Arsenic contaminated water remediation: a state-of-the-art review in synchrony with sustainable development goals

Sayan Bhattacharya[1*], Avishek Talukdar[2], Shubhalakshmi Sengupta[3], Tuyelee Das[4], Abhijit Dey[4], Kaushik Gupta[5], Nalok Dutta[6]

[1] School of Ecology and Environment Studies, Nalanda University, Bihar-803116, India.

[2] Department of Zoology, University of Calcutta, Kolkata –700019, West Bengal, India.

[3] Department of Chemistry, School of Applied Science and Humanities, Vignan's Foundation for Science, Technology and Research (VFSTR), deemed to be university, Andhra Pradesh-522213, AP, India.

[4] Department of Life Sciences, Presidency University, West Bengal-700073, India.

[5] Belur High School (H.S), Howrah, West Bengal, India.

[6] Biochemical Engineering Department, University College London, Gower Street, London WC1E 6BT, UK.

*Corresponding author, email: sbhattacharya@nalandauniv.edu.in, sayan.evs@gmail.com

Abstract. Arsenic (As) is a highly abundant metalloid with detrimental effects on ecosystems and human health. Several research works have focused on the development and application of suitable materials capable of removing arsenic effectively from water. In this regard, nano-materials have been given considerable importance due to their unique properties. In addition to nano-materials, single, multi and doped metal oxides have also received substantial attention because of their high surface-to-volume ratio, increased magnetic properties, catalytic properties, etc. These metal oxides have been developed using several methods like solid state reaction, vapour deposition, chemical precipitation, etc. among which chemical precipitation is quite user friendly. Single and mixed metal oxides have been applied widely in arsenic removal since they usually have high arsenic adsorption capacity. Several biomaterials including biochar showed promising results in arsenic removal from water. Desorption studies showed that NaOH, KOH were effective in regenerating the adsorbents from the nanomaterials. Graphene based materials usually show very high surface area due to their open structure, thus, they are effective materials in arsenic removal from water. Water treatment using nanomaterials can be one of the sustainable solutions and in synchrony with Goal 6 in UN Sustainable Development Goals (SDGs), which aims to ensure availability and sustainable water management and sanitation for the global population. Nevertheless, there is a significant research gap between the application of these nano-materials in laboratory settings and their real-world field conditions. Additionally, only a limited number of studies have investigated the potential effects of these nanomaterials on the environment and living organisms. However, by carefully selecting appropriate materials and conducting thorough environmental risk assessments, we can overcome these challenges and move towards successful implementation of long term arsenic remediation.

Keywords: Arsenic, Water, Adsorption, Desorption, Nanomaterials, Sustainable development goals (SDGs).

1. Introduction:

Arsenic, a toxic metalloid, has been utilized by human societies since ancient times. Unfortunately, its use has resulted in numerous cases of illness and even fatalities due to its toxic nature. Arsenic exposure occurs in humans through multiple routes, including ingestion of contaminated water, consumption of contaminated food, inhalation of arsenic in air particles, and contact with arsenic-contaminated soil (Mondal and Suzuki, 2002). In terms of abundance, arsenic is the 20th most found element in earth's crust. It is more abundant in seawater (14^{th}) and even more abundant in the human body (12^{th}) (Mondal and Suzuki, 2002). There are more than 200 naturally existing mineral forms of arsenic in the form of arsenates, sulphides, arsenides, sulfosalts, oxides, etc. (Bissen and Frimmel, 2003; Bhattacharya et al., 2012). Contamination of groundwater by arsenic is mainly reported from South Asian countries like China, India, Taiwan, etc. and several North and South American countries (Bhattacharya et al., 2012). In these countries, the situation of arsenic contamination is severe, with arsenic concentrations in specific regions exceeding the permissible limits prescribed by the World Health Organization (WHO) (WHO, 2001). Arsenic has bioaccumulated in the food chain as a result of contamination in irrigation water (Bhattacharya et al., 2012; Bhattacharya et al., 2021).

Numerous methods exist for arsenic removal and treating contaminated water, and their effectiveness largely depends on the chemical state in which arsenic is present in a particular area (Ray and Shipley, 2015, Alka et.,2021). Metals, metal oxides and nanoparticle-based materials are commercially available for arsenic removal. Some low-cost nanotubes, nanoparticle impregnated adsorbents, and other nanocomposites are also available commercially for use (Ray and Shipley, 2015; Bhattacharya et al., 2013; Bhattacharya et al., 2021; Maity et al., 2021; Türkmen et al., 2022). Arsenic removal from water and other environmental sources requires multiple separation processes and adsorbents. Membrane separation processes are regarded as viable alternatives for the removal of arsenic (Moreira et al., 2021). Adsorption is commonly utilized for removal, especially in economically poor countries. The use of natural, easily accessible adsorbents in diverse processes provides multiple benefits to impoverished countries, including cost-effectiveness, increased accessibility, and lower carbon dioxide emissions (Asere et al., 2019). Scientific research has examined several types of arsenic-removing adsorbents. Activated carbon can adsorb a wide range of pollutants, including arsenic, due to its large surface area and porosity (Zhang et al., 2007). Iron oxides, aluminium and hydroxides can also adsorb arsenic (Giles et al., 2011). Metal-organic frameworks (MOFs), which are porous and adjustable, can be optimized for arsenic removal (Wang et al., 2015). Zero-valent iron (ZVI) efficiently removes arsenic and converts it into less hazardous molecules (Mamindy-Pajany et al., 2011). Arsenic can be taken up by graphene-based adsorbents and their derivatives because they have a large surface area and are capable of adsorption (Tolkou et al., 2020). These adsorbents may reduce arsenic in water, improving water quality and human health.

Nanoscience is the study and application of materials at the nanoscale dimension (1-100 nm) (Rotello, 2003; Gregory, 2008). It involves the systematic development of two- or three-dimensional structures (nanomaterials) from molecular scale building blocks (Rosi and Mirkin, 2005). Nanoparticles (NPs) can be of two major types: engineered and non-engineered. Engineered nanoparticles can be synthesized in the laboratory conditions, with a general size range of 1-100 nm. and having quite different properties from the bulk material of similar composition (Auffan et al., 2009). NPs could be classified as carbon-based materials such as carbon nanotubes (SWNT, MWNT), graphene; inorganic nanoparticles and polymer nanocomposites (Mauter and Elimelech, 2008). Inorganic nanoparticles include pure metal oxides, quantum dots, mixed metal oxides and pure metals (Shah and Ahmed, 2011; Savage and Diallo, 2005). Different nanomaterials have diverse morphologies and shapes like tubes, thin films, spheres, rods, prisms, buds etc. The materials can execute various enhanced properties (catalytic, optical, electric, magnetic etc.) in the nanoscale range (Roco and Brainbridge, 2001). Researchers from different parts of the world have given considerable attention to these unusual and enhanced properties of nanomaterials. Government organizations and Industrial sectors are also giving attention and raising research funds to develop this prospective research area. Nanomaterials have diverse fields of application, including electronics, biosensors, pharmaceuticals, biomedicines, environmental monitoring tools, catalysis, cosmetics, agricultural products, optics and photography, sports, textiles etc (Schmid, 2004). Several factors are responsible for the development of special properties in the nanomaterials:

1. Size: Nanomaterials are nearly the molecular dimension that affects the mean free path of electrons or phonons, a coherency length, or screening length. These size factors control the electrical, optical, and magnetic properties of the materials.

2. Surface area: Due to their minuscule dimensions, nanomaterials usually have large surface area which makes them useful in the field of catalysis.

3. Structural defects: Different types of structural defects in the nanocrystals control the properties of the materials (Khan et al., 2019).

However, such factors predominate in nanocrystals containing different atoms or molecules from several phases rather than single-phase nanocrystalline materials.

Several methods are available for the synthesis of size-regulated and well-defined nanomaterials, though the synthesis processes are not easy for standardization and execution (Shah and Ahmed, 2011; Savage and Diallo, 2005); many of these techniques are low-yielding. Researchers have made several modifications to the techniques to increase the production of materials, making them more applicable in field conditions. Nanomaterials possess various properties, such as a large surface-to-volume ratio, high catalytic potential, self-assembly ability, and high reactivity. These unique attributes make nanomaterials suitable for pollution control and environmental protection measures, as they offer promising capabilities to safeguard the environment (Bhattacharya et al., 2013).

Several papers have been published previously which demonstrated the applications of novel materials in arsenic treatment. However, the present article brings the holistic view of arsenic remediation by including both the conventional and recent technologies, including the cutting-edge techniques which have emerging very recently, highlighting their usefulness and economic feasibility in application. The paper has an objective to show the gradual development in arsenic mitigation technologies, their comparative performances and how these approaches are synchronized with some of the sustainable development goals (SDGs). Among all other reviews published in recent times, this paper, for the first time, established the connections between arsenic mitigation and SDGs.

2. Conventional arsenic removal technologies:

Several technologies are available for treating drinking water with arsenic contamination which have been tested both under laboratory and field conditions. The chemical form in which arsenic exists in water is an important factor that needs to be considered before water treatment (Singh et al., 2015a). Since arsenite (As^{+3}) is uncharged at pH below 9.2, most of the available technologies are efficient in removing arsenate (As^{+5}) (Johnston and Heijnen, 2015). Some commonly used techniques for arsenic removal are (i) oxidation followed by precipitation, (ii) ion exchange, (iii) coagulation/electrocoagulation/co-precipitation, (iv) membrane technique and (v) adsorption onto sorbtive media (Nicomel et al., 2016; Ghosh (Nath) et al., 2019; Yadav et al., 2021).

2.1. Oxidation followed by precipitation

This method is a simple, low-cost process of *in situ* removal of arsenic (Mohan and Pittman, 2007, Samuel et al., 2022). Since arsenic is mostly present as arsenite near neutral pH, oxidation is an important step in remediation. The oxidizing agents may be oxygen, ozone, free chlorine, hypochlorite, permanganate, and Fenton's reagent (Mohan and Pittman, 2007; Nicomel et al., 2016). An important factor that needs special consideration before the selection of an appropriate oxidant is the presence of other interfering substance/s which have an influence on the kinetics of As(III). The oxidation process, particularly of drinking water, may be problematic due to t chemical residue of oxidant, by-product formation from oxidation of the organic and inorganic matters present in water, and operational complication (efficient control of pH and oxidation step). Therefore, oxidants should be selected carefully to remove arsenic efficiently from a solution by oxidation (Nicomel et al., 2016).

2.2. Ion exchange

In this physiochemical method, an equivalent number of ions from the aqueous substrate are exchanged for solid-phase ions (Paul and Sarkar, 2016). The ion exchange process generally extracts arsenite from water, not arsenate (Jadhav et al., 2015). Efficacy of arsenic removal in ion-exchange process is hindered by dissolved salts (Jadhav et al., 2015), competitive ions (Litter et al., 2010), concentration of arsenic, and high sulfate (salts) (Sarkar and Paul, 2016). Ion exchange resins are cross-linked polymer matrix to which charged functional groups (carboxylate, sulphonate, tertiary or quaternary amines) are attached by covalent bonding. Anion exchange resins are categorized into two types: strong base and weak base, depending on the adhered functional groups. Strong base anion exchange resins are quite effective over a wide range of pH. On the other hand, weak base anion exchange resins function in acidic range. Several factors influence ion exchange among which pH, resin type, arsenic concentration and other competing ions are the major determinants (Paul and Sarkar, 2016). The metal-loaded resins are more efficient in arsenic removal (Dambies, 2005). Costly resins, costly and skilled operation, higher maintenance cost and disposal of toxic wastes are some of the drawbacks of this method (Mohan and Pittman, 2007). The removal of arsenic from potable water by ion exchange resin was reported by Karakurt

(2019). Arsenic remediation below the permissible limit was achieved using Hybrid Ion Exchange/Electrodialysis (IXED) method (Ortega et al., 2017), similarly, Rivero et al. (2018) also conducted the same for arsenate ion removal using a laboratory scale IXED found satisfactory results. Dong (2019) reported about a Hybrid Ion Exchange Process (HIX-CO_2) which can remove contaminants from brackish water without the requirement of a semi-permeable membrane.

2.3. Coagulation/ electrocoagulation/co-precipitation

Coagulation and precipitation (by chemical processes) and filtration (by physical processes) are very cost-effective and user-friendly. Iron salts and aluminum sulphate have been commonly used for coagulating arsenic. Treatment of water using alum and ferric salts can remove arsenic effectively from contaminated water (Bissen and Frimmel, 2003). However, both ferric and alum are more efficient in As(V) removal than over a wide range of pH. Removal efficiency is strongly dependent on the solution pH, not on the coagulant dosage or initial As(V) concentration. In case of As(III), the removal is independent of solution pH and strongly dependent on the coagulant dosage and As(III) concentration (Happer and Kingham, 1992). Ferric chloride has been found to be the most effective arsenic coagulant. Though it is an efficient method for arsenic removal, this method suffers from the problem of sludge disposal and dose control in rural condition are extremely difficult. Additionally, this method enhances total dissolved solids plus anions like chloride in treated water. Alum coagulation has also other implications like the production of toxic sludge, low removal of arsenic, and requirement of pre-oxidation (Mohan and Pittman, 2007; Samuel et al., 2022).

Electrocoagulation (EC) involves complicated and interdependent mechanisms with compact treatment facility, complete automation, and high-efficiency removals, though it possesses some pitfalls like electrode passivation, EC reactor design optimization, and huge power consumption (Mohora et al. 2018) but can remove both arsenate and arsenite with efficiency in the range 93-99.9% (Demirbas et al., 2019). Metals like iron, aluminum, titanium can be used for As removal by electrocoagulation (Kumar et al., 2004). Various authors reported complete arsenic remediation by the EC process (Ucar et al., 2013; Vasudevan et al., 2010a) also removal of arsenite can be achieved by oxidizing to arsenate through EC method (Ratna Kumar et al., 2004). Adding an oxidant like hypochlorite oxidizes arsenite to arsenate which improves the efficiency of EC process (Flores et al., 2013). With the progression of time the EC process can rapidly remove As contamination owing to floc formation (Ratna Kumar et al. 2004). Recently, an alternative technique called Metal-Air Fuel Cell EC (MAFCEC) was proposed to resolve various drawbacks relating to high energy requirement in conventional EC process (Kobya et al., 2020; Maitlo et al., 2019), the integration of air-fuel cell with EC cycle is a fruitful way for As remediation without electricity requirement (Kobya et al., 2020; Maitlo et al., 2019).

2.4. Membrane technique

Membrane techniques, including ultra-filtration, nano-filtration (NF), reverse osmosis (RO), and electro-dialysis can remove various contaminants dissolved in water, including arsenic (Wiesner, 1993). Membrane technology is popularly regarded as the most effective technology for arsenic removal with efficiency around 96%. The membrane operational requirements are negligible, and no chemical is required (Ungureanu et al., 2015). Factors that significantly affect membrane performance are pore size and their distribution, surface charge, degree of hydrophilicity, flow of solution and presence of any functional groups (Abdullah et al., 2019). Generally, it was seen that As(V) removal is more effective than As(III). RO and NF remove As(V) with 91-99% efficiency, however, in case of As(III) only

20-55% removal efficiency is observed. Membrane techniques have high efficiency in diverse contaminant removal (including arsenic) without producing any harmful solid wastes during the process. However, the techniques are of high cost and consume considerable time for functioning (Mohan and Pittman, 2007; Samuel et al., 2022). Of all the processes employed for arsenic remediation from water viz. microfiltration, nanofiltration, ultra-filtration and reverse osmosis, nanofiltration and reverse osmosis are the most promising (Figoli et al., 2016). Membrane distillation (MD) is also an efficient process for the remediation of arsenic-contaminated water. The partial pressure developed over the hydrophobic microporous membrane facilitates the removal of water vapour and volatiles leaving the impurities below, for example, Arsenic (Criscuoli and Figoli, 2019). An adsorptive membrane was developed by membrane support layer modification by Fe_3O_4 microspheres immobilization through reverse filtration followed by dopamine polymerization, which showed higher arsenic adsorption capacity compared to virgin and blended membranes (Zhang et al. 2018).

