



Removal of arsenic from wastewater by using different technologies and adsorbents: a review

W. A. H. Altowayti¹ · N. Othman¹ · S. Shahir² · A. F. Alshalif⁶ · A. A. Al-Gheethi¹ · F. A. H. AL-Towayti³ · Z. M. Saleh⁴ · S. A. Haris⁵

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Abstract

A lot of anthropogenic activities can discharge arsenic into the ecosystem such as industrial wastes, incineration of municipal, pesticide production and wood preserving. In addition, most arsenic soluble species can enter surface waters via runoff and leach into the groundwater. Around forty million people from all over the world are affected by arsenic through drinking water above the maximum contaminant level of 0.01 mg/L. The affected by inorganic arsenic through drinking water can cause a lot of diseases especially a unique peripheral vascular disease and blackfoot disease. These diseases usually cause gangrene and end with amputation of the legs and can also cause severe systemic atherosclerosis. In addition, the wastewater treatment techniques can be divided into two groups, adsorbents and membrane separations such as electro dialysis, nanofiltration and reverse osmosis. Furthermore, most of these techniques do not function at a low level of concentration, so that moderate to high levels of concentration are required. However, the use of some of these arsenic removal approaches is costly because they require a lot of energy and reagents. Moreover, this review discusses readily adsorption technologies that have been applied to remove arsenic from wastewater along with an analysis of arsenic chemistry and contamination. This review is also focused on the removal of arsenic from wastewater using different adsorbents such as iron, aluminium, natural and biological adsorbents. Its goal is to increase our fundamental understanding of this developing research subject and to identify future research and development strategies for sustainable and cost-effective arsenic adsorption technology.

Keywords Arsenic removal · Water treatment · Adsorption technologies · Adsorbents · Pollution

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✉ W. A. H. Altowayti
wahidali@uthm.edu.my

- ¹ Micro-Pollutant Research Centre (MPRC), Department of Civil Engineering, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia
- ² Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, Johor, Malaysia
- ³ Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia
- ⁴ Department of Mathematics, Science and Computer, Politeknik Sultan Idris Shah, Selangor, Malaysia
- ⁵ Department of Cellular and Molecular Biology, Shahid Beheshti University, Tehran, Iran
- ⁶ Jamilus Research Centre for Sustainable Construction (JRC-SC), Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia

Introduction

Arsenic occurs in period 4 and group V in a periodic table, leaving five free electrons in the outer shell. This atomic formation allows the presence of arsenic in various compounds with different oxidation numbers. According to Jiang et al. (2012) and Nicomel et al. (2016), the existence of arsenic corresponds to four states of arsenic oxidation, namely arsenate (As^{+5}), arsenite (As^{+3}), arsenic (As^0) and arsine (As^{-3}). Arsenic can be found in both organic and inorganic forms in aquatic environments, although the concentration of organic forms is insignificant and has less harmful effects than inorganic forms, and does not cause problems in drinking water (Jain & Ali 2000).

Drinking contaminated water is the primary route of exposure, and secondary exposure occurs through irrigation of plants with water containing arsenic or directly through contaminated soils. It is estimated that 200 million people worldwide are exposed to water above the maximum



contaminant level of 0.01 mg/L (Amini et al. 2008; Flanagan et al. 2012; Kinniburgh & Smedley 2001, Mandal (2002). Bangladesh is considered "the greatest mass toxicity in its history" and is highly polluted. The arsenic level in the area is usually 10 times higher than the safety limit, with an estimated exposure of 30% of the population of 157 million (Flanagan et al. 2012; Hasan et al. 2019; Huq et al. 2020; Kinniburgh & Smedley 2001; Tabassum et al. 2019a). Different techniques of removing arsenic are suggested. The primary methods can be divided into three main classifications: precipitation, membrane technology and adsorption, exclusively for neutral or near-neutral pH treatment of drinking water or groundwater (Altowayti et al. 2019a, 2020c; Bahari et al. 2013).

In this review, we explained the arsenic chemistry and important issues associated with the toxicity of arsenic. We also compared and addressed the advantages and disadvantages of the main technologies listed in the literature for the removal of arsenic. Furthermore, the present review investigated the effects of generated arsenic on living things, as well as the removal of arsenic species from wastewater using various adsorbents and technologies, and also their future direction. However, no previous research has been done to show a direct comparison of main arsenic removal technologies and adsorbents under the same conditions (initial concentration, temperature, pH and adsorbent dosage). To the best of your knowledge, this is the first review that exposes this research gap and aims to illustrate it for future studies.

Arsenic chemistry

Arsenic has an atomic number of 33 and accounts for approximately 0.0005 percentage of the earth's crust. It has an atomic weight (74.9216), melts at 817 °C and boils at 28 atm at 613 °C. It also has a crystalline silver-grey colour and vapours at a pressure of 1 mm Hg at 372 °C, with a specific gravity of 5.73. When dissolved in water, it is odourless and colourless. Although the people of ancient civilizations discovered toxic metalloid arsenic, Albert Magnus, the German alchemist, isolated it for the first time and was characterized in 1250 AD. In addition, arsenic and nitrogen, phosphorus, antimony, and bismuth are included in the series of elements in the periodic table in group V. Due to its role in alchemy and poisoning, the discovery of the arsenic element attracted additional science curiosity (Mukherjee et al. 2006). Furthermore, arsenic can be highly reactive, causing biochemical changes in life with certain key organic and inorganic compounds (Al Lawati et al. 2012). The pH and the potential for oxidation or reduction are two main factors that regulate the presence of inorganic arsenic in the solution (Altowayti et al. 2019a, 2020c; Bahari et al. 2013;

Haris et al. 2018). The main species of arsenic and their structure are shown in Fig. 1:

Inorganic arsenite and arsenate are probably more prevalent in water than other forms of arsenic (Jain & Ali 2000). Arsenite (As^{+3}) species (H_3AsO_3 , H_2AsO_3^- and HAsO_3^{2-}) are recorded in anoxic reduction conditions such as groundwater, and the majority in pH 9.2 is an uncharged form of H_3AsO_3 . Arsenate (As^{+5}) species (H_3AsO_4 , H_2AsO_4^- , HAsO_4^{2-} and AsO_4^{3-}) are stable in the aerobic oxidation environment and have a greater oxidation potential than arsenite species. The H_3AsO_4 and AsO_4^{3-} are found in extremely acidic and alkaline environments, H_2AsO_4^- dominant in the low to middle pH (2–6.9) and HAsO_4^{2-} in the middle and high pH ranges (6.9–11.8) (Choong et al. 2007; Jiang et al. 2012; Nicomel et al. 2016). In addition, orpiment (As_2S_3) or realgar (AsS) and other arsenic sulphide species are found in low pH environments (Fig. 2) (Bin et al. 2019; Hu et al. 2020, Smedley & Kinniburgh 2001).

On the other hand (Fig. 3), Fig. 4 shows journals with high published articles about arsenic removal in the international framework from 2018 to 2021. Therefore, the most productive journals in this field were journals of hazardous material and chemosphere.

Arsenic sources

In the environment, arsenic is relatively abundant and the twentieth-largest chemical on the Earth's crust list (Kartinen & Martin 1995; Nicomel et al. 2016; Singh et al. 2015b). Moreover, both natural processing and human activity introduce arsenic into the water environment. Dissolution and the release of minerals containing arsenic into the groundwater are the major natural sources of arsenic. In nature, arsenic is mainly present in ore mineral products and arsenopyrite FeAsS accounts for the largest proportion of arsenic-enriched ores, following the realgar AsS or orpiment As_2S_3 (Siddiq et al. 2021). Minerals that form rocks are also reported to be arsenic sources, with the largest amount of arsenic in pyrite minerals.

The weathering of rocks or sediments also leads to the release of arsenic, although the average concentration of arsenic in different rocks and sediments is low (Smedley & Kinniburgh 2001). On the other hand, anthropogenic activities are the main culprit for the occurrence of arsenic, as a large amount of arsenic released to the environment is caused by human activities as shown in Fig. 4. There could be various typical human practices for elevating arsenic: minerals (mining, water percolation and smelting ore), agriculture (using fertilizers, insecticides and herbicides) and certain industrial activities (colouring or wood conservation) (Dv et al. 2009, Jiang et al. 2012; Singh et al. 2015b).

