma, S, Verma, PK, Chakrabarty, D, 2019. Arsenic bio-volatilization by engineered yeast promotes rice growth and reduces arsenic accumulation in grains. Int. J. Environ. Res. 13 (3), 475–485.

Wan, W, Pepping, TJ, Banerji, T, Chaudhari, S, Giammar, DE, 2011. Effects of water chemistry on arsenic removal from drinking water by electrocoagulation. Water Res. 45 (1), 384–392. https://doi.org/10.1016/jwatres20naz1008016.

Wang, S, Zhao, X, 2009. On the potential of biological treatment for arsenic contaminated soils and groundwater. J. Environ. Manage. 90 (8), 2367–2376. https://doi.org/10.1016/jjenvman200902001.

Wang, Z, Fu, Y, Wang, L, 2021. Abiotic oxidation of arsenite in natural and engineered systems: Mechanisms and related controversies over the last two decades (1999–2020). J. Hazard. Mater. 414, 125488 https://doi.org/10.1016/jjhazmat2021125488.

Wang, Z, Luo, Z, Yan, C, 2013. Accumulation, transformation, and release of inorganic arsenic by the freshwater cyanobacterium Microcystis aeruginosa. Environ. Sci. Pollut.Res. 20 (10), 7286–7295. https://doi.org/10.1007/s11356-013-1741-7.

Weerasundara, L, Ok, YS, Bundschuh, J, 2021. Selective removal of arsenic in water: a critical review. Environ. Pollut. 268, 115668 https://doi.org/10.1016/jenvpol2020115668.

Wei, M, Wu, J, Li, W, Zhang, Q, Su, F, Wang, Y, 2021. Groundwater geochemistry and its impacts on groundwater arsenic enrichment, variation, and health risks in Yongning County, Yinchuan Plain of northwest China. Expos. Health 1–20. https://doi.org/10.1007/s12403-021-00391-y.

Welch, AH, Lico, MS, Hughes, JL, 1988. Arsenic in ground water of the western United States. Groundwater 26 (3), 333–347. https://doi.org/10.1111/j1745-65841988tb00397x.

WHO 2018, World Health Organization, https://www.who.int/news-room/fact-sheets/detail/arsenic.

Wickramasinghe, SR, Han, B, Zimbron, J, Shen, Z, Karim, MN, 2004. Arsenic removal by coagulation and filtration: comparison of groundwaters from the United States and Bangladesh. Desalination 169 (3), 231–244. https://doi.org/10.1016/jdesal200403013.

Williams, M, Fordyce, F, Paijitprapapon, A, Charoenchaisri, P, 1996. Arsenic contamination in surface drainage and groundwater in part of the southeast Asian tin belt, Nakhon Si Thammarat Province, southern Thailand. Environ. Geol. 27 (1), 16–33.

Wongsasuluk, P, Chotpantarat, S, Siriwong, W, Robson, M, 2021. Human biomarkers associated with low concentrations of arsenic (As) and lead (Pb) in groundwater in agricultural areas of Thailand. Sci. Rep. 11 (1), 1–13.

World bank 2012. (Accessed on 03. 06. 2022) https://www. worldbank. org/en/news/feature/2012/03/06/india-groundwater-critical-diminishing.

World Bank 2020 (Accessed on 03. 06. 2022) List of economies - World Bank DataBank https://databank. worldbank. org/data/download/site-content/CLASS.xls.

Wu, R, Podgorski, J, Berg, M, Polya, DA, 2021. Geostatistical model of the spatial distribution of arsenic in groundwaters in Gujarat State, India. Environ. Geochem. Health 43 (7), 2649–2664. https://doi.org/10.1007/s10653-020-00655-7.

Yadav, IC, Devi, NL, Mohan, D, Shihua, Q, Singh, S, 2014. Assessment of groundwater quality with special reference to arsenic in Nawalparasi district, Nepal using multivariate statistical techniques. Environ. Earth Sci. 72 (1), 259–273. https://doi.org/10.1007/s12665-013-2952-4.

Yamauchi, H, Takata, A, 2019. Arsenic Contamination Asia. Springer, New York, pp. 1–11.

Yinlong, J, 2001. Progress on arsenic in China. In: Proceedings of the First International workshop on arsenic pollution of Drinking Water in South Asia and China. National Institute of Environmental Studies, pp. 35–39.

Zakhar, R, Derco, J, Cacho, F, 2018. An overview of main arsenic removal technologies. Acta Chimica Slovaca 11 (2), 107–113.

Zecchin, S, Crognale, S, Zaccheo, P, Fazi, S, Amalfitano, S, Casentini, B, Callegari, M, Zanchi, R, Sacchi, GA, Rossetti, S, Cavalca, L, 2021. Adaptation of microbial communities to environmental arsenic and selection of arsenite-oxidizing bacteria from contaminated groundwaters. Front. Microbiol. 12, 364. https://doi.org/10.3389/fmicb2021634025.

Zhai, W, Qin, T, Li, L, Guo, T, Yin, X, Khan, MI, Hashmi, MZ, Liu, X, Tang, X, Xu, J, 2020. Abundance and diversity of microbial arsenic biotransformation genes in the sludge of full-scale anaerobic digesters from a municipal wastewater treatment plant. Environ. Int. 138, 105535 https://doi.org/10.1016/jenvint2020105535.

Zhou, X, Speer, RM, Volk, L, Hudson, LG, Liu, KJ, 2021. Arsenic co-carcinogenesis: Inhibition of DNA repair and interaction with zinc finger proteins. In Seminars in Cancer Biology (Vol. 76. Academic Press, pp. 86–98.

Zhu, N, Yan, T, Qiao, J, Cao, H, 2016. Adsorption of arsenic, phosphorus and chromium by bismuth impregnated biochar: adsorption mechanism and depleted adsorbent utilization. Chemosphere 164, 32–40.

Zkeri, E, Aloupi, M, Gaganis, P, 2018. Seasonal and spatial variation of arsenic in groundwater in a rhyolitic volcanic area of Lesvos Island, Greece. Environ. Monit. Assess. 190 (1), 1–20. https://doi.org/10.1007/s10661-017-6395-3.