2.5. Adsorption method

Adsorption technology has advantages over other methods and is widely accepted by different researchers across the world. This method can remove various contaminants from water including heavy metals and offers some advantages like high removal efficiency, low energy and technical requirement, and minimal chances of secondary pollution (Burakov et al., 2018). Absorbent should possess some desired characteristics like a larger specific surface area, high mechanical strength, greater thermal stability, environmental friendliness, controlled morphology, and easy processing, which would result in greater performance in terms of adsorption capacity and efficiency, selectivity, cheap cost, and reusability. This method can be applied conveniently in low-income countries because of its cost effectiveness (Bhattacharya et al., 2012).

pH is an important factor for arsenic adsorption. As(V) removal is more efficient than As(III) at pH below 7 (Grafe et al., 2001; Wilkie and Hering, 1996; Zhu et al., 2013; Raven et al., 1998). Competing ions are also a limiting factor as they have competition with arsenic for accessing the adsorption sites (e.g. phosphate, silicate, HCO_3 and Ca^{2+}) (Zhu et al., 2013; Kanematsu et al., 2013; Giles et al., 2011).

Adsorption by carbon: Temperature, ionic strength, pH and activated carbon influence the adsorption efficiency of materials (Mohan and Pittman, 2007; Samuel et al., 2022). Commercially available activated carbons are reported to adsorb up to 2860 mg/g in the case of commercial coal-derived carbon (Navarro and Alguacil, 2002; Lorenzen et al., 1995). Both As(III) and As(V) are adsorbed by activated carbon at different pH although the two forms may be adsorbed differently (Eguez and Cho, 1987). Activated carbon having a high amount of ash is more effective in As(V) removal (Navarro and Alguacil, 2002; Lorenzen et al., 1995). Recent research focused on the use of iron oxide and activated carbon composites which showed an adsorption efficiency of 95% for arsenic. This is achieved due to the magnetic properties of iron and the adsorption properties of activated carbon (Gallios et al., 2017; Yao et al., 2014).

Adsorption by inorganic materials and biomaterials: Because of their biocompatible and environment-friendly nature, bio-composites are considered useful materials in arsenic removal from contaminated water. Composite materials are composed of matrix and activated components (Samuel et al., 2022).

In certain cases, agricultural waste and its byproducts like rice husk have been reported to be used for arsenic adsorption (Asif and Chen, 2017; Amin et al., 2006; Pillai et al., 2020).

Inexpensive agricultural waste when used for removing arsenite from contaminated water showed good adsorption capacities (Mohan et al. 2019). Similarly industrial wastes like coals and chars have also been utilized (Allen et al., 1997, Sharma et al., 2022). Char from different plant species shows differential adsorption of arsenic with pine bark char showing maximum efficiency (Mohan et al., 2007). Compared to non-loaded biochar, the birnessite biochar has the potential to enhance arsenic adsorption in soil and water (Zhu et al., 2019). Interestingly, red mud also exhibits arsenic adsorption properties with favorable As(III) removal at high pH and As(V) removal at acidic pH (Wu et al., 2017; Altundoan et al., 2002). Treated and coated sands have also been used for removing arsenic (Devikarani et al., 2006). Coated sand with iron oxide is highly efficient in arsenic adsorption. Further modification by sulfate enhances its property to adsorb both As(III) and As(V) at alkaline and acidic pH respectively (Devi et al., 2014; Vaishya and Gupta, 2003). Both natural as well as synthetic zeolites also display As(III) and As(V) adsorption properties (Chutia et al., 2009; Khatamian et al., 2017). Hydrous iron (III) oxide incorporated with calcium ion shows 90% arsenite removal efficiency and this occurs through a chelation mechanism (Ghosh et al., 2019). An Adsorption-Ultrafiltration (UF) process was applied based on arsenic-spiked water by Hao et al. (2018), the resulting adsorbent after six adsorption-regeneration cycles retained extremely high adsorption using the combined adsorption-UF method with a 10 wt percent NaOH and NaCl eluant.

Researchers also studied the adsorption of arsenic from water by applying eucalyptus bark fibers (hybrid of *Eucalyptus urophylla* and *E. grandis*) and aquatic macrophyte leaves. Treated eucalyptus bark has good efficiency in adsorption of arsenic anions, and can be considered as a promising, cost effective and ecologically sustainable material in arsenic removal (Guisela et al., 2022).

In recent researches, fly ash was collected from several coal power stations and its arsenic removal capacity from contaminated water was studied. Lignite based fly ash showed higher efficiency in arsenic removal at pH 4.0 compared to pH 7.0. The maple wood ash adsorbent was efficient in remediating more than 80% arsenic in dynamic column experiments (Samuel et al., 2022).

However, due to issues related to permeability, stiffness, thermal stability, crystallinity and processing issues, these compounds cannot be applied effectively in some cases. Further research is required to increase the efficiency of bio-composites in heavy metals and arsenic removal from contaminated wastewater (Samuel et al., 2022).

The arsenic sorption mechanism on bioadsorbent is shown in figure 1. Possible chemical interactions like electrostatic interaction, hydrogen bonding, chelation, surface oxidation, ion exchange, precipitation etc. are shown on the surface of the bioadsorbent.

Adsorption by metal oxides: Metal oxides can adsorb both As(III) and As(V) from contaminated water (Min et al., 2009; Violante et al., 2009; Wen et al., 2014; Yamani et al., 2012). Manganese dioxide (MnO_2) can oxidize As(III). This also leads to MnO_2 surface alteration resulting in higher adsorption of As(V) (Wen et al., 2014; Manning et al., 2002). Similarly, titanium dioxide can oxidize As(III) to As(V) (Lata and Samadder, 2016; Nicomel et al., 2015). Iron oxides as discussed previously are similarly very effective in adsorbing both As(III) and As(V) at different pH (Guo and Chen, 2005; Wang et al., 2015; Basu et al., 2015). Several factors determine the efficiency of arsenic adsorption. For example, goethite nanoparticles adsorb As(V) maximally at pH 3.0. The pattern of adsorption was monolayer, as evidenced by the Langmuir isotherm equation. An adsorbent dose of 6g L^{-1} in 50mg L^{-1} As(V) containing solution removed 99% As(V) (Ghosh et al., 2012). Amorphous FeO(OH) has a high surface area resulting in its high adsorption capacity (Li et al., 2017). Cai et al

(2022) reported the removal of As(III) by iron-manganese composite coupled with sulfite (FeMnOx/S(IV)). Almost all of As(III) was oxidized to As(V) in a 10 minutes time frame. Recently an iron/olivine hybrid was employed for arsenic adsorption, together with an artificial neural network and surface response approach (Ghosal et al. 2018). Calcined polyvinyl alcohol and sodium alginate present in alum sludge was also employed column studies, batch-test capabilities and adsorption kinetics for enhancing arsenic remediation kinetics (Kang et al., 2019).

Adsorption by activated alumina: The large surface area of activated alumina (AA) due to its micro and macro pores makes it a suitable material for arsenic adsorption (Singh and Pant, 2004; Das et al., 2013). As(V) adsorption is quite effective at a pH range of 6-8 on positively charged AA. Manganese oxide or ferric hydroxide modification of AA surface further enhances AA adsorption efficiency (Lescano et al., 2015; Maliyekkal et al., 2009).

The high iron content of groundwater is a major setback to the adsorption method since it clogs the filters and reduces its lifespan (AIIH, 2001).

3. Synthesis and applications of nanostructured materials in arsenic removal:

Nanoparticles (NPs) and nanocomposites are more efficient in removing arsenic in comparison to micro sized materials (Lata and Samadder, 2016). The synthesis and applications of nanostructured materials in arsenic removal have gained significant attention in recent years. Nanostructured materials, characterized by their unique properties at the nanoscale, offer enhanced surface areas, high reactivity, and improved adsorption capacities, making them promising candidates for efficient arsenic removal from water sources.

The synthesis of nanostructured materials for arsenic removal involves various methods, such as sol-gel, hydrothermal, co-precipitation, and chemical vapor deposition. These techniques allow precise control over the size, shape, and composition of the nanomaterials, enabling the tailoring of their properties to suit specific arsenic removal requirements.

Some common nanostructured materials used for arsenic removal include:

1. Metal Oxide Nanoparticles: Metal oxides such as iron oxide (Fe_3O_4), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3) nanoparticles have shown excellent arsenic adsorption capabilities due to their high surface area and surface reactivity.

2. Carbon-Based Nanomaterials: Carbon nanotubes (CNTs) and graphene oxide (GO) have been explored for arsenic removal due to their large surface area and strong adsorption interactions with arsenic species.

3. Nanocomposites: Hybrid materials, such as metal oxide-graphene composites, have demonstrated synergistic effects in arsenic removal, combining the advantages of both components.

4. Biomaterials: Several adsorptive materials derived and developed from biological materials (including biochar) are cost-effective materials useful in arsenic removal from water.

The applications of nanostructured materials in arsenic removal include both batch experiments in laboratory settings and continuous flow systems in field conditions. Some advantages of using nanostructured materials for arsenic removal include higher removal efficiencies, rapid kinetics, and the potential for regeneration and reusability.

However, challenges remain in implementing these nanomaterials on a larger scale. Issues such as material stability, cost-effectiveness, and potential environmental impacts require further investigation. Moreover, careful consideration of the risks and benefits associated with nanotechnology in arsenic removal is essential to ensure safe and sustainable applications. Research efforts are ongoing to bridge the gap between laboratory-scale success and real-world field conditions, bringing these promising nanostructured materials closer to practical and effective arsenic removal solutions. As discussed earlier, nanoparticles have a have a high surface to volume ratio with other special properties of high catalytic efficency, reactivity, etc. (Qu et al., 2013; Hristovski et al., 2007) which makes them suitable materials of choice as adsorbants (Mohan and Pittman, 2007; Nicomel et al., 2016; Bhattacharya et al., 2013).

3.1. Metal-based nanomaterials: Several metal-based nanomaterials were synthesized and tested for their efficiency by different researchers and many of them were found to be useful in arsenic remediation. Hydrated Cerium Oxide nanoparticle was synthesized by precipitation method and applied for arsenic sorption study (Li et al., 2012). A kinetic study using the adsorbent showed that 87% As(III) and 83% As(V) were removed from the solution in the first 30 minutes of contact time. It was found that the adsorbent was highly effective in arsenic removal even at very low concentrations. α and δ- phase manganese dioxide nano-adsorbents were synthesized and studied for their As(V) adsorption behavior (Singh et al., 2010). α-MnO_2 nanosphere having diameter within the range 1-3μm was synthesized by the process of catalytic oxidation of Mn(II) acetate (Zhang and Sun, 2013). The maximum monolayer As(V) sorption capacity of the adsorbent was 14.5mg/g. 56% of adsorbed As(V) was desorbed with 1mol/L NaOH solution. As(V) sorption on the adsorbent surface took place by inner-sphere surface complex formation. The MnO_2 sphere could be effectively recovered by the microfiltration process and reused (Zhang and Sun, 2013).

Hierarchical nanostructure CuO had been synthesized and high arsenic adsorption capacity was found (Cao et al., 2007). The mono-layer As(III) sorption capacity was 5.7 mg/g. The CuO adsorbent could be successfully regenerated by rinsing the material with arsenic-free water and could be reused for arsenic sorption. CuO nanoparticles were synthesized and arsenic removal from groundwater was studied (Martinson and Reddy 2009). Arsenic adsorption happened in a short period of time and CuO nanoparticles were able to remove both As(III) and As(V) efficiently between pH 6 and 10, having a maximum adsorption capacity was 26.9 mg/g and 22.6 mg/g for As(III) and As(V) respectively (Martinson and Reddy 2009). Cylindrical shape CuO nanoparticles were efficient in arsenic removal from groundwater samples containing different ions like silicate, sulphate, phosphate, nitrate etc (Martinson and Reddy 2009). The adsorbent could be regenerated by using NaOH (Reddy et al., 2013).

A novel photo-oxidation and adsorption-based $CuO-Fe_3O_4$ magnetic material has been synthesized for As(III) removal. Under light irradiation, The nanoparticles are able to oxidize As(III) to As(V) completely through photo-oxidation within 60 minutes (Sun et al., 2017). Subsequently As(V) is adsorbed on the nanoparticles efficiently. Figure 2 shows the synthesis pathway of novel photo-oxidation and adsorption based $CuO-Fe_3O_4$ magnetic material for As(III) removal.

3.2. Mixed oxide and multi-metal nanomaterials: Nano-agglomerates of mixed oxides like iron-titanium, iron-chromium, iron-cerium, iron-manganese, iron-zirconium, cerium-aluminium, cerium-manganese etc. have been applied to remove arsenic from contaminated groundwater (Mohan and Pittman, 2007; Bhattacharya et al., 2013; Zhang et al., 2007; Gupta et al., 2011; Gupta et al., 2012). The characterization of these oxides was done using a transmission electron microscope (TEM), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscope (SEM), X-ray powder diffraction (XRD), and BET surface area analysis. The thermodynamic properties for sorption, the effect of pH and sorption kinetics of these materials have also been studied (Stanić, M.H., Nujić, 2015). Gupta et al. synthesized and characterized ceria-associated manganese oxide nanoparticles. TEM images of the nanoparticles showed garland-like chain structure with void space, with varied particle sizes of 70-90 nm. and 15-20 nm. in two different samples (figure 3). SEM images showed that the particles were interconnected in a sheet-like structure (figure 4). Cerium manganese nanoparticles demonstrated their efficiency in arsenic (V) adsorption (Gupta et al., 2011).

Multi-metal oxide nanomaterials were synthesized and studied for arsenic remediation. Several experiments proved that multi-metal oxides have greater sorption capacity than individual metal oxides. The underlying reason may be due to the increase of surface energy, number of active sites per unit volume, surface area etc. In many studies, multivalent metal oxides show magnetic properties which make the separation process easier during the sorption process. Several nanostructured binary metal oxides like iron-titanium, iron-zirconium, iron-manganese and cerium-manganese mixed oxides were synthesized, characterized and applied for arsenic removal from groundwater (Gupta et al., 2008; Gupta et al., 2009; Gupta and Ghosh, 2009; Gupta et al., 2010; Gupta et al., 2011; Gupta et al., 2012). All of these metal oxides executed very high capacity of arsenic removal (> 90%) in both As(III) and As(V). Desorption studies showed that NaOH and KOH were effective in regenerating the adsorbents. Nanostructured Fe(III)-Cu(II) binary oxide was synthesized by a simple precipitation method and was applied for arsenic removal (Zhang et al., 2013). The effect of solution pH showed that the material could be effectively used within the pH range 6.5-8.5 for the removal of both forms of arsenic. The adsorbent could be regenerated by NaOH application. Micro and nano multi-functional polymeric adsorbents doped with bimetals like Fe, Al was synthesized and studied for arsenic removal from contaminated water. As(V) sorption capacity of these materials was found to be very high (40 mg/g). Several metal oxide nanomaterials had been utilized in fixed bed columns for arsenic sorption from groundwater. All the nanomaterials showed very high As(V) adsorption (Mohan and Pittman, 2007; Kumar et al., 2011; Bhattacharya et al., 2013).

A synergistic approach of molecular imprinting and metal–organic ligand chemistry was applied for synthesizing a new polymer-based nano-adsorbent specific for As(V). The imprinted polymer with nanopores (nano MIP) displayed high arsenic adsorption capacity with an efficiency of 98%. Washing with 0.1 M HNO_3 solution regenerated the material, leading to its reuse for up to 10 consecutive cycles (Mankar et al., 2020).

Combustion synthesis of iron oxide/iron-coated carbons like As activated carbon, cellulose fibre, anthracite, and silica are also efficient nano-materials in arsenic sorption (Hristovski et al., 2019). Alumina crucibles are applied for performing chemical reactions. The arsenic removal percentage varied between 25.8%-96.7% for different samples (Hristovski et al., 2019).