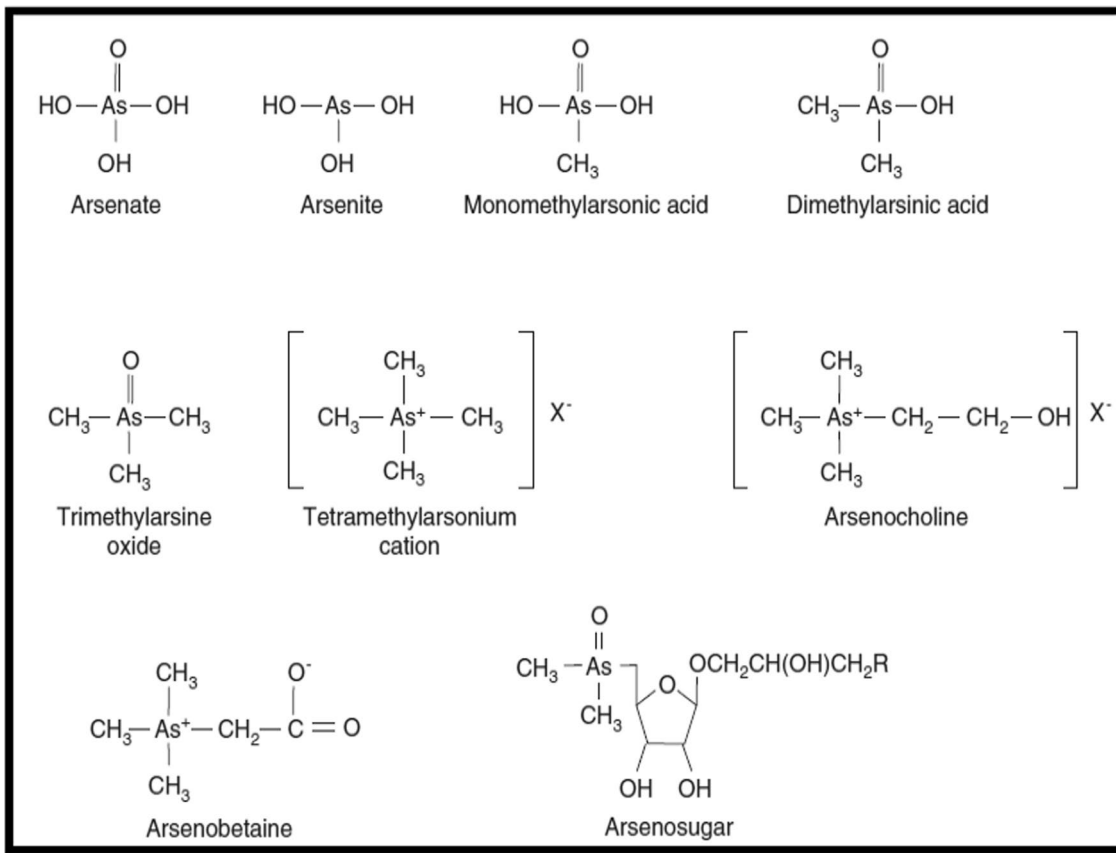
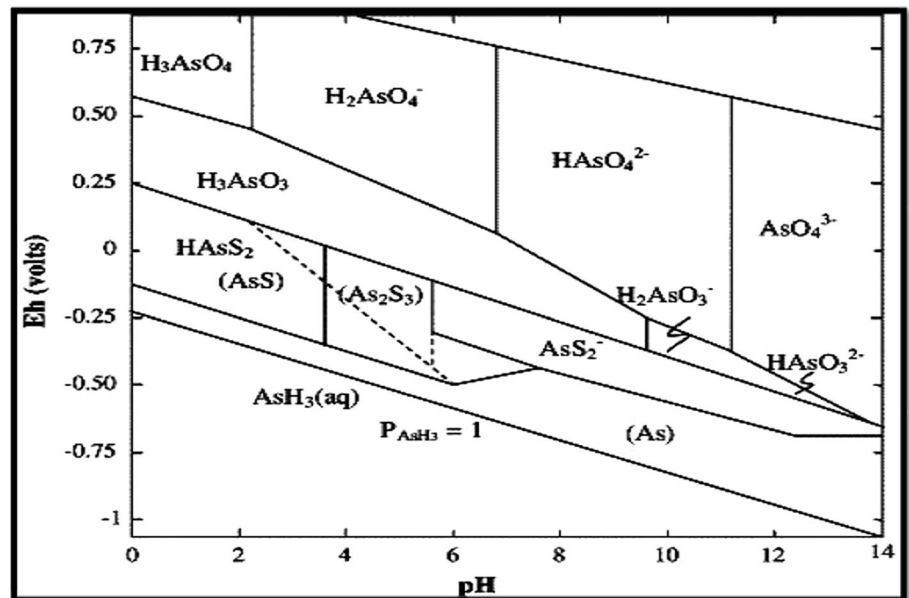


Fig. 1 The most common structure formula of arsenic species

Fig. 2 Arsenic element found in water in various compounds. Eh is oxidation/reduction potential and pH is acid/base potential (Ferguson & Gavis 1972)



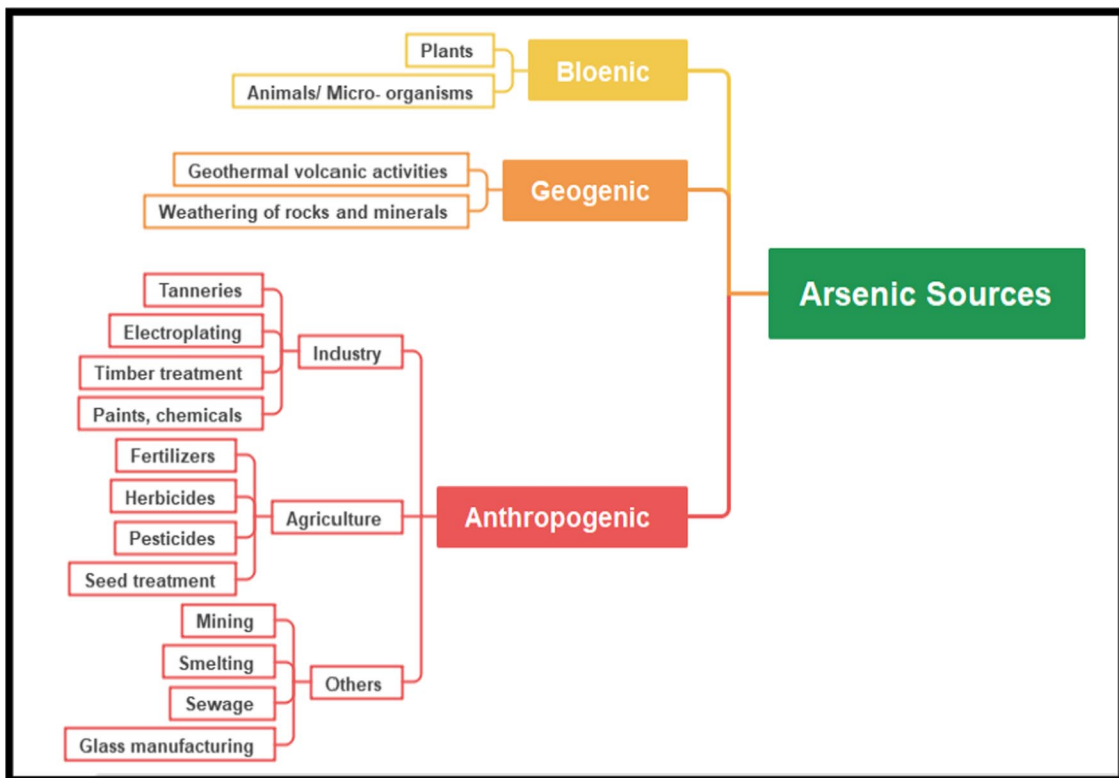


Fig. 4 The natural and anthropogenic sources of arsenic contamination in the environment

Vietnam, Taiwan, China, India, Cambodia and Bangladesh (Bundschuh et al. 2012; Mukherjee et al. 2006). In these Asian countries, the source of water for drinking and irrigation is generally obtained by drilling into groundwater. In nature, groundwater is confined or unrestricted and often contains both permeable sediments and waterproof aquitards. These sediments contain minerals that contain arsenic, and arsenic can be released into the water by various mechanisms (Datta et al. 2009; Dhar et al. 2011; Polya & Middleton 2017; Stute et al. 2007). Figure 5 indicates which countries are conducting the most research on arsenic removal, with China topping the list, followed by the USA, India and Iran.

The arsenic in water

The major soluble species of arsenic in water are As (III) and As (V). The relative proportion of As (V) and As (III) in water is diverse according to microbial, pH and redox conditions and sources. Kim and Nriagu (2000) evaluated that the As (III) half-lives in water saturated with air ranging from 4 to 9 days.

Moreover, Azcue and Nriagu (1995) mentioned that the percentage of arsenic (III)/arsenic (V) can be increased according to the depth of groundwater. This can occur because biological activities can reduce the levels of oxygen at the lake's bottom. Moreover, the evaluated arsenic upward diffusion flux of the sediments was ranging from 0.81 to 7.09 Ag/cm²/yr (Azcue & Nriagu 1995) and orgAs forms concentrations are usually low or negligible (Chen et al. 1995). In the summer, the methylated compound concentrations can be increased because of increasing in microbial activity (Hasegawa 1997). Furthermore, Fig. 6 illustrates the most frequently used terms in arsenic removal studies from 2018 to 2021.

Arsenic maximum contaminant level

In 1942, the United States Public Health Services (USPHS) regulated arsenic for indoor potable water for the first time at 50 ppb. In 1962, however, the USPHS found that arsenic should not exceed 10 ppb in drinking water and is trying to set this as its target (Shakya & Ghosh 2019). The Environmental Protection Agency (EPA) estimated in 1988 that

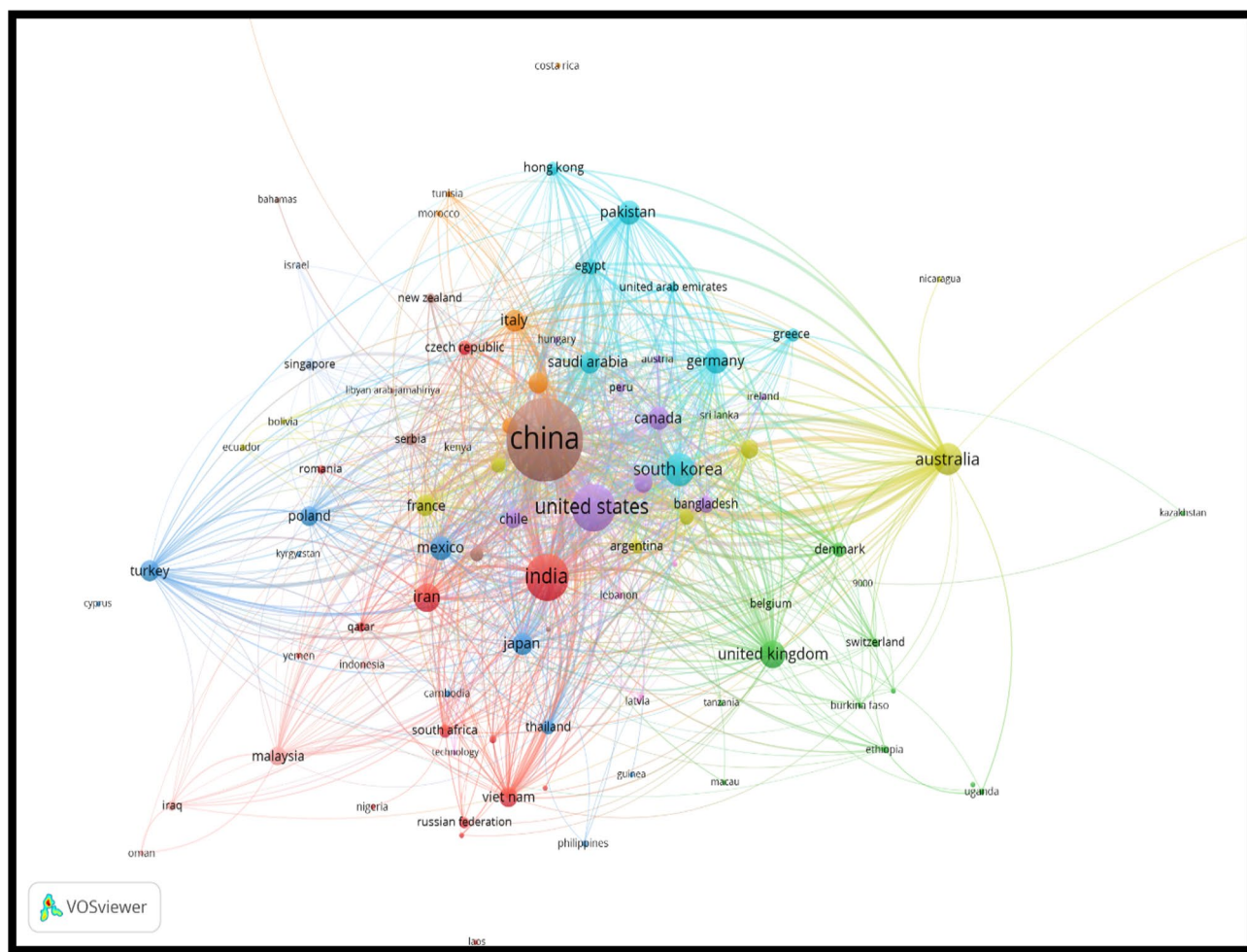


Fig. 5 Network of relationships between countries with research teams. *Source* Data from the literature (2018–2021), generated using VOSviewer

intake of 50 ppb arsenic could lead to skin cancer with a chance of 1 person in 400. Hence, the World Health Organization recommended that the maximum level of arsenic contaminants in drinking water be reduced to 10 ppb in 1993. By January 2000, Congress requested the EPA to adopt a new standard for arsenic drinking water. The EPA subsequently proposed a 5 ppb standard but sought to comment on whether to maintain it or to look at levels of 3, 10 and 20 ppb. However, in March 2001 the Bush administration blocked the proposed 10 ppb standard. Furthermore, the national debate was held on whether the proposed 10 ppb standard was scientifically too low and whether the cost of such a standard would be necessary. Thus, on 20 March 2001, the EPA decided to request a panel of scientific experts from the National Academy of Sciences to assess the cost, benefit and science of the plausibility of this standard. As a result, the World Health Organization has reduced the permissible level of arsenic from 50 to 10 ppb due to harmful

health risks and accidents related to the consumption of arsenic-polluted water (Alka et al. 2020b; Choong et al. 2007). Moreover, the maximum contaminant level (MCL) of arsenic for some countries is shown in Table 1:

Health impacts of arsenic contaminated

The consumption of arsenic in drinking water has a negative impact on human health, which corresponds to exposure periods: chronic and acute. After a short time, vomiting, stomach ache and diarrhoea are likely to occur after drinking arsenic polluting water. In some cases, due to high arsenic poisoning, numbness, muscle cramping or even death have been reported. Arsenic has several chronic health effects. Skin problems are apparent due to long-term arsenic exposure, including skin lesions, over-pigmentation and hyperkeratosis. Furthermore, the classification of arsenic



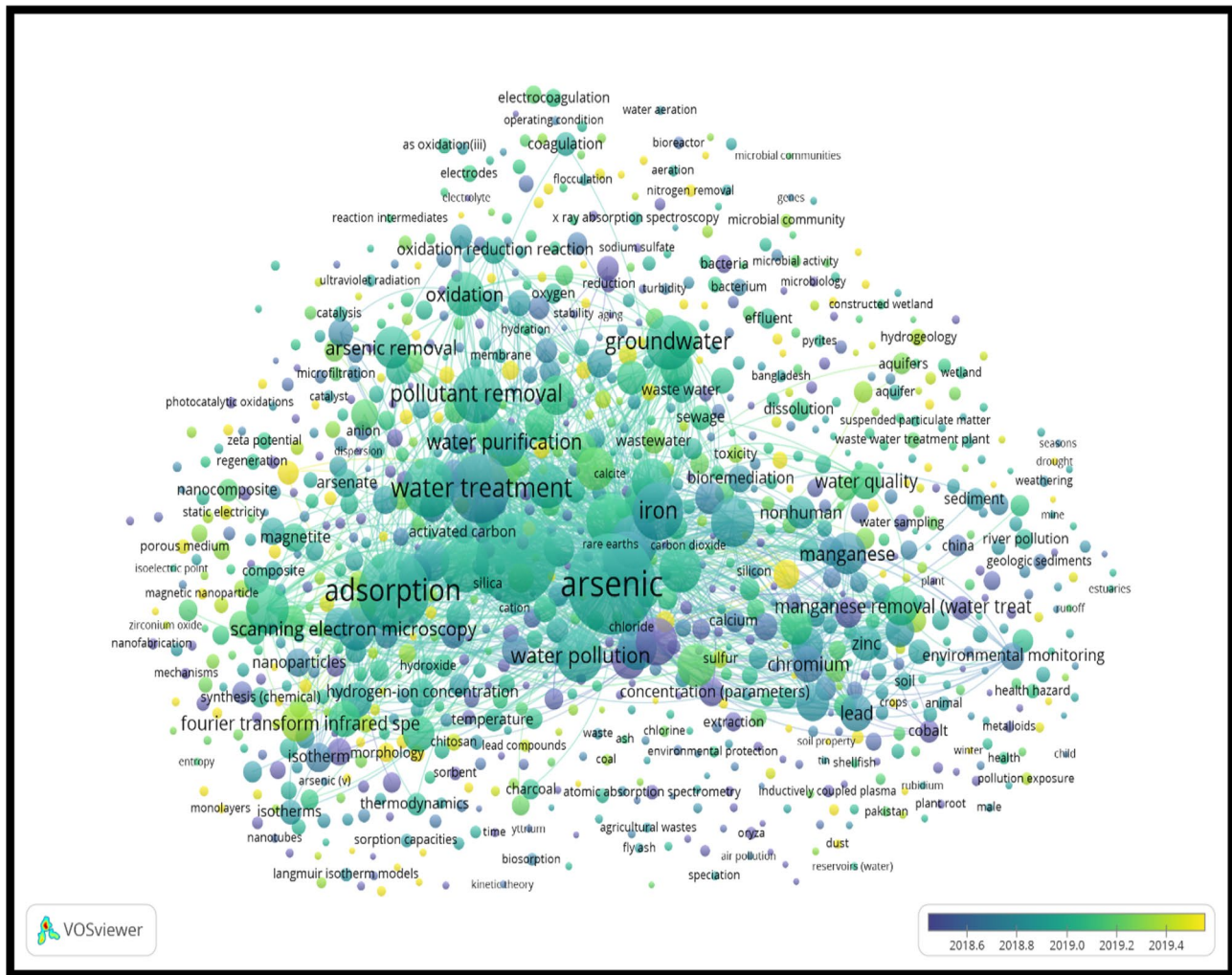


Fig. 6 Network of relationships between keywords used in different studies. *Source* data from literature (2018–2021), generated using VOSviewer

as human carcinogenic is based on the diagnosis of many victims of liver, kidney, prostate and lung cancer in chronic toxic arsenic (Abdul et al. 2015). Furthermore, the consequences of arsenic poisoning should also include diabetes, depression of the bone marrow, cardiovascular diseases or higher blood pressure. In utero exposure to arsenic or in conceiving women who consume water contaminated with arsenic, birth defects, respiratory infections or delays are found (Abdul et al. 2015, Dv et al. 2009). In addition, more than 200 human body enzymes are inactive, causing cholera, such as symptoms, liver and renal damage (Mandal 2002). For instance, As (V) has been reported to interrupt the production of adenosine triphosphate (ATP) and a comprehensive biochemistry description of arsenic is well examined (Hayes 1997; Kitchin 2001; Miller et al. 2002; Naujokas et al. 2013). Table 2 is summarizing and discussing health

effect for consumption of arsenic in drinking water on human health.