3.3. Iron-based nanomaterials: Iron-based compounds and its oxides and hydroxides have been successfully used for arsenic removal. Various forms of iron used for the purpose include goethite, hematite, iron-based LDHs, iron nanoparticles, activated carbon doped with iron, mineral oxides doped with iron, etc. (Maity et al., 2021). Due to the existence of unpaired electrons in Fe(II) and Fe(III), their oxides exhibit magnetic behaviour, this property is exploited for the remediation of arsenic from water. Various iron oxide derivatives like magnetite (Fe_3O_4), hematite (α-Fe_2O_3), maghemite (γ-Fe_2O_3), goethite (α-FeOOH), and amorphous hydrous ferric oxide (Fe(O)-OH) assist in Arsenic remediation (Bach et al., 2010; Cornell and Schwertmann, 2003).

High-gradient magnetic separation (HGMS) is a useful method to separate iron nanoparticles from other solutions like water (Yeap et al., 2017). Additionally, the high surface-to-volume ratio, ease of surface modifications as per need, and low toxicity make iron nanoparticles and their derivatives a material of choice for arsenic removal (Mohmood et al., 2013). Iron compounds like maghemite (γ-Fe_2O_3), hematite (α-Fe_2O_3), goethite (α-FeOOH), ferrihydrite ($Fe_5HO_8 \cdot 4H_2O$), akaganeite (β-FeOOH) and lepidocrocite (δ-FeOOH) are widely used for arsenic remediation. All these materials have a low leaching property (Ghanizadeh et al., 2010; Feng et al., 2012; Nassar, 2012).

Magnetite nano-particles were synthesized by different researchers and used for the purpose of both As(III) and As(V) removal (Khodabakhshi et al., 2011; Yavuz et al., 2010; Mayo et al., 2007; Yavuz et al., 2006; Yean et al., 2005; Chowdhury and Yanful, 2011). Magnetite nano-particles can be separated from the liquid phase after adsorption by the application of an external magnetic field column separator. The percentages of As(III) and As(V) removal depend on the size of the particles. Nanosized Hydrated Ferric Oxide (HFO)-Loaded Polymeric hybrid sorbents were synthesized for arsenate removal (Zhang et al., 2008). The sorbents were very efficient in removing arsenic in the column experiment. A mixture of 4% NaCl and 8% NaOH was used to regenerate the sorbent (Zhang et al., 2008). Many researchers reported that nano-sized iron oxide is much more efficient in arsenic removal than micro sized iron oxide (Raven et al., 1998; Siddiqui and Chaudhry, 2017a, b; Mayo et al., 2007). Tang et al. (2011) used a solvent thermal technique to create sphere-shaped ultrafine iron oxide, α-Fe_2O_3 NPs having size of 5 nm. On particle aggregation, a highly porous structure with a large surface area was formed, where the surfaces of the NPs were coated by hydroxyl groups, which aided in the removal of arsenic. Fe_2O_3 NPs (90 mm) can remediate 60–80% of As(III) from contaminated water (Prasad et al., 2011) having 1.94mg/g of highest monolayer removal success. Iron oxy hydroxide NPs having highly porous structure (δ-FeOOH) showed efficiency for arsenic remediation, with a size of 20 nm, surface area of 135 m2/g, pore diameters of 18 nm, and zero charge potential of 8.4 (Faria et al., 2014) with highest adsorption capacity in non-ideal monolayer formation was found to be 37.3 mg/g. However, arsenic (AsIII and AsV) decreased to 50% from 90% under anoxic conditions. Liu et al. (2016a) used graphene-like super paramagnetic **γ**- Fe_2O_3 nano sheets, reported adsorption of 100 and 39 mg/g for As(III) and As(V) respectively. Ferrihydrite particles of nano sized have potential to become suitable absorptive substance. Similarly, naturally occurring iron oxide minerals like α- Fe_2O_3, Fe_3O_4, α-FeOOH and iron-rich laterite soil have been utilised to remediate arsenic at pH levels ranging from 4 to 11 (Aredes et al., 2012), with efficiencies in the order α-FeOOH > Fe_3O_4 > α-Fe_2O_3. Raul et al., (2014) used non-magnetic polycrystalline iron oxide hydroxide NPs for remediation of As(III) contamination in drinking water with highest removal efficiency of 475 µg/g for As(III). Various report findings indicating that granular $Fe(OH)_3$ offers promise in the field of arsenic water remediation, Badruzzaman et al. (2004), Banerjee et al. (2008), and Westerhoff et al. (2005) found that it has a substantial removal capability of granular $Fe(OH)_3$ for arsenic. In both natural waters and model systems, GFH has a high potential for adsorption (Hassan, 2023). Other iron oxides, such as akaganeite, feroxyhyte, and lepidocrocite, had also been studied for arsenic removal from water. Because akaganeite has a larger surface area than α-FeOOH and ferrihydrite and a hollandite-like crystal structure with a tunnel, it has a higher adsorption capacity than α-FeOOH and ferrihydrite. Kolbe et al. (2011) calculated akaganeite's maximal adsorption capacities for As(III) and As(V) to be 45.5 and 108.3 mg/g, respectively.

Amine-rich Fe_3O_4/bacterial cellulose nano□composite (BC@MH nano-composite) was able to remediate 90 mg/g of As(V) from water (Nata et al., 2011). FeO_x composite can remove 10 and 12.5 mg/g, of As(III) and As(V), respectively (Thakkar et al., 2015). Iron-oxide nano-composite (CINs) modified with Chitosan can remove 267.2 mg/g of As(III) at pH 6.0 from water (Gerard et al., 2016). Electro spun polyacrylonitrile modified super paramagnetic iron oxide NPs (SPION) were developed which were used for As(V) ions removal from water (Morillo et al., 2016). Batch studies with porous charred granulated attapulgite-supported hydrated iron oxide showed maximum As(III) and As(V) removal capacity of 3.25 and 5.09 mg/g respectively (Yin et al., 2017). More recently, mercaptobenzothiazole (MBT)- functionalized SiO2@Fe_3O_4 nano-composite have shown 93% As(V) remediation under optimum conditions (Sheikhmohammadi et al., 2018). Other nano composites that have demonstrated intense affinity towards arsenic having higher capacity for adsorption and are easily separable includes γ-Fe_2O_3/SBA-15 nano-composite (Peng et al., 2018), manganese iron oxide ($MnFe_2O_4$) (Qi et al., 2018), and Fe_3O_4-ZIF-8 core-shell composites (Huo et al., 2018), calcium-based magnetic biochar (Ca-MBC) (Wu et al., 2018b). Yttrium-doped iron oxide magnetic adsorbent was found to have maximum adsorption capacity of 170.48 and 84.22 mg/g for As(III) and As(V) respectively (Yu et al., 2018). clay-activated carbon composite beads modified by iron oxide have been found to be efficient for arsenic remediation (Pawar et al., 2018).

3.4. Nanostructured alumina: Arsenate sorption on nano active alumina was reported by X.H. Guan and co-workers (Guan et al., 2009). The average particle size of the material was 2.99 nm., with a specific surface area of 359 m^2/g. Effect of initial solution pH study on As(V) sorption showed that the sorption capacity depends on the initial loading of arsenic. W. Li also reported an arsenic sorption study of highly ordered mesoporous alumina (Li et al., 2011). The team synthesized different alumina samples having pore sizes ranging from 3.8 nm. to 6.6 nm. The mesoporous alumina has a wide pH range at which it can remove arsenate ions (pH 4-9). The material showed arsenate and arsenite sorption capacity of 19.8 mg/g and 5.0 mg/g respectively at low concentration range. Mesoporous γ-Al_2O_3 sized between 2–10 nm showed excellent results when employed for removal of arsenic from water (Patra et al., 2012). Various types of activated nonporous alumina with large surface area (200-300 m^2/g) are used for arsenic remediation; the large surface area increases the sorption sites. Recently Prabhakar and Samadder (2018) constructed a cheaper Al_2O_3 NP and observed an adsorption capacity of 500 µg/g at 25 ◦C. Alumina supported iron nanoparticles was reported to totally remediate As(III) from water at optimal concentrations (Jain and Agarwal 2017), having maximum adsorption capacity of 15.50 mg/g.

3.5. Nanoscale zerovalent iron: Zerovalent iron (nZVI) has the ability to adsorb several toxic metals which includes arsenic. Due to its high capacity of adsorption, nZVI is a good material of choice for treating arsenic-contaminated water (Li et al., 2006; Morgada et al., 2009). nZVI has greater efficiency to adsorb arsenic in comparison to sorptive media and granular iron particles (Li et al., 2006). A combination of ZVI with potassium permanganate and ferrous ions (Fe(II)-$KMnO_4$-ZVI) is highly efficient and is able to remove toxic As (III) at a broad pH range and concentration (20-100 mg/L) (Deng et al., 2017). However, the mechanism associated with nZVI immobilization is unclear. Arsenic removal by nZVI involves surface precipitation, reduction, adsorption, co-precipitation with different iron corrosion products like ferric/ferrous oxides and hydroxides (Mak et al., 2009).

Recently, green routes have been followed for synthesizing low cost nZVI. Leaf extracts of cherry, mulberry and oak have been used for the preparation of nZVI (Sofija et al., 2016). During green synthesis of zZVI, as reducing agents, extracts of *Vaccinium corymbosum* leaves and shoots have been used (Cerda et al., 2017). However, green nZVI is less efficient than chemically synthesized nZVI.

Now-a-days nanoscale zero valent iron (NZVI) is successfully used to remediate contaminants due to their low cost and high remediation efficiency. Due to the low particle size and high surface area of very low amount of NZVI can effectively and safely remediate arsenic (AsIII) from water (Rahmani et al. 2011). NZVI is also successful in removing As(V) in acidic environment (Visanu et al. 2011). Presence of phosphate (PO_4^{3-}), Bicarbonate (HCO^{3-}) and Humic Acid (HA) inhibits AS(III) remediation by NZVI while Chloride (Cl^-) and Calcium (Ca^{2+}) enhances AS(III) remediation, Chloride (Cl^-) and Bicarbonate (HCO^{3-}) slightly affects removal of As(V) (Haoran et al., 2012). 100% arsenic removal was achieved from smelting wastewater using NZVI with average removal capacity of 239 mg/g (Li et al., 2014a). Li et al. (2017b) obtained 100% As(III) concentration reduction. Plant leaf extracts have been used to manufacture NZVI for cost reduction (Sofija et al., 2016), which showed good results (Adio et al. 2017). But, green NZVI are slower than chemically synthesised NZVI (green NZVI optimum time 120 min against 60 min of chemical NZVI) though the performance can be improved by addition of oxidants in the solution like persulfate (PS), peroxymonosulfate (PMS) and hydrogen peroxide (HP) for As(III) removal (Kang et al., 2018).

Recently, a nanoscale polyaniline/Fe0 composite was developed which showed As(III) and As(V) ions removal capacities of 232.5 mg/g and 227.3 mg/g, respectively (Bhaumik et al., 2015). The montmorillonite-supported core-shell Fe(0) nanostructured composite showed maximum adsorption capacity of 59.9 and 45.5 mg/g, for As(III) and As(V), respectively (Bhowmick et al. 2014). Similarly, fuller's earth immobilized NZVI, and removed 50.08 and 91.42 mg/g of As(III) and As(V), respectively, from aqueous solution (Yadav et al., 2016). Starch-derived mesoporous carbonaceous material after modification with NZVI resulted in the removal of 27 mg/g As(III) (Baikousi et al., 2015). Similarly, chitosan after NZVI modification was able to remove 115 mg/g and 87 mg/g of As(III) and As(V) respectively (Su et al., 2016). Horzum et al., (2013) and Liu et al., (2016b) reported arsenic remediation by using chitosan fiber supported NZVI (CFS-NZVI) and chitosan modified NZVI supported pumice (CS-P-NZVI) respectively. For large scale applications nanobunches (NBZI) have been put forward for arsenic removal and have shown 60 times greater As(III) removal capacity than NZVI at pH 7 (Tang et al., 2017). Wang et al., (2017) found that a stabilizer needs to be used for NZVI since its aggregation affects the As(V) removal capacity. Also, nowadays various modified nano-composites of NZVI like hydroxyl-functionalized TiO_2@SiO_2@Ni/NZVI nano-composite (Huang et al., 2018e), and Zeolite-supported NZVI (Li et al., 2018) have showed better results compared to virgin NZVI.

3.6. Carbon nanotubes: Due to their superior adsorption capability, carbon nanotubes (CNTs) and their composites have received considerable interest in recent times (Bhattacharya et al., 2013). High metal enrichment and detection sensitivity, and selectivity are characteristics of CNTs. CNTs can directly interact with water pollutants through various interactions due to their carbonaceous nature and highly reactive surface area (Hasnain and Nayak, 2019). Their surface can be modified easily by processes like acid treatment, metal impregnation, and functional molecules/group grafting. Although CNTs are challenging to remove from adsorption solutions, the introduction of CNTs-based magnetic hybrids has solved the issue. Iron nanoparticle-enriched modified activated carbons and zeolites showed increased heavy metal adsorption capabilities (Stani, M.H., Nuji, 2015). Cerium oxide supported on carbon nanotubes (CeO_2-CNTs) was created as a unique sorbent having a high surface area (189 m^2/g), and a high capacity for removing arsenic. Ca^{2+} and Mg^{2+} eliminated 81.9 and 78.8 mg/g of As(V) respectively (Peng et al., 2005). Magnetite-coated multiwalled carbon nanotubes (Fe_3O_4-MWNTs) was synthesized which was capable to remove both As(V) and As(III) (Mishra and Ramaprabhu, 2010). Magnetic iron oxide nanoparticles combined with multiwalled carbon nanotubes (MIO-MWCNTs) were capable of adsorbing

As(III) at pH 1.6 to 6.8 and As (V) at pH 1.7 to 7.9 (Li et al., 2016). As(III) and As(V) were more readily absorbed by a nanocomposite synthesized by trapping iron oxide within a carbon nanosphere compared to activated carbon, mesoporous carbon and CNTs (Su et al., 2017).

An important advantage of CNTs is that they can be functionalized for increasing their metal ion removal efficiency. Polyethylene glycol (PEG) functionalization of CNTs results in its improved capacity to remove As(V) from contaminated water. Metal ion adsorption on PEG CNTs shows strong pH dependence (Nicomel et al., 2016; Velickovic et al., 2013).

As(V) removal efficiency of Ti-loaded basic yttrium carbonate (BYC) from contaminated media was studied. The composite showed high capacity of adsorption in a wide pH range of 3 to 11 (Lee et al., 2015).

3.7. Titanium based nanomaterials: Research has indicated that titanium dioxide (TiO_2) and TiO_2-based materials are quite potent in arsenic removal (Ashraf et al., 2019; Nazari et al., 2021, Bhattacharya et al., 2021). TiO_2 has strong photo-oxidizing power and redox selectivity which is helpful for the oxidizing step for As(III) oxidation and their nanofibers have also demonstrated arsenic adsorption capability (Demirel et al., 2017; Jegadeesan et al., 2010; Yan et al., 2016). It has been observed that equilibrium adsorption of As(III) and As(V) by nanocrystalline TiO_2 follows pseudo-second-order kinetics (Guan et al., 2012; Peng et al., 2005). It is reported that 70% of trivalent arsenic is adsorbed in 30 minutes by crystalline hydrous titanium dioxide (Manna et al., 2004). Fe_3O_4-TiO_2 nanoparticle which displays super paramagnetism, has the ability to remove both As(III) and As(V). These nanoparticles removed about 100 µg/L of As(V) with complete efficiency and 100 µg/L of As(III) with 93% efficiency (Beduk, 2016). Fe_2O_3-TiO_2 porous ceramic (Fe/TiPC) beads are extensively reusable and within 2 hours, remove up to 90% As (V) and As(III) by UV irradiation. These nanomaterials exhibit photocatalytic properties (Su et al., 2017). Crystalline TiO_2 adsorbed As(V) better while amorphous TiO_2 showed partial oxidation of As(III) (Jegadeesan et al. 2010), Xu et al., (2010) successfully remediated As(III) using highly porous, hydrous TiO_2 NPs (3–8 nm). Anatase (a form of TiO_2) has shown maximum adsorption of 16.98 mg/g for arsenic (Kocabas and Yurum, 2013). TiO_2 nano-crystals show maximum adsorption efficiency between pH 8 and 4, while at pH 12 adsorption capacity was lowest for both As(III) and As(V) (Wei et al. 2016).