Arsenic removal technologies

A number of existing technologies have demonstrated high efficiency in the treatment of arsenic. For instant, coagulation and flocculation are one of the most common treatment techniques used to add coagulants to crude water with a positive charge or anionic flocculants. This leads to the formation, precipitation and filtering of large particles containing arsenic during treatment. Furthermore, arsenic is effectively eliminated by an adsorption method through attachment to solid sorbents, such as activated carbon, activated alumina or iron-based medium. Another reliable treatment method is the exchange of ions in which



Table 1 Maximum contaminant level (MCL ppb) of arsenic for some countries

Country	MCL (ppb)	References
Australia	7	(Zakhar et al. 2018)
France	15	(Zakhar et al. 2018)
India	10	(Sarkar et al. 2005)
Bangladesh	50	(Ahmad et al. 2005)
Vietnam	10	(Agusa et al. 2006)
Mexico	50	(Ongley et al. 2001)
Malaysia	10	(Huang et al. 2015)
Denmark	5	(Kowalski 2014)
China	50	(Juan Guo et al. 2001)
New Zealand	10	(Robinson et al. 2003)
Taiwan	10	(Tseng et al. 2005)
USA	10	(Thornburg & Sahai 2004)
Nepal	50	(Mondal & Garg 2017)
Argentina	50	(Bhattacharya et al. 2006)
Japan	10	(Kowalski 2014)
Brazil	50	(Kowalski 2014)
Chile	50	(Caceres et al. 2005)
Saudi Arabia	50	(Kowalski 2014)
Oman	50	(Kowalski 2014)
Bahrain	50	(Kowalski 2014)
Egypt	50	(Kowalski 2014)

chloride and/or hydroxide ions replace arsenic ions due to a strong affinity to exchange when water passes through resin columns. In addition, various membrane types (nanofiltration, ultrafiltration or microfiltration) at high water flow pressure also offer high efficiency for arsenic removal thanks to a selective barrier of billions of membrane pores. Furthermore, arsenic may be removed by co-precipitation with fixable particles in some other treatment techniques, such as calcium carbonate with an improved lime softening method or iron hydroxides with an oxidation/filtration method (Choong et al. 2007; Nicomel et al. 2016; Singh et al. 2015b).

Precipitation/encapsulation

Precipitation is the most common treatment method for arsenic in mining (Adams 2016). The concept is that soluble arsenic should be transformed into insoluble solids, then sedimented or filtered from the water body. The dominance of the arsenic kind As (III), which is not charged in a pH less than 9.2 according to the arsenic chemistry, is difficult to precipitate in most water structures. Consequently, arsenite should usually be oxidized to arsenate. The arsenic removal onto the surface of the adsorbent is essentially depending on the concentrations of arsenic dissolved in water. Subsequently, the removal of arsenic onto

adsorbent under acidic conditions can be decreased. Also, the greatest proportions of arsenic in the cores of sediment were dependent on sulphides and iron oxides. The affinity of the surfaces of iron solid to adsorb arsenic was essential for treating arsenic from an aqueous solution. The oxides of manganese and iron can be used for coating sand to eliminate arsenic from underground water (Bajpai & Chaudhuri 1999; Habib et al. 2020; Joshi & Chaudhuri 1996; Nguyen et al. 2020b). Moreover, the speciation and compositions of functional groups onto the surface of adsorbent can be affected by the pH of the solution via deprotonation and protonation processes and this can change the efficiency of adsorption. Table 3 demonstrates precipitants and related chemical reactions for arsenic removal reported in the literature.

Membrane technologies

Membrane technology is highly prospective in the water and wastewater industries (Boussouga et al. 2021; Chen et al. 2018; Meng et al. 2018; Siddique et al. 2020). In most commercial membranes, permeability and selectivity are frequently tradeoffs; therefore, more permeable membranes tend to have lower selectivity, and vice versa (Dai et al. 2020). Furthermore, membrane surface charges play an essential part in boosting the efficiency of ion removal and extending the top selectivity/permeability trade-off (Marjani et al. 2020; Zhang et al. 2021). In order to control the charged characteristics of the membrane surface, there are currently two major ways for preparing charged membranes: (1) incorporating charged components into membrane-forming materials, and (2) using dip-coating to introduce charged groups using dip-coating (Sarango et al. 2018), grafting (Zhang et al. 2020) and interfacial polymerization (Weng et al. 2020). These chemical-charged systems, on the other hand, have several disadvantages, such as a complicated reaction process, difficulties in manipulation, the use of toxic chemicals and strict management of the fixed charge (Pu et al. 2021). Furthermore, in order of the size of the particle that may be separated, the four most prominent pressure-driven membrane filtration techniques for liquid separation are: (i) reverse osmosis, (ii) nanofiltration, (iii) ultrafiltration and (iv) microfiltration (Siddique et al. 2020). Reverse osmosis membranes may effectively remove arsenic; nevertheless, they are energy-intensive and have a greater operational cost. Furthermore, nanofiltration has attracted the attention of researchers due to its great efficiency and cheap operating costs (Pal 2015). The nanofiltration membrane separation technique is based on size sieving and Donnan exclusion, and it effectively rejects multivalent dissolved ions in water. These characteristics make it an excellent separation method for removing arsenic (Criscuoli & Figoli 2019).

Table 2 Chronic exposure to arsenic to human health

System	Health effects	References
Integumentary	Skin Disorders	(Lindberg et al. 2008)
	Skin Lesions such as Pigmentation, Keratosis and Melanosis	(Rahman et al. 2009)
	Skin Complications such as Hyperkeratosis	(Liu et al. 2002)
	Formation of Distinct White Lines (Mees lines) in the nails of fingers and toes	(Ratnaik 2003)
	Alopecia	(Amster et al. 2007)
Nervous	Paraesthesia, pain and numbness in the soles of the feet	(Vahidnia et al. 2007)
	Oxidative stress	(Mundey et al. 2013)
	Neuronal apoptosis	(Namgung & Xia 2001)
Respiratory	Lung Dysfunction	(Parvez et al. 2011)
	Respiratory Complications such as Rhinitis, Bronchitis, Laryngitis and Chronic Cough	(Saha et al. 1999)
	Tuberculosis	(Parvez et al. 2013)
Cardiovascular	Hypertension	(Huda et al. 2014)
	Endemic Black Foot Disease	(Tseng et al. 2005)
	Atherosclerosis, Arrhythmias and Ischaemic Heart Diseases	(Simeonova & Luster 2004)
Hematopoietic	Hemolysis	(Lu et al. 2004)
	Circulatory Disorders	(Biswas et al. 2008)
	Bone Marrow Depression	(Szymanska-Chabowska et al. 2002)
Immune	Affects Human Lymphocytes	(Singh et al. 2013)
	Increase the expression of inflammatory molecules in the body	(Wu et al. 2003)
	Impaired thymic development of the baby via immunosuppression	(Raqib et al. 2009)
Endocrine	Disrupts hypothalamic–pituitary–adrenal axis	(Goggin et al. 2012)
	Impaired Thymic Functions	(Ahmed et al. 2012)
	Decreases the Secretion of Insulin	(Lu et al. 2011)
hepatic	Impair Liver Function	(Vantroyen et al. 2004)
	Hepatic Fibrosis, Non-cirrhotic Portal Fibrosis and Cirrhosis	(Kapaj et al. 2006)
renal	Cytotoxicity in Renal Tissue	(Madden & Fowler 2000)
	Damage to Capillaries and Glomeruli of the kidney	(Rahman et al. 2009)
Reproductive	Foetal loss and Premature delivery	(Chakraborti et al. 2003)
	Impaired embryonic development	(Li et al. 2012)
	Low birth weight	(Kwok et al. 2006)
	Prostate cancer	(Crawford 2003)

Table 3 Precipitants and associated responses used for arsenic removal

Precipitant	Possible reaction	References
Sulphides	$\text{AsO}_2^- + \text{HS}^- + \text{H}^+ \rightarrow \text{As}_2\text{S}_3 (\text{s})$	(Opio 2013)
Lime	$\text{Ca}(\text{OH})_2 + \text{AsO}_4^{3-} \rightarrow \text{Ca}_3(\text{AsO}_4)_2 (\text{s})$	(Nazari et al. 2017)
Aluminium	$\text{Al}^{3+} + \text{H}_2\text{O} \rightarrow \text{Al}(\text{OH})_3 + \text{H}^+$	(Baskan & Pala 2010)
Sulphate	$\text{H}_2\text{AsO}_4^- + \text{Al}(\text{OH})_3 \rightarrow \text{Al-As complex} (\text{s})$	
Ferric salts	$\text{Fe}^{3+} + \text{AsO}_4^{3-} \rightarrow \text{FeAsO}_4 (\text{s})$	(Jadhav et al. 2015)

The removal of arsenic using membrane distillation was initially reported by Macedonio and Drioli (2008), who achieved 100% of As (III) and As (V) removal. When compared to other pressure-driven membrane separation technologies like reverse osmosis, membrane distillation occurs at a significantly lower pressure (Hubadillah et al. 2020a). Nanofiltration membranes were shown to be capable of retaining 80–99% of arsenic, making them a viable

alternative to reverse osmosis (Jarma et al. 2021). Conversely, at pH 8, nanofiltration membranes can only reject around half of the As (III) (Boussouga et al. 2021). Moreover, Figoli et al. (2020) have shown that transmembrane pressure does not impact As (V) rejection by nanofiltration in operational conditions. Reverse osmosis membranes, on the other hand, have the smallest pore size (about 0.1 nm) and the highest removal rate. Schmidt et al. (2016) used a

Table 4 Removal of arsenic by membrane-based methods

Technique	Initial concentration	As (III) %	As (V) %	References
Distillation	0.3–2 mg/L	98%	–	(Dao et al. 2016)
Forward osmosis	500 µg/L	–	98%	(Mondal et al. 2014)
Reverse osmosis	100 µg/L	–	98%	(Abejón et al. 2015)
Nanofiltration	100 µg/L	–	98%	(Kosutic et al. 2005)
Nanofiltration	1–50 µg/L	–	80%	(Fang & Deng 2014)

small-scale reverse osmosis system to conduct pilot research on arsenic removal from groundwater in India. The value was in accordance with the WHO Guideline value and the National India Standard of 10 g/L, with a rejection rate of 99 percentage. For membrane distillation applications, ceramic membranes are now considered as an innovative technology (Hubadillah et al. 2020b, 2020c).

Semi-permeable membranes, including nanofiltration and reverse osmosis, are used to selectively filter arsenic as shown in Table 4. This large-scale processing technology is extremely efficient in removing arsenic to a safety limit. But, due to the material costs of membranes and the energy and maintenance costs of the pressurized operating system, this is one of the most expensive operating costs. This method also leads to the disposal of relatively large volumes of residual water. In addition, due to the small size of arsenite and arsenate molecules, micro- and ultrafiltration are not effective. Furthermore, as in precipitation, smaller arsenite molecules are converted into larger arsenate molecules by an oxidation step to increase the overall removal efficiency (Guo et al. 2019; Uddin et al. 2007).

Adsorption

Adsorption is one of the best and most distinguished technologies for removing arsenic from water systems. Since 1500 B.C., the Egyptians have used carbonized wood as a medical adsorbent and purifier (Mohan et al. 2007). In aqueous systems, arsenic species can interact physically or chemically with the appropriate adsorbents. Van der Waals forces between adsorbates and adsorbents usually lead to physical adsorption. This force is relatively weak and can be easily broken by exchanging solvents, sonication or calcination. In contrast, true chemical bonds between adsorbents and adsorbents are formed in the field of chemisorption. Therefore, the regeneration of used adsorbents is usually carried out by chemical treatment to increase the surface charges (Nicomel et al. 2016). Different adsorbents, including activated carbon (Hashim et al. 2019), resin ion exchange (Çermikli et al. 2020), metal oxides (Zhang et al. 2019) and biosorbents (Alka et al. 2020a), have been reported for the removal of arsenic ion species.

Table 5 The list of representative studies for arsenic removal by using iron-based adsorbents

Iron-based adsorbents	Adsorption Conditions				Adsorption Capacity		References
	Concentration	Temperature °C	pH	Dosage	As (III) mg/g	As (V) mg/g	
Activated hematite (Fe ₂ O ₃) iron ore	0.5 M	25	–	15 g/L	14.46	–	(Memon et al. 2021)
Iron oxide/nano-porous carbon magnetic composite	5 mg/L	Room	8	1.8 g/L	6.69	–	(Joshi et al. 2019)
Fe/Cu nanoparticles	100 µg/L	20 ± 2	7	100 mg/L	19.68	21.32	(Babae et al. 2018)
Sulphide-modified nanoscale zero-valent iron (nZVI)	10–100	–	7	0.5 g/L	89.29	79.37	(Singh et al. 2021)
Porous hydrogels with hydrated ferric oxide nanoparticles	4.5 mg/L	Room	7.2	0.1 g	–	2.25	(Zowada & Foudazi 2019)
Polymer-based hydrated iron oxide adsorbent	50 mg/L	Room	7	100 mg/L	–	71.5	(Liu et al. 2020)
Zero-valent Fe ⁰ -based nanomaterials	5 mg/L	22 ± 2	3–9	333 mg/L	26	32–36	(Das & Bezbaruah 2021)
Graphene oxide supported nanoscale zero-valent iron	5 mg/L	22 ± 2	3–9	333 mg/L	36	43–49	(Das & Bezbaruah 2021)
Treated ferromanganese slag (TFS)	0.2–20 mg/L	25	7	0.5 g/L	1.010	1.614	(Jain & Maiti 2021)
HSb–Fe	1 mg/L	40	6	0.5 g/L	12.81	–	(Wu et al. 2021)

Adsorbents

Fe-based adsorbent Fe-based adsorbents have received a lot of attention due to their high performance in arsenic removal, environmental friendliness and availability on Earth. Moreover, Fe-based nanoparticles, iron-doped inorganic minerals, iron-doped polymer/biomass composites, iron-containing mixed metal oxides, iron-doped activated carbon, iron-based layered double hydroxides (LDHs) and zero-valent iron (ZVI) are potential adsorbents for arsenic removal from water (Hao et al. 2018). Arsenic species have been removed from water using iron-based adsorbents, which have been widely developed (Leus et al. 2018). Some adsorbents, such as granular ferric hydroxide (GFH) and zero-valent iron, have been commercially manufactured on a large scale (Pintor et al. 2018). In addition, many iron-based adsorbents are magnetic, which allows the saturated material to be easily separated from water in an external magnetic field. The list of representative studies for arse-

nic removal by using iron-based adsorbents are shown in Table 5

Al-based adsorbent Aluminium hydroxide, layered double hydroxides, gibbsite (mineral $\text{Al}(\text{OH})_3$) and activated alumina are among the several adsorbents based on aluminium that are increasingly being used as adsorbents for the detoxification of arsenic-contaminated water and wastewater (Giles et al. 2011; Kumar et al. 2014). The surface chemical behaviour of these compounds is mostly characterized by their surface structure, but environmental conditions also have a significant impact on their reaction to toxic ions in aqueous solutions (Li et al. 2011; Mahfoudhi & Boufi 2020). As a result of its amphoteric nature, it's one of the best options for general use in water treatment systems. The main advantages of using activated alumina as an adsorbent are that it requires little operator attention, is very porous and has a large surface area (Chen et al. 2021). These adsorbents have recently been utilised successfully to treat

Table 6 List of different Al-based adsorbents and their arsenic adsorption capacities

Al-based adsorbents	Adsorption conditions				Adsorption capacity		References
	Concentration	Temperature °C	pH	Dosage g/L	As (III) mg/g	As (V) mg/g	
Aluminium (hydr) oxide-coated red scoria and pumice	0.1–20 mg/L	25	7	5	–	2.68	(Asere et al. 2017)
γ -aluminium oxide nanoparticles	6.5–8.5 $\mu\text{g/L}$	25	6.5–8.5	0.5–0.75	769.23	1000	(Ghosh et al. 2019)
Al_2O_3	200 $\mu\text{g/L}$	–	6	0.5	0.17	–	(Jeong et al. 2007)
Aluminium Oxide/Hydroxide nanoparticles	500 $\mu\text{g/L}$	–	–	–	1309.8 $\mu\text{g/g}$	–	(Rathore & Mondal 2021)
Aluminium oxide nanoparticles	500 ppb	25	6.5	2	555.5	–	(Prabhakar & Samadder 2018)
Aluminium loaded Shirasu-zeolite	0.13 mM	24	3–10	0.05	–	0.1	(Xu et al. 2002)
$\gamma\text{-Al}_2\text{O}_3$	100	25	4	0.5	–	54	(Inchaurrondo et al. 2019)
Aluminium hydroxide ($\text{Al}(\text{OH})_x$)	0.05 mol/L	20	6	5	–	315 mmol/kg	(Pigna et al. 2006)

Table 7 List of different Fe-Al-based adsorbents and their arsenic adsorption capacities