Chitin hydro-gel with reinforced TiO_2 NPs showed 3.1 mg/g of maximum arsenic removal capacity (Ramos et al., 2016). nano-composite of TiO_2 polymer was reported to remediate 150 mg/g of As(V) (Urbano et al., 2015). cysteine@ZnS:TiO2 NPs modified molecularly imprinted biofouling-resistant 3D filtration membrane is able to remediate 95% of As(III) and As(V) ions (Roy et al., 2016). High As(III) adsorption capacity of 114 mg/g was shown by Granular TiO_2-La composite (Yan et al., 2017). Munoz ˜ et al. (2017) found higher oxidation rate of As(III) onto TiO_2 + zero valent iron (ZVI) compared to ZVI. Fe_3O_4@SiO_2@TiO_2 nano sorbent showed maximum adsorption capacity at pH 9 of 31.4 mg/g and 10.2 mg/g for As(III) and As(V), respectively (Feng et al. 2017). Nano-TiO_2/feldspar embedded chitosan composite was able to adsorb arsenic via linear and nonlinear modelling (2 and 2.02 mg/g) respectively (Yazdani et al., 2017). Recently, for photocatalytic oxidation and subsequent adsorption of arsenic various materials were utilised namely microscopic TiO_2 and $TiOF_2$ materials (Gomaa et al., 2018), hydroxyl-functionalized TiO_2@SiO_2@Ni/NZVI nano-composites (Huang et al., 2018e), cerium-doped titanium (Li et al., 2011), and g-C_3N_4/TiO_2 (Jiang et al., 2018b). Fe-TiOx magnetic NPs was developed on surface of pineapple-peelings (CPa-Fe/TiOx) which showed 40 mg/g of adsorption (Rosales et al. 2018). $MgO/TiO_2/Ag$ composite also showed excellent affinity for As(V) having maximum adsorption capacity of 90.66 mg/g at pH 7.0 (Zhang and Jia 2018).

3.8. Zirconia and zirconia-based nanomaterials: Zirconia nanoparticles were applied for both As (III) and As (V) removal (Ma et al., 2011; Zheng et al., 2012). Granular activated carbon media impregnated with zirconium dioxide nanoparticles (Zr-GAC) is quite effective in arsenic removal from contaminated water (Sandoval et al., 2011). Though limited literature is available, but ZrO_2 NPs are stable, more suitable to regenerate, and have high adsorption capacities for arsenic compared to iron or aluminium NPs. ZrO_2 NPs have shown high absorptivity especially for arsenic, and can effectively remediate As(III) without the need for any pre-oxidation step (Zheng et al. 2012). Dual pore structured nano-sized ZrO_2 spheres having large surface area (98 m2/g) were more efficient compared to ZrO_2 NPs for remediation of As(III) and As(V) (Cui et al., 2013).

3.9. Graphene: Distinct features of graphene materials are their large surface area and presence of surface functional groups which make them great choices for water remediation (Bhattacharya et al., 2013). Additionally, it is reusable, can be separated magnetically, has a high removal efficiency and kinetics. Graphene sheets have been developed by hydrogen-induced exfoliation of graphitic oxide. This is followed by functionalization to further improve its arsenic binding properties (Mishra and Ramaprabhu, 2011). The sheets are very efficient in removing As(III) and As(V) from both contaminated fresh water and sea water. Nanohybrids of graphene oxide and manganese ferrite ($MnFe_2O_4$) magnetic NPs have also been developed and their efficiency in arsenic removal been evaluated (Kumar et al., 2014). In a study, graphene nanoplate-supported $CuFe_2O_4$ composite (GNPs/$CuFe_2O_4$) adsorbed up to 58mg/g at various different pH conditions (La et al., 2017). A nanocomposite of Cu-exchanged zeolite A

(Cu-ZEA), reduced graphene oxide (RGO), and magnetite nanoparticles (Fe_3O_4) has a high surface area and removes 50.51 mg/g arsenic (Khatamian et al., 2017).

Graphene oxide has been used as a substrate to support zirconium hydroxide ($ZrO(OH)_2$) nanoparticles and it removes both As(III) and As(V) from contaminated media. It displayed high adsorption efficiency for both arsenic forms (Luo et al., 2013).

Arsenic removal efficiency was studied by using two–dimensional and three-dimensional graphene-based nanomaterials from contaminated water. Removal of arsenic was studied as a function of varying pH, temperature, co-existing ions and loaded metal or metal oxide. Maximum removal capacity for As(III) was 138.79 mg/g and that of As(V) was 183.11 mg/g respectively (Yang et al., 2016).

Kumar and Jiang (2017) have studied b-cyclodextrin decorated functionalized graphene oxide as a material for As(III) and As(V) adsorption. In the presence of hydroxyl and carboxyl groups on the surface of graphene oxide modified magnetite (Fe_3O_4) nanoparticles, this adsorbent shows high adsorption capacity for As(III) and As(V). It is also separable magnetically which is an added advantage. Another advantage is that the adsorbent is reusable as it can be regenerated by NaOH (Kumar and Jiang, 2017). Magnetic graphene oxide (MGO) has also been synthesized in order to remove As(III) from aqueous solutions. It is reusable and does not significantly lose its performance even after 4 adsorption cycles (Sherlala et al., 2018). Chitosan-magnetic-graphene oxide (CMGO) nanocomposites' adsorption isotherm has shown that the adsorption data fits well to Langmuir isotherm model, suggesting that the adsorption is a homogeneous process. Thermodynamic analysis has indicated that As(III) adsorption is exothermic and spontaneous. The superparamagnetic properties of the nanocomposite assist in magnetic recovery (Sherlala et al., 2019).

Macroporous 3D GO hydrogel (MGOH) was effective in adsorbing both the arsenic species, having a sorption capacity of 74.2 mg g−1 and 25.1 mg g−1 for for As(V) and As(III), respectively (Liang et al., 2019).

By using a sol-gel process technique, iron/iron oxide (Fe/FexOy) core-shell structured iron nanoparticles (FeNPs) have been coated on the surface of graphene oxide to create a graphene oxide iron nanohybrid (GFeN) (GO). In the instance of GFeN, removal capacities of 306 mg/g 306 mg/g for As(III) and 431 mg/g for As(V) have been observed. About 99% arsenic is removed in less than 10 minutes using this nanohybrid. It has been suggested that electrostatic interaction and surface complexation are involved in arsenic removal by GFeN (Das et al., 2020).

Materials based on Graphene oxide have also been used in heavy metal remediation (Liu et al., 2019a) also grapheme in its reduced from is successfully used for water treatment (Saikia et al., 2019; Upadhyay et al., 2020). Barik et al. (2020) created a mesoporous silica 3D scaffold doped with graphene oxide flakes (GOFs) and showed its ability to remove Pb^{2+} and As^{3+} ions from groundwater samples.

A novel nanocomposite adsorbent material was synthesized by a group of researchers, using graphene oxide (GO) and a zirconium-based metal–organic framework, i.e., UiO-66-NDC $[Zr_6O_4(OH)_4(1,4\text{-}NDC)_6]n$. The adsorbent was applied as an adsorbent to remove As(V) from water. The UiO-66-NDC/GO showed good performance in As(V) removal across a wide pH range of 1 to 10; the best adsorption efficiency was noted at pH 3. At the ideal pH, UiO-66-NDC/GO showed extremely high efficiency in As(V) removal (147.06 mg/g), which is the highest arsenate adsorption capacity recorded so far (Singh et al., 2022).

3.10. Nanocellulose materials: For removing hazardous compounds from waste water, cellulose nanocrystals (CNCs), cellulose fibres (CF), and nanocellulose (NC) are all thought to be particularly effective adsorbents. Owing to the functionalization of its surface O-H groups it can be used for a wide range of applications (Abou-Zeid et al., 2018; Curvello et al., 2019; Norrrahim et al., 2021). Dialdehyde nanocrystalline cellulose grafted with diethylene triamine (DETA-g-DA-NCC) was effectively used for adsorption of As(III) and As(V). The results showed 92.84% removal for As(III) and 97.86% removal for As (V) respectively at equilibrium (Singh et al., 2015b). Nath et al (2016) showed the application of a bimodal nanocomposite fabricated from Zno, CeO_2: nanocellulose and polyaniline exhibiting arsenic removal efficiency of about 95% along with antibacterial properties. So, dual properties involving arsenic removal and antimicrobial properties was demostrated using this novel bio-nanocomposite. Nanocomposite synthesized using hydroxyapatite-bentonite-clay-nanocrystalline cellulose was used to remove As(III) from water solution with a removal efficiency of 95% within 5 minutes (Hokkanen et al., 2019).

Likewise, Chai et al (2021) synthesized pH-sensitive nanomaterials based on nanocellulose (NC) crosslinked with polyethylemeimine (PI) using the crosslinker glutaraldehyde (GA). This adsorbent was pH sensitive and achieved an adsorption capacity of 255.19 mg/g for As(V) in 10 minutes time at pH 3. Along with its enhanced adsorption in acidic pH, it also showed improved adsorption properties after undergoing eight regeneration cycles. Thus, pH sensitive nanomaterial based on nanocellulose executed high efficiency in removal of arsenic from wastewater.

Iron impregnated micro-fibrillated cellulose (FeNP/MFC) and chitosan beads (MICB) both showed arsenic adsorption capacity. FeNP/MFC remediated As(V) by 2.46 mmol/g (Hokkanen et al., 2015) while MICB capacity to remediate As(V) and As(III) was 35.7 and 35.3 mg/g, respectively (Wang et al., 2014b).

3.11. Biochar materials: Biochars are sustainable, cost-effective and efficient materials for remediation of toxic metals including arsenic from contaminated water. Biochar is synthesized by the process of thermochemical conversion of biomass in oxygen-deprived or oxygen-free conditions (Lee et al., 2019). Biochar is generally produced by using biological wastes generated from wood, leaves, manure, agricultural by-products and residues, sewage sludge etc., which are easily available and cheap. Use of various organic wastes to produce biochar can be a useful strategy in waste management (Alkurdi et al., 2019).

Biochar has various oxygen-containing functional groups and minerals, which play significant roles in arsenic removal by adsorption and oxidation mechanisms (Deng et al., 2020). However, pristine biochar has limited capacity to adsorb arsenic, as its negatively charged surface limits arsenic adsorption because of the electrostatic repulsion between biochar and As oxyanions (Sun et al., 2022). Several modification processes were experimented in order to improve arsenic removal or immobilization by enhancing both chemical and physical properties of biochar. Such modification processes include acid and alkali modification, iron modification, multi-metal modification (Sun et al., 2022). Biochar coating with metal oxides, carbon nanotubes or graphene were recently developed to enhance the properties of biochar for the removal of selected contaminants including toxic metals. Coating of metal oxides with different particle sizes (micro to nano scale range) was applied to improve arsenic removal potential. Pristine biochar is found to be is comparatively less efficient in arsenic sorption from contaminated media than modified or engineered biochars (Amen et al., 2020). The modified biochar has better capacity to retain arsenic because of the higher porosity of the materials, higher surface area and presence of the useful functional groups, which are capable of removing comparatively more arsenic from contaminated media (Amen et al., 2020; Sun et al., 2022). Biochars which are pyrolyzed at high temperature are comparatively more efficient in removal of arsenic from contaminated water than those synthesized at lower temperature, which may be because of the high aromaticity and porous structure, as well as abundant presence of mineral-phases (e.g., $CaPO_4$, $CaCO_3$) (Amen et al., 2020). Adsorption on biochar can be increased during or after the initial manufacturing processes. Ni/Mn modification in post-pyrolysis phase can lead to higher capacity of adsorption (6.52 g/kg) than modification in pre-pyrolysis phase (0.549 g/kg). Chemical, physical, steam activation, impregnation of metals or their oxides, gas purging, and other methods are applied to improve sorption capacity of biochar, based on the target pollutant (Hassan, 2023). Figure 5 illustrates the possible mechanisms for arsenic removal on biochar-based materials.

Various feedstock materials are applied in biochar synthesis to study their usefulness in arsenic removal, such as cotton wood, mulberry wood, coconut shell, corn stem, poplar wood, pinewood, pine bark, rice straw, perilla leaf, Japanese oak wood, oak bark, grape seeds, peanut shell, even sewage sludge materials (Sun et al., 2022; Alkurdi et al., 2019). Application of biochar materials can help in developing more effective management of wastes, leading to the reduction of greenhouse gas emission from the landfills. However, more research works are required to study the utility of biochar materials in natural field conditions, their cost-effectiveness and environmental risk assessment (Amen et al., 2020).

Wang et al., (2016) developed two composites from biochar for arsenic remediation from water, one through Ni/Mn oxide-modified pinewood feedstock (NMMF) pyrolysis and another one by Ni/Mn-LDHs (NMMB) precipitation. The maximum adsorption capacity of the two composites NMMF and NMMB were found to be 0.549 and 6.52 g/kg of As(V), respectively. Wang et al. (2015b) developed Fe-Mn binary oxide onto pinewood biomass (FMM) and pinewood biochar (FMB) for removal of arsenic from water, having As(V) adsorption capacity of 3.44 and 0.50 mg/g for FMB and FMM respectively. (Fe)-impregnated biochar (FBC) was manufactured by pyrolysis of corn straw treated with $FeCl_3$ and showed As(V) adsorption efficiency of 6.80 mg/g, which was more than unmodified biochar (He et al.2018). Recently, researchers applied a spectral induced polarization (SIP) method for monitoring of As adsorption on Fe-modified biochar, synthesized from date-palm leaves. The technique was sensitive to the interfacial conductivity and adsorption properties of biochar, and can be a novel technique to monitor wastewater treatment (Kirmizakis et al., 2022).

Several mechanisms have been studied and explained for As(III) and As(V) adsorption by nanomaterials (Sun et al., 2017; Samuel et al., 2022). Most of the research works established the prominence of electrostatic interactions followed by the redox reactions between the As species and the adsorbent material. General schematic diagram of As sorption on the surface of agglomerated nanoparticles by different pathways like H-bonding, electrostatic interaction, surface oxidation, complex formation, pore diffusion are demonstrated in Figure 6.

An overview of various methods (like adsorption, ion-exchange, phytoremediation, Nano phytoremediation, phytobial remediation, reverse osmosis, chemical precipitation membrane technology, electrocoagulation etc.) applied for arsenic removal is shown in Table 1. Comparative arsenic removal capacity of different adsorbents is shown in Table 2.

4. Nanomaterial applications in arsenic treatment for achieving SDGs:

Cost-effectiveness of the nanomaterials is essential for wide applications in the low income and lower middle-income countries around the world. Many of these regions suffer from resource poor conditions, which further affect the livelihoods of the local inhabitants. This is also in synchrony with one of the significant goals (Goal 6) in UN Sustainable Development

Goals (SDGs), which aims to ensure availability and sustainable management of water and sanitation for all. Especially, target 6.a. under Goal 6 mentions "By 2030, expand international cooperation and capacity-building support to developing countries in water-and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies" (UN Sustainable Development Goals, 2022); water treatment using nanomaterials can be one of the sustainable solutions in this regard. The utilization of nanomaterials for arsenic removal plays a direct role in advancing Sustainable Development Goal 6, which aims to ensure the availability and sustainable management of clean water. The removal of arsenic from water sources provides communities with the opportunity to access water that is safe and suitable for consumption, thereby mitigating the potential health risks associated with arsenic exposure and fostering overall well-being (UNDP 2015). Moreover, the implementation of nanomaterial-based arsenic removal techniques can contribute to the advancement of Sustainable Development Goal 12 by promoting the adoption of responsible production and consumption practices. The proposed methodology aims to mitigate waste generation and enhance resource efficiency through the utilization of nanomaterials possessing exceptional adsorption capabilities and regenerative properties (Popescu et al., 2021).

5. Sustainable approaches towards selecting nanomaterials for arsenic treatment:

Nanomaterials are always given more preference for filtration than the bulk materials due their very high sorption capacity.

Certain approaches are indispensable for the synthesis, selection and application of nanomaterials in arsenic treatment, as follows:

(1) Nanomaterials need to be synthesized by applications of greener technologies in order to achieve more efficiency.

(2) The nanomaterials need to be designed in such ways that the materials can have high permeability with improved dynamic spots via the attachment of several metal organic functional groups;

(3) Formulations and modifications of several functional groups on the nanoadsorbents, depending on the requirements.

(4) Synthesis path of the nanostructured materials is expected to be simple. Large quantity of nanomaterials is expected to be synthesized in a single set of synthesis process, which is a difficult task till date.

(5) Ingredients should be of low cost in order to maintain a reasonable production cost.

(6) Nanomaterials tend to disperse in aqueous medium due to their minute particle sizes. Precautions need to be taken and techniques need to be followed in order to prevent nanomaterial dispersion in water.

(7) Nanomaterials need to be regenerated and reused for the convenience of using multiple times (Mohan and Pittman, 2007; Bhattacharya et al., 2013; Nicomel et al., 2016).

(8) Iron oxide nanoparticles have demonstrated remarkable adsorption capabilities for arsenic. The capacity to efficiently eliminate arsenic from water, even when present in low concentrations, has been demonstrated (Diephuis et al., 2022).

(9) The use of nanomaterials with additional treatment procedures like as membrane filtration has the potential to improve overall efficacy while lowering costs (Kotia et al., 2020).

(10) Synthesis and applications of multifunctional nanomaterials; focus should be on developing novel nanomaterials capable of removing two or more contaminants effectively.

Several initiatives tested the efficiency of different arsenic removal technologies. In West Bengal, ten different arsenic removal technologies were evaluated at the community level (Nadagouda and Lytle, 2011). In Bangladesh, nine technologies for removing arsenic from household levels were tested and evaluated (AIIH, 2001). Bangladesh Council of Scientific and Industrial Research (BCSIR) initiated and approved several technologies of arsenic treatment to be marketed, like ZVI (Sono), granular iron oxide (Neelima, SIDKO), activated alumina (MAGC/ALCAN), Ethylene–vinyl alcohol copolymer-born hydrous cerium oxide (Read-F), and Shwadesh (BAMWSP, 2001).

The utilization of nanomaterials in the process of arsenic removal holds promise for enhanced environmental sustainability compared to conventional methods. The utilization of nanomaterials and the implementation of green synthesis processes can effectively mitigate adverse impacts on ecosystems and diminish the overall carbon footprint associated with the treatment process (Feng et al., 2012). It is imperative to perform a life cycle assessment (LCA) on the process of arsenic removal using nanomaterials in order to comprehensively assess the environmental consequences associated with each stage of its life cycle, encompassing material extraction up to disposal. The utilization of Life Cycle Assessment (LCA) enables the identification of areas that require improvement and facilitates the informed selection of sustainable nanomaterials and treatment processes. There is a need for future life cycle assessment of arsenic removal using nanomaterials.

6. Risk factors and limitations of nanomaterials in arsenic treatment:

Nanoparticles can be discharged into the environment because of unsustainable environmental activities and introduction of new technologies without proper risk assessment. Studies related to assessment of their possible environmental threats should be performed, focusing on the mobility, bioavailability, toxicity and persistence of these nanoparticles (Jawed et al., 2020). It is still unclear whether nanomaterial exposure can affect aquatic and terrestrial organisms significantly. Engineered nanoparticles are being employed more in urban water systems, in addition to their quick expansion in purification of wastewater and treatment of drinking water. This raises the issue of how to get rid of these nanoparticles. It might be necessary to remove nanoparticles once their saturation point is reached. In case of metals and organics, combustion is a reliable method for their removal (Mohan and Pittman, 2007; Bhattacharya et al., 2013). However, the major risk associated with combustion is that the volatile arsenic oxides will find their way out into the atmosphere and result in health hazard in a wide area (Khan, 2010). Solidification of arsenic contaminated material followed by proper disposal in sealed landfills can be a better way of disposal. However, it must be ensured that the landfill is not leaky (Mohan and Pittman, 2007; Bystrzejewska-Piotrowska et al., 2009; Saiz et al., 2014; Nicomel et al., 2016). The best alternate seems to be the use of recyclable adsorbents which have a higher recycling frequency. Studies have highlighted that several adsorbents (discussed through the sections of this review) can be recycled form any cycles without losing their properties (Leist et al., 2000; Tuutijärvi et al., 2012; Hu et al., 2005; Hu et al., 2006).

Use of nanomaterials for arsenic removal from ground water is widely applicable since it produces small amount of sludge with less disposal problem. However, indiscriminate and unscientific use of nanomaterials for water treatment may cause environmental pollution (Banerjee and Chen, 2007). Nanoparticles like nanoscale zerovalent iron shows very high mobility into water, which may cause transportation of adsorbed arsenic into water. Nanoparticles, due to their minute sizes, can pass through the cell membrane by endocytosis which is very harmful to all biological systems. However, detail study is needed on the nature and degree of toxic effects of different nanoparticles. Nano titanium dioxide, fullerene, carbon nanotubes etc. were found to be harmful for different species of fishes (Karn et al., 2009; Cheng et al., 2007). The fate of nanomaterials in the environment after use should be studied and analyzed thoroughly.

There is also a chance of leaching of nanoparticles in the treated water; however, there are no such record documented so far. However, thorough investigations on the leaching of sorbents are required to examine the application of various sorbents on a commercial basis. Arsenic adsorption is effectively prevented by phosphate, carbonate, and bicarbonate ions, which can increase arsenic leaching from mineral surfaces (Handy et al., 2008). Figure 7 shows a schematic representation of the risk factors associated with nanomaterial application in arsenic treatment and possible mitigation options to minimize the risk.

7. Conclusions:

Nanotechnology has emerged as one of the newest and widely used buzzwords in recent times. As shown by the growing trends in research, this area has enormous potential to be evolved into an effective way in water treatment in the 21st century. Developing flexible, mechanically stable and multi-functional nanomaterials is a real challenge, yet could be a major driver in water and wastewater treatment processes, if applied and implemented successfully (Siddiqui and Chaudhry, 2017; Siddiqui et al., 2019). This article provides a summary of diverse absorbents reported (both chemical and biological) by various studies for treatment of arsenic-contaminated water. According to the experiments, nanomaterials are far superior to bulk materials at removing arsenic (both As III and AsV) from water. However, many of the techniques of arsenic treatment involving nanotechnology have only been investigated in laboratory scales, and yet to be studied in natural conditions. Natural conditions are much more complex and interactive, in which the efficiency of these particles need to be proved, especially in a long-term and sustainable manner. Another significant obstacle faced by the hydrologists is the inclusion of nanomaterials into the current arsenic purification technologies. More laboratory research works and pilot scale testing are required to incorporate innovative nanostructured membranes into conventional arsenic purification systems. Combining both inorganic and biomaterials shows promise in enhancing the effectiveness of arsenic removal procedures. Additionally, the application of different metal oxide nanomaterials to decorate graphene oxide can offer improved results. However, while nanotechnology presents opportunities for arsenic purification, potential hazards must be carefully addressed and monitored to ensure long-term sustainability and environmental safety. Vigilance in assessing the benefits and risks of using nanotechnology in arsenic purification is crucial for successful and responsible implementation.

References:

Abdullah, N., Yusof, N., Lau, W.J., Jaafar, J., Ismail, A.F., 2019. Recent trends of heavy metal removal from water/wastewater by membrane technologies. J. Ind. Eng. Chem. 76, 17–38. http://dx.doi.org/10.1016/j.jiec.2019.03.029.

Abou-Zeid, R. E., Dacrory, S., Ali, K. A., & Kamel, S. (2018). Novel method of preparation of tricarboxylic cellulose nanofiber for efficient removal of heavy metal ions from aqueous solution. *International journal of biological macromolecules*, *119*, 207-214.

Adio, S.O., Omar, M.H., Asif, M., Saleh, T.A., 2017. Arsenic and selenium removal from water using biosynthesized nanoscale zero-valent iron: a factorial design analysis. Process Saf. Environ. Prot. 107, 518–527.

AIIH, 2001. Arsenic mitigation programme for technology and park on arsenic removal devices. In: Basu, B.B. (Ed.), Convenor Director. School of Fundamental Research, Kolkata, India.

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. *Journal of cleaner production*, *278*, 123805.

Alkurdi, S.S.A,, 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. doi: 10.1016/j.envint.2019.03.012.

Allen, S.J., Whitten, L.J., Murray, M., Duggan, O., Brown, P., 1997. The adsorption of pollutants by peat, lignite and activated chars. J. Chem. Technol. Biotechnol. 68, 442–452. doi:10.1002/(SICI)1097-4660(199704)68:4<442::AID-JCTB643>3.0.CO;2-2

Altin, A., Degirmenci, M., 2005. Lead (II) removal from natural soils by enhanced electrokinetic remediation. Sci. Total Environ. 337 (1-3), 1-10.

Altundoan, H.S., Altundoan, S., Tümen, F., Bildik, M., 2002. Arsenic adsorption from aqueous solutions by activated red mud. Waste Manag. 22, 357–363. doi:10.1016/S0956-053X(01)00041-1

Amen, R., Bashir, H., Bibi, I., Shaheen, S.M., Niazi, N.K., Shahid, M., Hussain, M.M., Antoniadis, V., Shakoor, M.B., Al-Solaimani, S.G., Wang, H., Bundschuh, J., & Rinklebe, J. 2020. A critical review on arsenic removal from water using biochar-based sorbents: The significance of modification and redox reactions. *Chemical Engineering Journal, 396*, 125195.

Amin, N., Kaneco, S., Kitagawa, T., Begum, A., Katsumata, H., Suzuki, T., Ohta, K., 2006. Removal of arsenic in aqueous solutions by adsorption onto waste rice husk. Ind. Eng. Chem. Res. 45, 8105–8110. doi:10.1021/ie060344j

Aredes, S.,Klein, B., Pawlik,M., 2012. The removal of arsenic from water using natural iron oxide minerals. J. Clean. Prod. 29-30, 208–213.

Asere TG, Stevens CV, Du Laing G. Use of (modified) natural adsorbents for arsenic remediation: a review. Science of the total environment. 2019 Aug 1;676:706-20.

Ashraf, S.; Siddiqa, A.; Shahida, S.; Qaisar, S. Titanium-based nanocomposite materials for arsenic removal from water: A review. Heliyon 2019, 5, e01577.

Asif, Z., Chen, Z., 2017. Removal of arsenic from drinking water using rice husk. Appl. Water Sci. 7, 1449–1458. doi:10.1007/s13201-015-0323-x

Auffan, M.; Rose, J.; Bottero, J.Y.; Lowry, G.V.; Jolivet, J.P.; Wiesner, M.R. (2009) Towards a definition of inorganic nanoparticles from an environmental, health and safety perspective. *Nat. Nanotechnol.* 4, 634-641.

Bach, A., Maor, A.Z., Semiat, R., 2010. Characterization of iron oxide nanocatalyst in mineralization processes. Desalination 262, 15–20.

Badruddoza, A.Z.M., Shawon, Z.B.Z., Rahman, M.T., Hao, K.W., Hidajat, K., Shahabuddin, M., 2013. Ionically modified magnetic nanomaterials for arsenic and chromium removal from water. Chem. Eng. J. 225, 607–615.

Badruzzaman, M., Westerhoff, P., Knappe, D.R.U., 2004. Intraparticle diffusion and adsorption of arsenate onto granular ferric hydroxide (GFH). Water Res. 38, 4002–4012.

Baikousi, M., Georgiou, Y., Daikopoulos, C., et al., 2015. Synthesis and characterization of robust zero valent iron/mesoporous carbon composites and their applications in arsenic removal. Carbon 93, 636–647.

BAMWSP, DFID, WAB, 2001. Rapid Assessment of Household Level Arsenic Removal Technologies. Phase II Report, Dhaka.

Banerjee, K., Amy, G.L., Prevost, M., et al., 2008. Kinetic and thermodynamic aspects of adsorption of arsenic onto granular ferric hydroxide (GFH). Water Res. 42, 3371–3378.

Banerjee, S.; Chen, D. Fast removal of copper ions by gum arabic modified magnetic nano-adsorbent. J. Hazard. Mater. **2007**, 147, 792–799.

Barik, B., Kumar, A., Nayak, P.S., Achary, L.S.K., Rout, L., Dash, P., 2020. Ionic liquid assisted mesoporous silica-graphene oxide nanocomposite synthesis and its application for removal of heavy metal ions from water. Mater. Chem. Phys. 239, 122028. http://dx.doi.org/10.1016/j.matchemphys.2019. 122028.

Basu, H., Singhal, R.K., Pimple, M. V., Reddy, A.V.R., 2015. Arsenic removal from groundwater by goethite impregnated calcium alginate beads. Water. Air. Soil Pollut. 226. doi:10.1007/s11270-014-2251-z

Basu, T., Ghosh, U.C., 2011b. Arsenic(III) removal performances in the absence/presence of groundwater occurring ions of agglomerated Fe(III)-Al(III) mixed oxide NPs. J. Ind. Eng. Chem. 17, 834–844.

Basu, T., Nandi, D., Sen, P., Ghosh, U.C., 2013. Equilibrium modeling of As(III.,V) sorption in the absence/presence of some groundwater occurring ions by iron(III)–cerium(IV) oxide nanoparticle agglomerates., A mechanistic approach of surface interaction. Chem. Eng. J. 228, 665–680.

Beduk, F., 2016. Superparamagnetic nanomaterial Fe_3O_4–TiO_2 for the removal of As (V) and As (III) from aqueous solutions. Environ. Technol. 37, 1790–1801. doi:10.1080/09593330.2015.1132777

Bezbaruah, A.N., Kalita, H., Almeelbi, T., et al., 2013. Ca-alginate-entrapped nanoscale iron: arsenic treatability and mechanism studies. J. Nanopart. Res. 16, 2175–2183.

Bhattacharya, S., Gupta, K., Debnath, S., Ghosh, U.C., Chattopadhyay, D., Mukhopadhyay, A., 2012. Arsenic bioaccumulation in rice and edible plants and subsequent transmission through food chain in Bengal basin: a review of the perspectives for environmental health. Toxicol. Environ. Chem. 94, 429–441.

Bhattacharya, S., Saha, I., Mukhopadhyay, A., Chattopadhyay, D., Chand, U., 2013. Role of nanotechnology in water treatment and purification: potential applications and implications. Int. J. Chem. Sci. Technol. 3 (3), 59–64.

Bhattacharya, S., Sharma, P., Mitra, S., Mallick, I., Ghosh, A. 2021. Arsenic uptake and bioaccumulation in plants: A review on remediation and socio-economic perspective in Southeast Asia. Environmental nanotechnology, monitoring and management 9, Article number 100430.

Bhaumik, M., Noubactep, C., Gupta, V.K., McCrindle, R.I., Maity, A., 2015. Polyani□line/Fe0 composite nanofibers., an excellent adsorbent for the removal of arsenic from aqueous solutions. Chem. Eng. J. 271, 135–146.

Bhowmick, S., Chakraborty, S., Mondal, P., et al., 2014. Montmorillonite-supported nanoscale zero-valent iron for removal of arsenic from aqueous solution, Kinet□ics and mechanism. Chem. Eng. J. 243, 14–23.

Bissen, M., and Frimmel, F.H. 2003. *Arsenic – A Review. Part I: occurrence, toxicity, speciation and mobility.* Acta hydrochimica et Hydrobiologica 31: 9-18.

Burakov, A.E., Galunin, E.V., Burakova, I.V., Kucherova, A.E., Agarwal, S., Tkachev, A.G., Gupta, V.K., 2018. Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review. Ecotoxicol. Environ. Saf. 148, 702–712. http://dx.doi.org/10.1016/j. ecoenv.2017.11.034.