Fe-Al-based adsorbent	Adsorption conditions				Adsorption Capacity		References
	Concentration	Temperature °C	pH	Dosage	As (III) mg/g	As (V) mg/g	
$\text{FeOOH}/\gamma\text{-Al}_2\text{O}_3$ granules	10–100 mg/L	25	8.5	1.10 g	4.264	–	(Wang et al. 2018)
$\text{Fe}/\text{AlO}(\text{OH})$	150 ppm	Room	3	1 g	–	102	(Muedi et al. 2021)
$\text{Fe}_3\text{O}_4@/\text{Al}_2\text{O}_3@/\text{Zn-Fe}$	65.6 $\mu\text{g/L}$	–	4	28.9 mg	97.3	–	(Adlnasab et al. 2019)
Mesoporous $\gamma\text{-Al}_2\text{O}_3$	400–600 mg/L	Room	6.5–7	10–150 mg/L	–	19.8	(Tchida et al. 2016)
$\text{Fe-Al}_2\text{O}_3$	100 mg/L	25	8	0.5 g/L	–	41	(Inchaurrondo et al. 2019)
$\text{Fe}_2\text{O}_3/\text{AISBA-15}$	10 ppm	25	3.5	0.2 mg	–	2.25	(Mahato & Krithiga 2019)
Co-Al-Fe	57.6 ppm	–	7	0.1 g	130	76	(Penke et al. 2017)
	24 ppm						
Ni-Al-Fe	100 ppm	–	7	–	114	103	(Penke et al. 2016)
Cu-Al-Fe	0.1–150 ppm	Room	7	–	125	87	(Penke et al. 2019)

water containing large anionic contaminants such as arsenic ions. The different Al-based adsorbents for removing of arsenic are summarized in Table 6.

Fe-Al-based adsorbent Arsenic can be removed by precipitation as ferric arsenate. It was established that As precipitation with ferric salts is more efficient than aluminium salts (Hao et al. 2018, Mohan & Pittman Jr 2007). The combination of iron and aluminium, on the other hand, will improve the adsorbent's ability to remove arsenic from wastewater. Table 7 illustrates the capacity of several Fe-Al-based adsorbents in removing arsenic.

Natural material and its modified form

Natural adsorbents (laterite, red soil, fly ash, wheat straw, rice husk and others) have been investigated as an

alternative for current expensive adsorbents in removing arsenic from contaminated water due to their low cost, local availability and efficiency (Nguyen et al. 2020a; Rashid et al. 2021). Due to the natural occurrence of Fe and Al oxides/hydroxides in this material's composition, it can be employed as a possible adsorbent for arsenic removal (Glocheux et al. 2013). Unfortunately, pilot-scale and full-scale applications of those low-cost adsorbents are still limited. The removal efficiency of a variety of natural material adsorbents used to remove arsenic ions is summarized in Table 8.

Biosorption

Biosorbents are especially applicable since they are economic and environmentally sustainable (Podder & Majumder 2015). Table 9 provides an overview of some of the biomasses used for arsenic removal in the literature. Rice husks

Table 8 The adsorption capacity of different natural material adsorbents for arsenic removal

Natural material adsorbents	Adsorption conditions				Adsorption capacity		References
	Concentration	Temperature °C	pH	Dosage	As (III) mg/g	As (V) mg/g	
Natural laterite from Thach That (NLTT)	200 µg/L	30	2–9	2.5 g	512 µg/g	580 µg/g	(Nguyen et al. 2020a)
Treated laterite (TL) collected from Kharagpur	1027 µg/L	25–30	7	0.5 g	0.580	3.501	(Maiti et al. 2010b)
Raw laterite from Bankura (BRL)	1000 µg/L	32	7.2	20 g/L	0.18	0.19	(Maiti et al. 2013)
Natural laterite (NL) from Kharagpur	5 mg/L	25	7.2	20 g/L	0.58	–	(Maiti et al. 2007)
Treated laterite (TL)	385 µg/L	32	7.4	0.5 g/L	9.4	21.6	(Maiti et al. 2012)
Acid-activated laterite (AAL)	2 mg/L	32	6.6–7	5 g/L	0.633	0.598	(Maiti et al. 2010a)
Red soil with ferromanganese oxide–biochar composites	10–50 mg/L	25	6	2 g	0.687	–	(Lin et al. 2018)
Wheat Straw	1–28	30	7	0.5 g/L	3.898	8.062	(Tian et al. 2011)
Rice wastes polish	1000 µg/L	20	7–4	20 g/L	138.88 µg/g	147.05 µg/g	(Ranjan et al. 2009b)
Rice husk	123 µg/L	150	6.5	5 g/L	94%	–	(Samad et al. 2016)
Chemical treated Fly ash	50 mg/L	25	2.5	2 g/L	–	19.46	(Li et al. 2009)

Table 9 Arsenic removal using biosorbents from water solutions

Biosorbents	Adsorption conditions				Adsorption capacity		References
	Concentration	Temperature °C	pH	Dosage	As (III)	As (V)	
Tea fungal biomass	1.3–0.9 mg/L	30	7.2	20 g/L	100%	76%	(Murugesan et al. 2006)
FeCl ₃ treated tea fungal biomass	1.3–0.9 mg/L	30	7.2	20 g/L	5.4 mg/g	10.26 mg/g	(Murugesan et al. 2006)
Rice polish	1000 µg/L	20	7–4	20 g/L	138.88 µg/g	147.05 µg/g	(Ranjan et al. 2009a)
Fungal biomass	100 µg/L	30–10	6	1 g/L	85.9 mg/g	100 mg/g	(Pokhrel & Viraraghavan 2008)
Chitosan	11,000 µg/L	23	6–4	0.5 g/L	500 µg/g	8000 µg/g	(Kwok et al. 2018)
Nanochitosan	11,000 µg/L	23	6–4	0.5 g/L	6100 µg/g	13,000 µg/g	(Kwok et al. 2018)
Functionalized nanocrystalline cellulose	50 mg/L	7.5 – 2.5	Room	0.5 g/L	10.56 mg/g	12.06 mg/g	(Singh et al. 2015a)
Stem of Tecomella undulata	600 – 800 µg/L	6–8	25	4 g/L	108 µg/g	159 µg/g	(Brahman et al. 2016)

have removed 96% of arsenic from Bangladesh's contaminated groundwater (Mohan et al. 2007). Rice husks could be attributed to arsenic adsorption. The hydroxyl groups on the surface exchanged with As (V) ions in the solution and the van der Waals forces with the As (III) neutral species. In addition, arsenic adsorption on biochars is also caused by various functional groups, such as amine and carboxyl, etc. (Mohan et al. 2007; Tabassum et al. 2019b). Similar to biosorptions in Chitins, Chitosan and Cellulose, protonated amine groups can interact with the opposite charges of arsenic species and neutral arsenic species through the van der Waals forces. Moreover, the mechanism of anion (nitrite) adsorption was examined by aminated silica carbon nanotubes, where an amine is a functional group capable of surface cations (Altowayti et al. 2019b).

Bacterial bio-adsorbent

Intensive cost, performance, design, operation and maintenance considerations are needed to choose the most suitable arsenic removal technique with high applicability. It is proposed that bacterial biomass be used for binding the arsenic during water treatment using a basic treatment technology (Altowayti et al. 2020a). Due to the active metabolism and the influence of metal on the metabolic activity of the cell and its effect on the food chain, arsenic can accumulate in live bacteria (Aguilar et al. 2020; Sher & Rehman 2019). However, further research has shown that, through various physicochemical processes, inactive/dead microbial biomass can bind metal ions by numerous mechanisms (Altowayti et al. 2019a, 2020b, 2020c). Moreover, different bacteria have different capacity to remove arsenic from contaminated water. Arsenic removal improved after pre-treatment of *Staphylococcus xylosum* biomass as shown in Table 10. Table 10 summarizes some of the significant results of arsenic removal using different bacterial biomass.

Mechanism of bioadsorption

Biosorption and bioadsorption depend not only on the type of biomass or chemical composition but also on external physicochemical factors and chemistry solutions. The mechanisms responsible for adsorption include complexation, chelation, coordination, ion exchange and precipitation (Hansda & Kumar 2015; Kanamarlapudi et al. 2018; Veglio & Beolchini 1997). As seen in Fig. 7, the most essential methods of arsenic removal using bacteria cells are adsorption and adsorption.

Complexation It is described as creating a complex by combining two or more species. Mononuclear (monodentate) complexes are formed between the metal ion and the ligands where the metal atom's central position is occupied. The polynuclear (multidentate) structure is produced by more than one metal ion in the centre and the metal atom can take a positive or neutral charge depending on the number of binding ligands. The complicated formation of the monodentate ligand is better than multidentate, as various ligands may result in several species being bound. The metal ion interacts in covalent bonds with ligands. The (FTIR) assessment of *B. cereus* strain SZ2 after As (III) biosorption proposed the participation of carboxyl, hydroxyl and amine groups through surface complexation (Bahari et al. 2013). Other studies revealed a similar biosorption mechanism using acidiphilium to remove Cd (II) (Chakravarty & Banerjee 2012) and termitomyces clypeatus to remove Cr (VI) (Ramrakhiani et al. 2011).