Bystrzejewska-Piotrowska, G.; Golimowski, J.; Urban, P.L. Nanoparticles: Their potential toxicity, waste and environmental management. Waste Manag. **2009**, 29, 2587–2595.

Cai, G., Li, L., Li, D., Wang, Q., Zhang, L., Zhang, J., ... & Tian, Y. (2022). Rapid purification of As (III) in water using iron–manganese composite oxide coupled with sulfite: Importance of the SO5•− radicals. Water Research, 118839.

Cao, A.; Monnell, J.D., Matranga, C.; Wu, J.; Cao, L.; Gao, D. (2007) Hierarchical Nanostructured Copper Oxide and Its Application in Arsenic Removal. *J. Phys. Chem. C* 111, 18624-18628.

Cerda, K.M., Cruces, E., Rubio, M.A., Reyes, C., Miranda, N.A., 2017. Preparation ofnanoscale iron (oxide, oxyhydroxides and zero-valent) particles derived fromblueberries: reactivity, characterization and removal mechanism of arsenate.Ecotoxicol. Environ. Saf. 145, 69–77.

Chai, F., Wang, R., Yan, L., Li, G., Cai, Y., & Xi, C. (2020). Facile fabrication of pH-sensitive nanoparticles based on nanocellulose for fast and efficient As (V) removal. *Carbohydrate polymers*, *245*, 116511.

Chen, M.L., Sun, Y., Huo, C.B., Liu, C.,Wang, J.H., 2015.Akaganeite decorated graphene oxide composite for arsenic adsorption/removal and it's pre-concentration at ultra-trace level. Chemosphere 130, 52–58.

Cheng, J.; Flahaut, E.; Cheng, S.H. (2007) Effect of carbon nanotubes on developing zebrafish (Danio Rerio) embryos. *Environ. Tox. Chem.* 26, 708-716.

Chowdhury, S.R.; Yanful, E.K. (2011) Arsenic removal from aqueous solutions by adsorption on magnetite nanoparticles. *Water Environ. J.* 25, 429-437.

Chutia, P., Kato, S., Kojima, T., Satokawa, S., 2009. Arsenic adsorption from aqueous solution on synthetic zeolites. J. Hazard. Mater. 162, 440–447. doi:10.1016/j.jhazmat.2008.05.061

Ciftci, T.D., Henden, E., 2015. Nickel/nickel boride NPs coated resin., A novel adsorbent for arsenic(III) and arsenic(V) removal. Powder Technol. 269, 470–480.

Cornell, R.M., Schwertmann, U., 2003. The Iron Oxides, Structure, Properties, Reactions, Occurrences and Uses. Wiley VCH, ISBN: 3-527-30274-3.

Criscuoli, A., Figoli, A., 2019. Pressure-driven and thermally-driven membrane op□erations for the treatment of arsenic-contaminated waters: a comparison. J. Hazard Mater. 370, 147-155.

Cui, H., Su, Y., Li, Q., Gao, S., Shang, J.K., 2013. Exceptional arsenic (III,V) removal performance of highly porous, nanostructured ZrO2 spheres for fixed bed reactors and the full-scale system modeling. Water Res. 47, 6258–6268.

Curvello, R., Raghuwanshi, V. S., & Garnier, G. (2019). Engineering nanocellulose hydrogels for biomedical applications. *Advances in colloid and interface science*, *267*, 47-61.

Dambies, L., 2005. Existing and prospective sorption technologies for the removal of arsenic in water. Sep. Sci. Technol. 39 (3), 603e627.

Das, B., Devi, R.R., Umlong, I.M., Borah, K., Banerjee, S., Talukdar, A.K., 2013. Arsenic (III) adsorption on iron acetate coated activated alumina: thermodynamic, kinetics and equilibrium approach. J. Environ. Heal. Sci. Eng. 11, 42. doi:10.1186/2052-336X-11-42

Das, G.K., Bonifacio, C.S., Rojas, J.D., et al., 2014a. Ultra-long magnetic nanochains for highly efficient arsenic removal from water. J. Mater Chem. A 2, 12974–12981.

Das, T.K., Sakthivel, T.S., Jeyaranjan, A., Seal, S., Bezbaruah, A.N. 2020. Ultra-high arsenic adsorption by graphene oxide iron nanohybrid: Removal mechanisms and potential applications. Chemosphere, 253, 126702 (Article in press).

Demirbas, E., Kobya, M., Oncel, M.S., S¸ ık, E., Goren, A.Y., 2019. Arsenite removal from groundwater in a batch electrocoagulation process: optimization through response surface methodology. Separ. Sci. Technol. 54 (5), 775-785.

Demirel, C.S.U., Birben, N.C., Bekbolet, M., 2017. Elucidation of background organic matter matrix effect on photocatalytic treatment of contaminants using TiO2: a review. Catal. Today 284, 202–214.

Deng, W., Zhou, Z., Zhang, X., Yang, Y., Sun, Y., Wang, Y., Liu, T., 2017. Remediation of arsenic (III) from aqueous solutions using zero-valent iron (ZVI) combined with potassium permanganate and ferrous ions. Water Sci. Technol.

Devi, R.R., Umlong, I.M., Das, B., Borah, K., Thakur, A.J., Raul, P.K., Banerjee, S., Singh, L., 2014. Removal of iron and arsenic (III) from drinking water using iron oxide-coated sand and limestone. Appl. Water Sci. 4, 175–182. doi:10.1007/s13201-013-0139-5

Devikarani, R., Thiruvenkatachari, V., Yee-Chung, J., 2006. Iron Oxide Coated Sand for Arsenic Removal: Investigation of Coating Parameters Using Factorial Design Approach. Pract. Period. Hazardous, Toxic, Radioact. Waste Manag. 10, 198–206. doi:10.1061/(ASCE)1090-025X(2006)10:4(198)

doi:10.1016/j.chemosphere.2020.126702

Diephuis WR, Molloy AL, Boltz LL, Porter TB, Aragon Orozco A, Duron R, Crespo D, George LJ, Reiffer AD, Escalera G, Bohloul A. The effect of agglomeration on arsenic adsorption using iron oxide nanoparticles. Nanomaterials. 2022 May 9;12(9):1598.

Dong, H., 2019. "Development of Hybrid Ion Exchange Processes Driven by Carbon Dioxide (Hix-Co2)." Thesis. Type. Lehigh University.

Dong, H., Guan, X., Lo, I.M.C., 2012. Fate of As(V)-treated nano zero-valent iron, Determination of arsenic desorption potential under varying environmental conditions by phosphate extraction. Water Res. 46, 4070–4080.

Eguez, H.E., Cho, E.H., 1987. Adsorption of Arsenic on Activated Charcoal. Jom 39, 38–41. doi:10.1007/BF03258040

Faria, M.C.S., Rosemberg, R.S., Bomfeti, C.A., et al., 2014. Arsenic removal from contaminated water by ultrafine δ-FeOOH adsorbents. Chem. Eng. J. 237, 47–57.

Feng, C., Aldrich, C., Eksteen, J.J., Arrigan, D.W.M., 2017. Removal of arsenic from alkaline process waters of gold cyanidation by use of Fe3O4@SiO2@TiO2 nanosorbents. Minerals Eng. 110, 40–46.

Feng, L., Cao, M., Ma, X., Zhu, Y., Hu, C., 2012. Superparamagnetic high-surface-area Fe

$_3O_4$ nanoparticles as adsorbents for arsenic removal. J. Hazard. Mater. 217–218, 439–446. doi:10.1016/j.jhazmat.2012.03.073

Feng, L., Cao, M., Ma, X., Zhu, Y., Hu, C., 2012a. Superparamagnetic high-surfacearea Fe3O4 NPs as adsorbents for arsenic removal. J. Hazard. Mater. 217–218, 439–446.

Figoli, A., Hoinkis, J., Bundschuh, J. (Eds.), 2016. Membrane Technologies for Water Treatment: Removal of Toxic Trace Elements with Emphasis on Arsenic, Fluo□ride and Uranium. CRC Press.

Flores, O.J., Nava, J.L., Carreño, G., Elorza, E., Martínez, F., 2013. Arsenic removal from groundwater by electrocoagulation in a pre-pilot-scale continuous filter press reactor. Chem. Eng. Sci. 97, 1–6.

Gallios, G.P., Tolkou, A.K., Katsoyiannis, I.A., Stefusova, K., Vaclavikova, M., Deliyanni, E.A., 2017. Adsorption of arsenate by nano scaled activated carbon modified by iron and manganese oxides. Sustain. 9, 1–18. doi:10.3390/su9101684

Gerard, N., Krishnan, R.S., Ponnusamy, S.K., Cabana, H., Vaidyanathan, V.K., 2016. Adsorptive potential of dispersible chitosan coated iron-oxide nanocomposites toward the elimination of arsenic from aqueous solution. Process Saf. Environ. Prot. 104, 185–195.

Ghanizadeh, G., Ehrampoush, M.H., Ghaneian, M.T., 2010. Application of Iron Impregnated Activated Carbon for Removal of Arsenic From Water. Iranian J. Environ. Health Sci. Eng. 7, 145–156. doi:10.1016/j.jhazmat.2008.09.064

Ghosal, P.S., Kattil, K.V., Yadav, M.K., Gupta, A.K., 2018. Adsorptive removal of arsenic by novel iron/olivine composite: insights into preparation and adsorption process by response surface methodology and artificial neural network. J. Environ. Manag. 209, 176-187.

Ghosh (Nath), S., Debsarkar, A., Dutta, A., 2019. Technology alternatives for descontamination of arsenic-rich groundwater – a critical review. Environ. Technol. Innovation 13, 277–303.

Ghosh MK, Poinern GEJ, Issa TB, Singh P (2012) Arsenic adsorption on goethite nanoparticles produced through hydrazine sulfate assisted synthesis method. Korean J Chem Eng 29(1):95–102

Ghosh, A., Paul, S., Bhattacharya, S., Sasikumar, P., Biswas, K., Ghosh, U.C., 2019. Calcium ion incorporated hydrous iron(III) oxide: synthesis, characterization, and property exploitation towards water remediation from arsenite and fluoride. Environ. Sci. Pollut. Res. 26(5), 4618-4632. doi: https://doi.org/10.1007/s11356-018-3872-3

Giles, D.E., Mohapatra, M., Issa, T.B., Anand, S., Singh, P., 2011. Iron and aluminium based adsorption strategies for removing arsenic from water. J. Environ.Manage. 92, 3011–3022.

Gilhotra, V., Das, L., Sharma, A., Kang, T.S., Singh, P., Dhuria, R.S., Bhatti, M.S., 2018. Electrocoagulation technology for high strength arsenic wastewater: process optimization and mechanistic study. J. Clean. Prod. 198, 693-703.

UNDP. Goal 6: Clean water and sanitation". Retrieved on July 21, 2023, retrieved from: https://www.unep.org/explore-topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-6.

Gomaa, H., Shenashen, M.A., Yamaguchi, H., et al., 2018. Highly-efficient removal of AsV, Pb2+, Fe3+, and Al3+ pollutants from water using hierarchical, microscopic TiO2 and TiOF2 adsorbents through batch and fixed-bed columnar techniques. J. Clean. Prod. 182, 910–925.

Gomes, J.A., Daida, P., Kesmez, M., Weir, M., Moreno, H., Parga, J.R., Irwin, G., McWhinney, H., Grady, T., Peterson, E., Cocke, D.L., 2007. Arsenic removal by electrocoagulation using combined AleFe electrode system and characterization of products. J. Hazard Mater. 139 (2), 220-231.

Grafe, M., Eick, M.J., Grossl, P.R., 2001. Adsorption of arsenate (V) and arsenite (III) on goethite in the presence and absence of dissolved organic carbon. Soil Sci.Soc. Am. J. 65, 1680–1687.

Gregory, T. (2008) *Nanotechnology*, New York: Springer.

Guan, X., Du, J., Meng, X., Sun, Y., Sun, B., Hu, Q., 2012. Application of titanium dioxide in arsenic removal from water: A review. J. Hazard. Mater. 215–216, 1–16. doi:10.1016/j.jhazmat.2012.02.069

Guan, X.H.; Su, T. Wang, J. (2009) Quantifying effects of pH and surface loading on arsenic adsorption on NanoActive alumina using a speciation-based model. *J. Hazard. Mater.* 166, 39-45.

Guisela, Z., Ohana N, D.A., Dalvani S, D., Fermin G, V., Francisco Hm, L., Luis, N.-G., 2022. Adsorption of arsenic anions in water using modified lignocellulosic adsorbents. Results Eng. 13, 100340. https://doi.org/10.1016/j.rineng.2022.100340.

Guo, X., Chen, F., 2005. Removal of arsenic by bead cellulose loaded with iron oxyhydroxide from groundwater. Environ. Sci. Technol. 39, 6808–6818. doi:10.1021/es048080k

Gupta, A., Yunus, M., Sankararamakrishnan, N., 2012. Zerovalent iron encapsulated chitosan nanospheres–A novel adsorbent for the removal of total inorganic Arsenic from aqueous systems. Chemosphere 86, 150–155.

Gupta, K., Bhattacharya, S., Chattopadhyay, D., Mukhopadhyay, A., Biswas, H., Dutta, J., Ray, N.R., Ghosh, U.C., 2011. Ceria associated manganese oxide nanoparticles: Synthesis, characterization and arsenic(V) sorption behavior. Chem. Eng. J. 172, 219–229.

doi:10.1016/j.cej.2011.05.092

Gupta, K., Ghosh, U.C., 2009. Arsenic removal using hydrous nanostructure iron(III)-titanium(IV) binary mixed oxide from aqueous solution. J. Hazard. Mater. 161, 884–892.

Gupta, K.; Basu, T.; Ghosh, U.C. (2009) Sorption Characteristics of Arsenic(V) for Removal from Water Using Agglomerated Nanostructure Iron(III)−Zirconium(IV) Bimetal Mixed Oxide. *J. Chem. Eng. Data.* 54, 2222-2228.

Gupta, K.; Bhattacharya, S.; Chattopadhyay, D.J.; Mukhopadhyay, A.; Biswas, H.; Dutta, J.; Ray, N.R.; Ghosh, U.C. (2011) Ceria associated manganese oxide nanoparticles: Synthesis, characterization and arsenic(V) sorption behavior. *Chem. Eng. J.* 172, 219-229.

Gupta, K.; Bhattacharya, S.; Nandi, D.; Dhar, A.; Maity, A.; Mukhopadhyay, A.; Chattopadhyay, D.J.; Ray, N.R.; Sen, P.; Ghosh, U.C. (2012) Arsenic(III) sorption on nanostructured cerium incorporated manganese oxide (NCMO): a physical insight into the mechanistic pathway. *J. Colloid. Interf. Sci.* 377, 269-276.

Gupta, K.; Biswas, K.; Ghosh, U.C. (2008) Nanostructure Iron(III)−Zirconium(IV) Binary Mixed Oxide: Synthesis, Characterization, and Physicochemical Aspects of Arsenic(III) Sorption from the Aqueous Solution. *Ind. Eng. Chem. Res.* 47, 9903-9912.

Gupta, K.; Ghosh, U.C. (2009) Arsenic removal using hydrous nanostructure iron(III)-titanium(IV) binary mixed oxide from aqueous solution. *J. Hazard. Mater.* 161, 884-892.

Gupta, K.; Maity, A.; Ghosh, U.C. (2010) Manganese associated nanoparticles agglomerate of iron(III) oxide: synthesis, characterization and arsenic(III) sorption behavior with mechanism. *J. Hazard. Mater.* 184, 832-842.

Gupta, K.; Saha, S.; Ghosh, U.C. (2008) Synthesis and characterization of nanostructure hydrous iron–titanium binary mixed oxide for arsenic sorption. *J. Nanopart. Res.* 10, 1361-1368.

Han, C., Pu, H., Li, H., et al., 2013a. The optimization of As(V) removal over mesoporous alumina by using response surface methodology and adsorption mechanism. J. Hazard. Mater. 254-255, 301–309.