Chelation This means that a chelating agent attaches the metal ion to more than one place at a time to form a ring structure and the complex is called a chelate. The reaction to stable structures through multiple bindings is mainly engaged in polydentate ligands. Therefore, increased ligand attachment sites enhance structural stability. Because of sev-

Table 10 Arsenic removal (mg/g) using bacterial biomasses

Adsorbents	Adsorption conditions				Adsorption capacity As (III) mg/g	References
	Concentration	Temperature °C	pH	Dosage		
Bacterial biomass (<i>B. cereus</i> strain W2)	100 mg/L	30	7	20 g/L	1.164	(Miyatake 2011)
Bacterial biomass (<i>B. megaterium</i> strain UM-123)	1 mg/L	35	7	20 g/L	0.127	(Miyatake 2009)
<i>B. cereus</i> biomass	1–10 mg/L	30	7.5	6 g/L	32.42	(Giri et al. 2011)
<i>B. cereus</i> strain ZS2	80 µM	30	7	0.5 g/L	153.41	(Bahari et al. 2013)
Fe(III)-treated biomass (<i>Staphylococcus xylosum</i>)	50 mg/L	–	7	1 g/L	54.35	(Aryal et al. 2010)
Bacterial biomass (<i>Rhodococcus</i> sp. WB-12)	100 mg/L	30	7	1 g/L	77.3	(Prasad et al. 2011)
Bacterial biomass (<i>Arthrobacter</i> sp.)	100 mg/L	28	7	1 g/L	74.91	(Prasad et al. 2013)
<i>Yersinia</i> sp. strain SOM-12D3)	6.5 mg/L	30	7	0.5 g/L	159	(Haris et al. 2018)

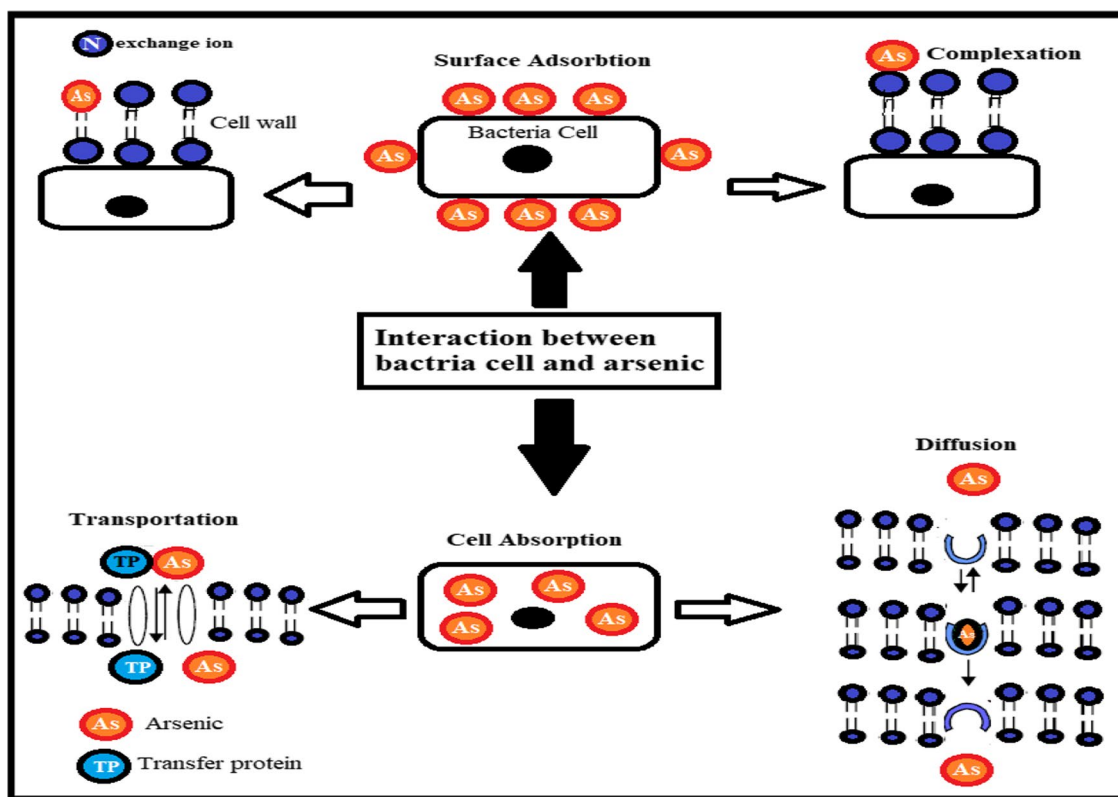


Fig. 7 Different mechanisms of arsenic ions bio-treatment using bacterial biomass

eral metal ion bindings in more than one place, chelates are more stable than complex. The Cd (II) biosorbed chelates on the surface of the biosorbents with functional groups such as C=C, C–O, O–H and carboxylic acids (Ding et al. 2012).

Coordination The complex's metal atom is bound to its immediate neighbours by accepting from the non-metal atom one single pair of electrons. The non-metal atom is called the donor and the metal atom accepting a couple of electrons is known to be the acceptor. Compounds with such bonds in their composition are known as coordinating compounds. For instance, coordinating groups are =NOH, –O–R, –S–, –OH, –N=, –NH, –NH₂ and =O (Kanamarlapudi et al. 2018).

Ion exchange In biosorption, the exchange of ions is an important concept involving the exchange of binary metal ions with counter-ions on the bio-sorbent surface. The exchange of ions can be achieved either through the cation or the anion. A good example of cation exchangers can be the carboxyl groups, whereby amino/imidazole groups represent anion exchangers. In addition, the processes of arsenic biosorption were studied by different bioadsorbents and there were three functional groups capable of sur-

face cations: phosphate, carboxyle and hydroxyle groups (Altowayti et al. 2019a, 2020c; Haris et al. 2018).

Precipitation The ions form precipitates with functional groups on the surface of the microbial cells and remain intact or enter the microbial cell. Insoluble inorganic metal precipitates are most commonly formed. Organic metal precipitates can be created when using microbial cells. The formation of organic precipitates includes most of the extracellular polymers excreted by the microbes. For example, Cu (II) precipitation of amorphous metabolites causes deformation, aggregation and damage to the cell surface as seen in the electrolyte analysis (SEM–EDX) or (FESEM–EDX) (Altowayti et al. 2020c; Mohamad et al. 2009).

Microbiology of arsenic mobilization

Several mineralogical and geochemical studies have been conducted to understand the different mechanisms of arsenic mobilization in different sediments (Berg et al. 2001; Datta et al. 2009; Gault et al. 2005; Héry et al. 2008; Horneman et al. 2004; Islam et al. 2004; Rizoulis et al. 2014; Rowland et al. 2007; Stute et al. 2007; Sun et al. 2016; Zheng et al. 2004). Arsenic research has recently focused on a

microbiological approach to arsenic mobilization. This approach thoroughly examines the interaction between different arsenic species and intracellular and extracellular bacterial species.

Intracellular interaction As arsenic enters the bacterial cell, a variety of intracellular contact biochemical modifications occur. Arsenic is methylated, demethylated, oxidised and reduced to either detoxify the system or provide energy to the system depending on different cellular biochemical shifts. The process was studied in a variety of aerobic and anaerobic bacteria such as *Alcaligenes* sp., *Pseudomonas* sp., *Achromobacter* sp., *Escherichia coli*, *Flavobacterium* sp., *Corynebacterium* sp., and *Proteus* sp., (Shariatpahani et al. 1983), *Klebsiella oxytoca*, *Xanthomonas* sp., and *P. putida* (Maeda et al. 1990), *Methanobrevibacter smithii* (Meyer et al. 2008), *Flavobacterium-cytophaga* spp. (Turpeinen et al. 2002). As (V) is reduced to As (III) in the cell until a methyl group was added and catalysed by the As (III) S-adenosylmethionine (ArsM) enzyme in the Oxidative Couplement Reaction (Dombrowski et al. 2005; Qin et al. 2006).

Extracellular interaction For determining the nature of the interaction between bacteria and metal substances, the interaction of surface bacteria with metals or metal compounds is significant (Handley et al. 2009; Hohmann et al. 2011). Interplays between bacteria and metal/metallic compounds are influenced by diverse parameters, including ion intensity, surface hydrophobicity and overall bacterial growth parameters, such as temperature and media ion concentration (Li & Logan 2004). In the aquatic environment for cations, anions, apolar compounds and other particles, the extracellular bacterial polymer (EPS) will act as a sieve in this interaction. The adhesive matrix catches or builds up the bacteria-contacted surface particles. The matrix traps hydraulic substances such as benzene, toluene and xylene, whereas in the cell wall of the bacteria accumulating polar heavy metal species (Flemming & Wingender 2010). Bacterial biosorption and chemical adsorption play a parallel role in all further biochemical processes in this relationship. Latest observations of species As (III) and As (V) removal using bioadsorption improved awareness of extracellular bacterial associations with arsenic (Altowayti et al. 2019a, 2020c; Giri et al. 2013; Prasad et al. 2011; Yan et al. 2010). While some analysis has shown that biofilms enhance the adsorption of As(V) (Prieto et al. 2013), further analysis indicates that arsenic is an electrostatic interaction with hydroxyl, amide and amino groups on the surface of the microorganism, and that interaction depends on initial concentration, pH temperature and dosage (Giri et al. 2013; Prasad et al. 2011; Yan et al. 2010).