Handy, R.D.; Kammer, Fv.; Lead, J.R.; Hassellöv, M.; Owen, R.; Crane, M. (2008) The ecotoxicology and chemistry of manufactured nanoparticles. *Ecotoxicol.* 17, 287-314.

Hao, L., Wang, N., Wang, C., Li, G., 2018. Arsenic removal from water and river water by the combined adsorption-UF membrane process. Chemosphere 202, 768-776.

Haoran, D., Xiaohong, G., Irene, M.C.L., 2012. Fate of As(V)-treated nano zero-valent iron., Determination of arsenic desorption potential under varying environmen□tal conditions by phosphate extraction. Water Res. 46, 4071–4080.

Happer, T.R.; Kingham; N.W. (1992) Removal of arsenic from waste water using chemical precipitation methods. *Water Environ. Res.* 64, 200-203.

Hasnain, M.S., Nayak, A.K., 2019. Background: Carbon nanotubes for targeted drug delivery. SpringerBriefs Appl. Sci. Technol. http://dx.doi.org/10. 1007/978-981-15-0910-0_1.

Hassan, H.R. 2023. A review on different arsenic removal techniques used for decontamination of drinking water, Environmental Pollutants and Bioavailability, 35:1, 2165964, DOI: 10.1080/26395940.2023.2165964

He, R., Peng, Z., Lyu, H., Huang, H., Nan, Q., Tang, J., 2018. Synthesis and characterization of an iron-impregnated biochar for aqueous arsenic removal. Sci. Total Environ. 612, 1177–1186.

Hokkanen, S., Doshi, B., Srivastava, V., Puro, L., & Koivula, R. (2019). Arsenic (III) removal from water by hydroxyapatite-bentonite clay-nanocrystalline cellulose. Environmental Progress & Sustainable Energy, 38(5), 13147.

Hokkanen, S., Repo, E., Lou, S., Sillanpää, M., 2015. Removal of arsenic(V) by magnetic nanoparticle activated microfibrillated cellulose. Chem. Eng. J. 260, 886–894.

Horzum, N., Demir, M.M., Nairat, M., Shahwan, T., 2013. Chitosan fiber-supported zero-valent iron NPs as a novel sorbent for sequestration of inorganic arsenic. RSC Adv. 3, 7828–7837.

Hristovski, K., Baumgardner, A., Westerhoff, P., 2007. Selecting metal oxide nanomaterials for arsenic removal in fixed bed columns: From nanopowders to aggregated nanoparticle media. J. Hazard. Mater. 147, 265–274. doi:10.1016/j.jhazmat.2007.01.017

Hu, J.; Chen, G.; Lo, I. Removal and recovery of Cr(VI) from wastewater by maghemite nanoparticles. Water Res. **2005**, 39, 4528–4536.

Hu, J.; Chen, G.; Lo, I.; Asce, M. Selective removal of heavy metals from industrial wastewater using maghemite nanoparticle: Performance and mechanisms. Environ. Technol. **2006**.

Hu, Y., Boyer, T.H., 2018. Removal of multiple drinking water contaminants by combined ion exchange resin in a completely mixed flow reactor. J. Water Supply Res. Technol. - Aqua 67 (7), 659-672.

Hua, J., 2018. Adsorption of low-concentration arsenic from water by co-modified bentonite with manganese oxides and poly (dimethyldiallylammonium chlo□ride). J. Environ. Chem. Eng. 6, 156–168.

Huang, P.P., Cao, C.Y., Wei, F., Sun, Y.B., Song, W.G., 2015. MgAl layered double hydroxides with chloride and carbonate ions as interlayer anions for removal of arsenic and fluoride ions in water. RSC Adv. 5 (14), 10412-10417.

Huang, Y., Zhang, W., Zhang, M., Zhang, X., Zhao, Y., 2018e. Hydroxyl-functionalized TiO2@SiO@Ni/nZVI nanocomposites fabrication, characterization and enhanced simultaneous visible light photocatalytic oxidation and adsorption of arsenite. Chem. Eng. J. 338, 369–382.

Huang, Y.H., Shih, Y.J., Cheng, F.J., 2011. Novel $KMnO_4$-modified iron oxide for effective arsenite removal. J. Hazard. Mater. 198, 1–6.

Huo, J.B., Xu, L., Yang, J.C.E., et al., 2018. Magnetic responsive Fe_3O_4-ZIF-8 coreshell composites for efficient removal of As (III) from water. Colloids Surf. A: Physicochem. Eng. Asp. 539, 59–68.

Jadhav, S.V., Bringas, E., Yadav, G.D., Rathod, V.K., Ortiz, I., Marathe, K.V., 2015. Arsenic and fluoride contaminated groundwaters: a review of current tech□nologies for contaminants removal. J. Environ. Manag. 162, 306-325.

Jain, A., Agarwal, M., 2017. Kinetic equilibrium and thermodynamic study of arsenic removal from water using alumina supported iron nano particles. J. Water Process Eng. 19, 51–59.

Jais, F.M., Ibrahim, S., Yoon, Y., Jang, M., 2016. Enhanced arsenate removal by lanthanum and nano-magnetite composite incorporated palm shell-waste based activated carbon. Sep. Purif. Technol. 169, 93–102.

Jawed, A., Saxena, V., Pandey, L.M. 2020. Engineered nanomaterials and their surface functionalization for the removal of heavy metals: A review. Journal of Water Process Engineering 33 (2020) 101009.

Jegadeesan, G., Al-Abed, S.R., Sundaram, V., et al., 2010. Arsenic sorption on TiO_2 NPs, Size and crystallinity effects. Water Res. 44, 965–973.

Jesitha, K., Harikumar, P.S., 2018. Application of nano-phytoremediation technology for soil polluted with pesticide residues and heavy metals. In: Phytoremediation. Springer, Cham, pp. 415-439.

Jézéquel, H., Chu, K.H., 2005. Enhanced adsorption of arsenate on titanium dioxide using Ca and Mg ions. Environ. Chem. Lett. 3, 132–135.

Jiang, W., Chen, X., Niu, Y., Pan, B., 2012. Spherical polystyrene-supported nanoFe3O4 of high capacity and low-field separation for arsenate removalfrom water. J. Hazard. Mater. 243, 319–325.

Jiang, X.H., Xing, Q.J., Luo, X.B., et al., 2018b. Simultaneous photoreduction of Uranium (VI) and photooxidation of Arsenic (III) in aqueous solution over g-C3N4/TiO2 heterostructured catalysts under simulated sunlight irradiation. Appl. Catal. B. Environ. 228, 29–38.

Jin, Y., Liu, F., Tong, M., Hou, Y., 2012. Removal of arsenate by cetyltrimethyl ammonium bromide modified magnetic NPs. J. Hazard. Mater. 227–228, 461–468.

Johnston, R.; Heijnen, H. Safe Water Technology for Arsenic Removal. Available online: http://archive.unu.edu/env/Arsenic/Han.pdf (accessed on 18 December 2015).

Kanematsu, M., Young, T.M., Fukushi, K., Green, P.G., Darby, J.L., 2013. Arsenic(III, V)adsorption on a goethite-based adsorbent in the presence of major co-existing ions: modeling competitive adsorption consistent with spectroscopic and molecular evidence. Geochim. Cosmochim. Acta 106, 404–428.

Kang, S., Park, S.M., Park, J.G., Baek, K., 2019. Enhanced adsorption of arsenic using calcined alginate bead containing alum sludge from water treatment facilities. J. Environ. Manag. 234, 181-188.

Kang, Y.G., Yoon, H., Lee, W., Kim, E.J., Chang, Y.S., 2018. Comparative study of peroxide oxidants activated by nZVI: removal of 1, 4-dioxane and arsenic (III) in contaminated waters. Chem. Eng. J. 334, 2511–2519.

Karakurt, S., 2019. Removal of carcinogenic arsenic from drinking water by the application of ion exchange resins. Oncogen J. 2 (1), 5.

Karn, B.; Kuiken, T.; Otto, M. (2009) Nanotechnology and in Situ Remediation: A Review of the Benefits and Potential Risks. *Environ. Health. Perpec.* 117, 1823-1831.

Khan, Khalid, S., Khan, I. 2019. Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry 12, 908-931.

Khan, M.R., 2010. Situation Analysis of Arsenic Mitigation in Bangladesh 2009. <http://www.academia.edu/348535/Situation_Analysis_of_Arsenic_Mitigation

Khatamian, M., Khodakarampoor, N., Saket-Oskoui, M., 2017. Efficient removal of arsenic using graphene-zeolite based composites. J. Colloid Interface Sci. 498, 433–441. doi:10.1016/j.jcis.2017.03.052

Khodabakhshi, A.; Amin, M.M.; Mozaffari, M. (2011) Synthesis of magnetite nanoparticles and evaluation of its efficiency for arsenic removal from simulated industrial wastewater. *Iran. J. Environ. Hlth. Sci. Eng.* 8, 189-200.

Kirmizakis, P.; Tawabini, B.; Siddiq, O.M.; Kalderis, D.; Ntarlagiannis, D.; Soupios, P. Adsorption of Arsenic on Fe-Modified Biochar and Monitoring Using Spectral Induced Polarization. Water **2022**, 14, 563.

Kobya, M., Soltani, R.D.C., Omwene, P.I., Khataee, A., 2020. A review on decontam□ination of arsenic-contained water by electrocoagulation: reactor configura□tions and operating cost along with removal mechanisms. Environ. Technol. Innovat. 17, 100519.

Kocabas, Z.O., Yurum, Y., 2013. Synthesis and characterization of anatase nanoadsor□bent and application in removal of lead, copper and arsenic from water. Chem. Eng. J. 225, 625–635.

Kolbe, F., Weiss, H., Morgenstern, P., et al., 2011. Sorption of aqueous antimony and arsenic species onto akaganeite. J. Colloid Interface Sci. 357, 460–465.

Kotia A, Yadav A, Rohit Raj T, Gertrud Keischgens M, Rathore H, Sarris IE. Carbon nanoparticles as sources for a cost-effective water purification method: A comprehensive review. Fluids. 2020 Dec 1;5(4):230.

Kumar SK, Jiang SJ (2017) Synthesis of magnetically separable and recyclable magnetic nanoparticles decorated with b-cyclodextrin functionalized graphene oxide an excellent adsorption of As(V)/(III). J Mol Liq 237:387–401.

Kumar, P.R., Chaudhari, S., Khilar, K.C., Mahajan, S.P., 2004. Removal of arsenic from water by electrocoagulation. Chemosphere 55 (9), 1245-1252.

Kumar, R., Patel, M., Singh, P., Bundschuh, J., Pittman Jr., C.U., Trakal, L., Mohan, D., 2019. Emerging technologies for arsenic removal from drinking water in rural and peri-urban areas: methods, experience from, and options for Latin America. Sci. Total Environ. 694, 133427.

Kumar, S., Nair, R.R., Pillai, P.B., Gupta, S.N., Iyengar, M.A.R., Sood, A.K., 2014. Graphene oxide-MnFe2O4 magnetic nanohybrids for efficient removal of lead and arsenic from water. ACS Appl. Mater. Interfaces 6, 17426–17436. doi:10.1021/am504826q

Kumar, V.; Talreja, N.; Deva, D.; Sankararamakrishnan, N.; Sharma, A.; Verma, N. (2011) Development of bi-metal doped micro- and nano multi-functional polymeric adsorbents for the removal of fluoride and arsenic(V) from wastewater. *Desalination*. 282, 27-38.

La, D.D., Nguyen, T.A., Jones, L.A., Bhosale, S. V., 2017. Graphene-Supported spinel $CuFe_2O_4$ composites: Novel adsorbents for arsenic removal in aqueous media. Sensors (Switzerland) 17. doi:10.3390/s17061292

Laatikainen, M., Sillanp€ aa, M., Sainio, T., 2016. Comparison of ion exchange process € configurations for arsenic removal from natural waters. Desalination and Water Treatment 57 (29), 13770-13781.

Lata, S., Samadder, S.R., 2016. Removal of arsenic from water using nano adsorbents and challenges: A review. J. Environ. Manage. 166, 387–406. doi:10.1016/j.jenvman.2015.10.039

Lee, C.-G., Kim, S.-B., 2016. Removal of arsenic and selenium from aqueous solutions using magnetic iron oxide nanoparticle/multi-walled carbon nanotube adsorbents. Desalin. Water Treat. 57, 28323–28339. doi:10.1080/19443994.2016.1185042

Lee, J., Sarmah, A.K., Kwon, E.E. 2019. Production and formation of biochar. In: Y.S. Ok, D.C.W. Tsang, N. Bolan, J.M. Novak (Eds.), Biochar from Biomass and Waste, Elsevier, pp. 3–18. https://doi.org/10.1016/B978-0-12-811729- 3.00001-7.

Lee, S.H., Choi, H., Kim, K.W., 2016. Removal of As (V) and Sb (V) in water using magnetic nanoparticle-supported layered double hydroxide nanocomposites. J. Geochem. Explor. 184, 247–254.

Lee, S.-H.; Kim, K.-W.; Lee, B.-T.; Bang, S.; Kim, H.; Kang, H.; Jang, A. Enhanced arsenate removal performance in aqueous solution by yttrium-based adsorbents. Int. J. Environ. Res. Public Health **2015**, 12, 13523.

Leist, M.; Casey, R.J.; Caridi, D. The management of arsenic wastes: Problems and prospects. J. Hazard.Mater. **2000**, 76, 125–138.

Lenoble, V., Bouras, O., Deluchat, V., Serpaud, B., Bollinger, J.C., 2002. Arsenic adsorption onto pillared clays and iron oxides. J. Colloid Interface Sci. 255, 52-58.

Lescano, M.R., Passalía, C., Zalazar, C.S., Brandi, R.J., 2015. Arsenic sorption onto titanium dioxide, granular ferric hydroxide and activated alumina: Batch and dynamic studies. J. Environ. Sci. Heal. Part A 50, 424–431. doi:10.1080/10934529.2015.987552

Li X-q, Elliott DW, W-x Z (2006) Zero-valent iron nanoparticles for abatement of environmental pollutants: materials and engineering aspects. Crit Rev Solid State 31:111–122

Li, C., Hou, H., Yang, J., Liang, S., Shi, Y., Guan, R., Hu, Y., Wu, X., Hu, J., Wang, L., 2019. Comparison of electrokinetic remediation on lead-contaminated kaolinite and natural soils. Clean 47 (4), 1800337.

Li, J., Gyoten, H., Sonoda, A., Feng, Q., Xue, M., 2017. Removal of trace arsenic to below drinking water standards using a Mn–Fe binary oxide. RSC Adv. 7, 1490–1497. doi:10.1039/C6RA26806D

Li, R.; Li, Q.; Gao, S.; Shang, J.K. (2012) Exceptional arsenic adsorption performance of hydrous cerium oxide nanoparticles: Part A. Adsorption capacity and mechanism. *Chem. Eng. J.* 185– 186, 127-135.

Li, S., Wang, W., Liang, F., Zhang, W.X., 2017b. Heavy metal removal using nanoscale zero-valentiron (NZVI), Theory and application. J. Hazards. Mater. 322, 163–171.

Li, S., Wang, W., Liu, Y., Zhang, W.X., 2014a. Zero-valent iron NPs (NZVI) for the treatment of smelting wastewater, A pilot-scale demonstration. Chem. Eng. J. 254, 115–123.

Li, W., Chen, D., Xia, F., et al., 2016. Extremely high arsenic removal capacity for mesoporous aluminium magnesium oxide composites. Environ. Sci. Nano 3, 94–106.

Li, W.; Cao, C.Y.; Wu, L.Y.; Ge, M.F.; Song, W.G. (2011) Superb fluoride and arsenic removal performance of highly ordered mesoporous aluminas. *J. Hazard. Mater.* 198, 143-150.

Li, Y., Liu, J.R., Jia, S.Y., et al., 2012b. TiO2 pillared montmorillonite as a photoactive adsorbent of arsenic under UV irradiation. Chem. Eng. J. 191, 66–74.