Comparison of arsenic removal technologies

All the arsenic removal techniques listed above have advantages and disadvantages. The advantages of precipitation are a simple operation, applicability in a wide range of pH and cost efficiency (Mondal et al. 2013). However, they also have certain disadvantages, such as the need for arsenite preoxidation and high toxic sludge production (Ungureanu et al. 2015). In the removal of arsenic, membrane technology is found to be very efficient but they also have some disadvantages, such as very high capital costs, operational and maintenance costs and coexisting ion interference (Mohan et al. 2007). Compared to precipitation and membrane technology, adsorption approaches share the advantages of cheap, easy handling, low energy requirements and high arsenic recovery. Adsorption methods for the removal of arsenic may also be limited by their drawbacks (e.g. toxic solidified waste production, exposure to coexisting ion interference and solution pH dependence). However, the selection of appropriate arsenic adsorbents can overcome these disadvantages (Mondal et al. 2013). Table 11 displays several technologies for removing arsenic, along with their advantages and disadvantages.

Comparison of different adsorbents for arsenic removal efficiency

While most adsorbents have great arsenic removal capability, there is still a lack of uniform literature tests to enable direct comparisons between the different types of adsorbents. Therefore, the experimental results cannot be directly compared due to the different systemic experimental conditions (initial arsenic concentration, temperature, pH and adsorbents dosage) as shown in Table 12.

Conclusion

Arsenic removals by different technologies and adsorbents have attracted increasing attention in recent years. This review summarizes adsorption technologies and different mechanisms for most types of adsorbents that electrostatic attraction and van der Waals forces were the dominant driving force for arsenic adsorption between arsenic species and the efficacy components of adsorbents. Besides, this review outlines the effects and optimization of operating parameters on arsenic removal efficiency mainly initial arsenic concentration, temperature, pH and adsorbents dosage. In addition, the various adsorbents and technologies for arsenic removal and their potential negative environmental consequences

Table 11 Summary of main techniques used to remove arsenic

Removal method	Description	Method	Advantages	Disadvantages	References
Precipitation/ Encapsulation/Coagulants	Chemicals are used to extract dissolved contaminants into an insoluble material or other insoluble product into which dissolved contaminants are absorbed and the material is either clarified or purified out of the liquid method. Although, by turning the contaminants into less soluble, active, or toxic forms, encapsulation wraps or encloses contaminants within a stabilised mass and chemically reduces the hazard potential of waste	Natural Fe aeration-filtration Coagulation-filtration by Fe Electrocoagulation of electrodes of Fe or Al In the presence of oxygen, natural corrosion of Fe(0)	High capacity for removal of Arsenic over broad pH range During Fe(II) oxidation, partial to complete arsenite (+3) oxidation Partial oxidation of arsenite (+3) during fast filtration of the sand Higher seasonal arsenic concentrations can be controlled by increasing the coagulant dosage	Preoxidation of arsenite (+3) is required by dosing a strong oxidant that increases the cost of treatment Owing to competing ions, the efficiency of removal is decreased At high pH, the removal efficiency of arsenic is lower The production of laced sludge	(Ahmad 2020) (Chiavola et al. 2019) (Murthy et al. 2019) (Song et al. 2019)
Membrane Technologies	Separates pollutants from water by going through a semi-permeable barrier membrane, while blocking some, the membrane allows certain constituents to enter	Nanofiltration (NF) Reverse Osmosis (RO)	Performance of high arsenic removal Treatment of various unwanted pollutants together	High costs of capital and operations Generation of laced arsenic concentrate, which may also contain other high-concentration toxins	(Boussouga et al. 2020) (Aktar et al. 2019)
Adsorption	The waste was adsorbed on the surface of the sorbent and thereby decreased its concentration in the bulk liquid form. In general, the adsorption media is normally crammed into a column, and as polluted water flows into the column, the pollutants are eliminated	Geological materials with low cost Nanoparticles	Wide variety of adsorption technologies commercially available High efficiency of arsenic removal	To prevent bed clogging with suspended solids, pre-treatment for the removal of suspended solids is needed Competing ions decrease the efficiency of arsenic removal	(Maity et al. 2019) (Srivastava et al. 2019)
Biological Treatment	It requires the use of microorganisms that either extract waste or create environmental conditions that cause the contaminant to escape from the surface or precipitate / coprecipitate from the water	Uses bacteria to reduce soil and water contamination	Eco-friendly and Low cost occurs naturally by using bacteria that accumulate arsenic from the environment inside their cell or adsorbed arsenic to their cell wall;	Time-consuming process; ph affect the arsenic removal; microbes produce additional toxic materials with metabolic processes of bacteria	(Altowayti et al. 2020b)



Table 12 Comparative evaluation of different adsorbents for arsenic removal

Adsorbents	Adsorption conditions				Adsorption capacity		References
	Initial concentration	Temperature	pH	Dosage	As (III)	As (V)	
Modified natural manganese oxide ore	0.5 mg/L	25 ± 1 °C	7	0.2 g/L	–	0.11 mg/g	(Nguyen et al. 2020b)
Tungstate	50 mg As L ⁻¹	20 °C	3	0.8 g L ⁻¹	–	44 mg/g	(Sierra-Trejo et al. 2020)
Molybdate	50 mg As L ⁻¹	20 °C	3	0.8 g L ⁻¹	–	75 mg/g	(Sierra-Trejo et al. 2020)
Iron oxyhydroxides coupled with submerged microfiltration unit	190 µg/L	20 °C	8	100 mg/L	–	0.61 µg/mg	(Usman et al. 2020)
Fe-impregnated canola straw	5 mg/L	25 °C	3	1 g/L	–	5.5 mg/g	(Benis et al. 2020)
Ameliorated waste molasses nanoadsorbents	76.25 ppb	room temperature	9.5	37.75 g L ⁻¹	–	217.98 g L ⁻¹	(Baruah et al. 2020)
FeAl ₁₂ -polyoxocations intercalated nanobentonite	10 mg L ⁻¹	25 ± 1 °C	10	2 g L ⁻¹	–	121.3 mg L ⁻¹	(Barakan & Aghazadeh 2020)
Bone Char	100 µg/L	35 °C	5	0.1 g/40 mL	–	0.75	(Villela-Martínez et al. 2020)
Novel calcined modified hydrotalcite	15 min 600 µg/L	25 °C	9	0.5 g/L	–	72.7	(Türk et al. 2019)
Exploiting an autochthonous Delftia sp. BAs29 and neutralized red mud	30 min 100 mM	30	4	1.5 g/L	–	274.1 mg/g	(Biswas & Sarkar 2020)
Iron hydroxide/manganese dioxide doped straw activated carbon	20 mg L ⁻¹	30	3	1 g L ⁻¹	75.82 mg g ⁻¹	–	(Xiong et al. 2017)
Modified jute fibres	25 °C	25	3–8	10 mg L ⁻¹	12.66	–	(Hao et al. 2015)
Yttrium-based adsorbents	50 mg/L	25	7	1 g/L	–	206.5 mg/g	(Lee et al. 2015)
Magnetite nanoparticles	0.133 molAs	25	4	400 mg/L	667 µmol/g	600 µmol/g	(Roy et al. 2013)
Modified calcined bauxite	2 mg l ⁻¹	30	7.5	5 g l ⁻¹	–	1.37 mg g ⁻¹	(Bhakat et al. 2006)
Rice polish	100–1000 µg/L	20	7–4	20 g /L	0.139	0.147	(Ranjan et al. 2009b)
Arsenic-Hypertolerant <i>Bacillus cereus</i> Strain SZ2	80 µM	30	7	0.5 mg/mL	153.41 mg/g	–	(Bahari et al. 2013)
Pretreated biomass of psychrotolerant <i>Yersinia</i> sp. strain SOM-12D3	6.5 ppm	30 °C	7	0.5 g/L	159 mg/g	–	(Haris et al. 2018)
Biomass of arsenic resistant <i>Bacillus thuringiensis</i> strain WS3	6 ppm	37 °C	7	0.50 mg/ml	10.94 mg/g	–	(Altowayti et al. 2019a)
Mixed dried biomass of three different genera, <i>Bacillus thuringiensis</i> strain WS3, <i>Pseudomonas stutzeri</i> strain WS9 and <i>Micrococcus yunnanensis</i> strain WS11	As (III): 7.5 (ppm) As (V): 9 (ppm)	37 °C	7	0.60 mg/ml	11.92 mg/g	14.66 mg/g	(Altowayti et al. 2020c)

need to be addressed so that a significant and influential decision can be taken to limit health risks and increase the efficiency of arsenic removal. However, selecting the best system is challenging since all adsorbents and technologies have their own set of advantages and disadvantages. Thus, more environmentally friendly and long-term approaches are significant. As a result, sustainable treatment methods and an efficient way for improving arsenic removal from wastewater are approaches that do not generate secondary environmental contamination, consume less energy and are less cost-effective. Moreover, further research is required to determine the most appropriate adsorbents and technologies for arsenic removal efficiency under the same adsorption conditions.

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Declarations

Conflict of interest The authors declared that there is no conflict of interest.

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