Li, Z., Qu, J., Li, H., Lim, T., Liu, C., 2011. Effect of cerium valence on As(V) adsorption by cerium-doped titanium dioxide adsorbents. Chem. Eng. J. 175, 207–212.

Li, Z., Wang, L., Meng, J., Liu, X., et al., 2018. Zeolite-supported nanoscale zero-valent iron: new findings on simultaneous adsorption of Cd (II), Pb (II), and As (III) in aqueous solution and soil. J. Hazards. Mater. 344, 1–11.

Liang, J.J., He, B.H., Li, P., Yu, J., Zhao, X.L., Wu, H.Y., et al., 2019. Facile construction of 3D magnetic graphene oxide hydrogel via incorporating assembly and chemical bubble and its application in arsenic remediation. Chem. Eng. J. 358, 552–563.

Lin, S., Lu, D., Liu, Z., 2012. Removal of arsenic contaminants with magnetic-Fe2O3 NPs. Chem. Eng. J. 211-212, 46–52.

Litter, M.I., Morgada, M.E., Bundschuh, J., 2010. Possible treatments for arsenic removal in Latin American waters for human consumption. Environ. Pollut. 158 (5), 1105-1118.

Liu, H., Zuo, K., Vecitis, C.D., 2014a. Titanium dioxide-coated carbon nanotube network filter for rapid and effective arsenic sorption. Environ. Sci. Technol. 48, 13871–13879.

Liu, R., Liu, J.F., Zhang, L.Q., Sun, J.F., Jiang, G.B., 2016a. Low temperature synthesized ultrathin-Fe2O3nanosheets show similar adsorption behaviour for As(III) and As(V). J. Mater. Chem. A. 4, 7606–7614.

Liu, S., Kang, S., Wang, G., Zhao, H., Cai, W., 2015. Micro/nanostructured porous Fe–Ni binary oxide and its enhanced arsenic adsorption performances. J. Colloid Interface Sci. 458, 94–102.

Liu, T., Yang, Y., Wang, Z.L., Sun, Y., 2016b. Remediation of arsenic(III) from aqueous solutions using improved nanoscale zero-valent iron on pumice. Chem. Eng. J. 288, 739–744.

Liu, X., Ma, R., Wang, Xiangxue, Ma, Y., Yang, Y., Zhuang, L., Zhang, S., Jehan, R., Chen, J., Wang, Xiangke, 2019a. Graphene oxide-based materials for efficient removal of heavy metal ions from aqueous solution: A review. Environ. Pollut. 252, 62–73. http://dx.doi.org/10.1016/j.envpol.2019.05.050

Lorenzen, L., van Deventer, J.S.J., Landi, W.M., 1995. Factors affecting the mechanism of the adsorption of arsenic species on activated carbon. Miner. Eng. 8, 557–569. doi:10.1016/0892-6875(95)00017-K

Luo, X.; Wang, C.; Wang, L.; Deng, F.; Luo, S.; Tu, X.; Au, C. Nanocomposites of graphene oxide-hydrated zirconium oxide for simultaneous removal of As(III) and As(V) from water. Chem. Eng. J. 2013, 220, 98–106.

Ma, Y.; Zheng, Y.M.; Chen, J.P. (2011) A zirconium based nanoparticle for significantly enhanced adsorption of arsenate: Synthesis, characterization and performance. *J. Colloid. Interf. Sci.* 354, 785-792.

Mahamudur, I., Prakash, C.M., Rajkishore, P., 2011. Arsenate removal from aqueous solution by cellulose-carbonated hydroxyapatite nanocomposites. J. Hazard. Mater. 189, 755–763.

Mahanta, N., Valiyaveettil, S., 2013. Functionalized poly(vinyl alcohol) based nanofibers for the removal of arsenic from water. RSC Adv. 3, 2776–2783.

Maitlo, H.A., Kim, J.H., Kim, K.H., Park, J.Y., Khan, A., 2019. Metal-air fuel cell electrocoagulation techniques for the treatment of arsenic in water. J. Clean. Prod. 207, 67-84.

Maity, J.P., Chen, C.Y., Bhattacharya, P., Sharma, R.K., Ahmad, A., Patnaik, S., Bundschuh, J. 2021. Advanced application of nano-technological and biological processes as well as mitigation options for arsenic removal. Journal of hazardous materials 405: 123885.

Maji, S., Ghosh, A., Gupta, K., et al., 2018. Efficiency evaluation of arsenic (III) adsorption of novel graphene oxide@ iron-aluminium oxide composite for the contaminated water purification. Sep. Pur. Technol. 197, 388–400.

Mak MSH, Rao P, Lo IMC (2009) Effects of hardness and alkalinity on the removal of arsenic(V) from humic acid-deficient and humic acid-rich groundwater by zero-valent iron.Water Res 43:4296–4304

Maliyekkal, S.M., Philip, L., Pradeep, T., 2009. As (III) removal from drinking water using manganese oxide-coated-alumina: Performance evaluation and mechanistic details of surface binding. Chem. Eng. J. 153, 101–107. doi:10.1016/j.cej.2009.06.026

Mamindy-Pajany Y, Hurel C, Marmier N, Roméo M. Arsenic (V) adsorption from aqueous solution onto goethite, hematite, magnetite and zero-valent iron: effects of pH, concentration and reversibility. Desalination. 2011 Oct 17;281:93-9.

Mankar, J.S., Sharma, M.D., Krupadam, R.J. 2020. Molecularly imprinted nanoparticles (nanoMIPs): an efficient new adsorbent for removal of arsenic from water. *Journal of materials science* **55:** 6810–6825. https://doi.org/10.1007/s10853-020-04377-0.

Manna, B., Dasgupta, M., Ghosh, U.C. 2004. *Crystalline Hydrous Titanium (IV) Oxide (CHTO): An Arsenic (III) Scavenger.* Journal of Water Supply: Research and Technology 53(7): 483-495.

Manna, B., Ghosh, U.C., 2007. Adsorption of arsenic from aqueous solution on synthetic hydrous stannic oxide. J. Hazard. Mater. 144, 522–531.

Manning, B.A., Hunt, M.L., Amrhein, C., Yarmoff, J.A., 2002. Arsenic (III) and Arsenic (V) Reactions with Zerovalent Iron Corrosion Products. Environ. Sci. Technol. 36, 5455–5461. doi:10.1021/es0206846

Mao, X., Han, F.X., Shao, X., Guo, K., McComb, J., Arslan, Z., Zhang, Z., 2016. Electrokinetic remediation coupled with phytoremediation to remove lead, arsenic and cesium from contaminated paddy soil. Ecotoxicol. Environ. Saf. 125, 16-24.

Martinson, C.A.; Reddy, K.J. (2009) Adsorption of arsenic(III) and arsenic(V) by cupric oxide nanoparticles. *J. Colloid. Interf. Sci.* 336, 406-411.

Mauter, M.S.; Elimelech, M. (2008) Environmental Applications of Carbon-Based Nanomaterials *Environ. Sci. Technol.* 42, 5843-5859.

Mayo, J.T.; Yavuz, C.; Yean, S.; Cong, L.; Shipley, H.; Yu, W.; Falkner, J.; Kan, A.; Tomson, M.; Colvin, V. L. (2007) The effect of nanocrystalline magnetite size on arsenic removal. *Sci. Technol. Adv. Mater.* 8, 71-75.

Min, S.-Y., Kim, B.-K., Park, S.-J., Chang, Y.-Y., Yang, J.-K., 2009. Removal Efficiency of Arsenic by Adsorbents having Different Type of Metal Oxides. Environ. Eng. Res. 14, 134–139. doi:10.4491/eer.2009.14.2.134

Mishra, A.K., Ramaprabhu, S., 2010. Magnetite Decorated Multiwalled Carbon Nanotube Based Supercapacitor for Arsenic Removal and Desalination of Seawater. J. Phys. Chem. C 114, 2583–2590. doi:10.1021/jp911631w

Mishra, A.K., Ramaprabhu, S., 2011. Functionalized graphene sheets for arsenic removal and desalination of sea water. Desalination 282, 39–45. doi:10.1016/j.desal.2011.01.038

Mohan, D., Dey, S., Dwivedi, S.B., Shukla, S.P., 2019. Adsorption of arsenic using low cost adsorbents: guava leaf biomass, mango bark and bagasse. Curr. Sci. 117 (4), 00113891.

Mohan, D., Pittman, C.U., Bricka, M., Smith, F., Yancey, B., Mohammad, J., Steele, P.H., Alexandre-Franco, M.F., Gómez-Serrano, V., Gong, H., 2007. Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production. J. Colloid Interface Sci. 310, 57–73. doi:10.1016/j.jcis.2007.01.020

Mohan, D.; Pittman, C.U., Jr. Arsenic removal from water/wastewater using adsorbents—A critical review. J. Hazard. Mater. **2007**, 142, 1–53.

Mohmood, I., Lopes, C.B., Lopes, I., Ahmad, I., Duarte, A.C., Pereira, E., 2013. Nanoscale materials and their use in water contaminants removal-a review. Environ. Sci. Pollut. Res. 20, 1239–1260. doi:10.1007/s11356-012-1415-x

Mohora, E., Ron□cevi□c, S., Agbaba, J., Zrni□c, K., Tubi□c, A., Dalmacija, B., 2018. Arsenic removal from groundwater by horizontal-flow continuous electrocoagulation (EC) as a standalone process. J. Environ. Chem. Eng. 6 (1), 512-519.

Mondal, B.K., and Suzuki, K.T. 2002. *Arsenic round the world: a review.* Talanta 58: 201–235.

Morgada ME, Levy IK, Salomone V, Farías SS, López G, Litter MI (2009) Arsenic(V) removal with nanoparticulate zerovalent iron: effect of UV light and humic acids. Catal Today 143:261–268

Morillo, D., Faccini, M., Amantia, D., et al., 2016. Superparamagnetic iron oxide nanoparticle-loaded polyacrylonitrile nanofibers with enhanced arsenate removal performance. Environ. Sci. Nano 3, 1165–1173.

Moreira VR, Lebron YA, Santos LV, de Paula EC, Amaral MC. Arsenic contamination, effects and remediation techniques: A special look onto membrane separation processes. Process Safety and Environmental Protection. 2021 Apr 1;148:604-23.

Munoz, ˜ M.J.L.,Arencibia,A., Segura, Y., Raez, J.M., 2017. Removal ofAs (III)from aqueous solutions through simultaneous photocatalytic oxidation and adsorption by TiO2 and zero-valent iron. Catal. Today 280, 149–154.

Nabi, D., Aslam, I., Qazi, I.A., 2009. Evaluation of the adsorption potential of titanium dioxide NPs for arsenic removal. J. Environ. Sci. 21, 402–408.

Nadagouda, M.N.; Lytle, D.A. (2011) Microwave-Assisted Combustion Synthesis of Nano Iron Oxide/Iron-Coated Activated Carbon, Anthracite, Cellulose Fiber, and Silica, with Arsenic Adsorption Studies. *J. Nanotechnol.* 2011, 1-8.

Najib, N., Christodoulatos, C., 2019. Removal of arsenic using functionalized cellulose nanofibrils from aqueous solutions. J. Hazard Mater. 367, 256-266.

Nassar, N.N., 2012. Iron Oxide Nanoadsorbents for removal of various pollutants from wastewater: An overview. Appl. Adsorbents Water Pollut. Control 81–118. doi:10.1073/pnas.0703993104

Nata, I.F., Kumar, M.S., Lee, C.K., 2011. One-pot preparation of amine-rich magnetite/bacterial cellulose nanocomposite and its application for arsenate removal. RSC Adv. 1, 625–631.

Nath, B. K., Chaliha, C., Kalita, E., & Kalita, M. C. (2016). Synthesis and characterization of ZnO: CeO2: nanocellulose: PANI bionanocomposite. A bimodal agent for arsenic adsorption and antibacterial action. Carbohydrate polymers, 148, 397-405.

Navarro, P., Alguacil, F.J., 2002. Adsorption of antimony and arsenic from a copper electrorefining solution onto activated carbon. Hydrometallurgy 66, 101–105. doi:10.1016/S0304-386X(02)00108-1

Nazari, A., Nakhaei, M., Yari, A.R. 2021. Arsenic Adsorption by TiO_2 Nanoparticles Under Conditions Similar to Groundwater: Batch and Column Studies. International journal of environmental research 15: 79–91. https://doi.org/10.1007/s41742-020-00298-7

Niazi, N.K., Bashir, S., Bibi, I., Murtaza, B., Shahid, M., Javed, M.T., Shakoor, M.B., Saqib, Z.A., Nawaz, M.F., Aslam, Z., Wang, H., 2016. Phytoremediation of arseniccontaminated soils using arsenic hyperaccumulating ferns. In: Phytoremediation. Springer, Cham, pp. 521-545.

Nicomel, N.R., Leus, K., Folens, K., Van Der Voort, P., Du Laing, G., 2015. Technologies for arsenic removal from water: Current status and future perspectives. Int. J. Environ. Res. Public Health 13, 1–24. doi:10.3390/ijerph13010062

Nicomel, N.R.; Leus, K.; Folens, K.; Van Der Voort, P.; Du Laing, G. Technologies for Arsenic Removal from Water: Current Status and Future Perspectives. *Int. J. Environ. Res. Public Health* **2016**, *13*, 62.

Nidheesh, P., Singh, T.A., 2017. Arsenic removal by electrocoagulation process: recent trends and removal mechanism. Chemosphere 181, 418-432.

Norrahim, M. N. F., Kasim, N. A. M., Knight, V. F., Misenan, M. S. M., Janudin, N., Shah, N. A. A., ... & Yunus, W. M. Z. W. (2021). Nanocellulose: A bioadsorbent for chemical contaminant remediation. RSC advances, 11(13), 7347-7368.

Nwadinigwe, A.O., Ugwu, E.C., 2018. Overview of Nano-Phytoremediation Applications Phytoremediation. Springer, pp. 377.

Onnby, L., Kumar, P.S., Sigfridsson, K.G.V., et al., 2014. Improved arsenic(III) adsorption by Al2O3 NPs and H2O2., Evidence of oxidation to arsenic(V) from X-ray absorption spectroscopy. Chemosphere 113, 151–157.

Ortega, A., Oliva, I., Contreras, K.E., Gonz□ alez, I., Cruz-Díaz, M.R., Rivero, E.P., 2017. Arsenic removal from water by hybrid electro-regenerated anion exchange resin/electrodialysis process. Separ. Purif. Technol. 184, 319-326.

Pan, B., Li, Z., Zhang, Y., et al., 2014. Acid and organic resistant nano-hydrated zirconium oxide (HZO)/polystyrene hybrid adsorbent for arsenic removal from water. Chem. Eng. J. 248, 290–296.

Parga, J.R., Cocke, D.L., Valenzuela, J.L., Gomes, J.A., Kesmez, M., Irwin, G., Moreno, H., Weir, M., 2005. Arsenic removal via electrocoagulation from heavy metal contaminated groundwater in La Comarca Lagunera Mexico. J. Hazard Mater. 124 (1-3), 247-254.

Patra, A.K., Dutta, A., Bhaumik, A., 2012. Self-assembled mesoporous-Al2O3 spher□ical NPs and their efficiency for the removal of arsenic from water. J. Hazard. Mater. 201-202, 170–177.

Paul, B., Sarkar, A. 2016. The global menace of arsenic and its conventional remediation – A critical review. Chemosphere, 158, 37-49.

Pawar, R.R., Lalhmunsiama, KimM., Kim, J.G., Lee, S.M., 2018. Efficient removal of hazardous lead, cadmium, and arsenic from aqueous environment by iron oxide modified clay-activated carbon composite beads. Appl. Clay Sci. 162, 339–350.

Pena, M., Korfiatis, G.P., Patel, M., Lippincott, L., Meng, X., 2005. Adsorption of As(V) and As(III) by nanocrystalline titanium dioxide. Water Res. 39, 2327–2337.

Peng, X., Luan, Z., Ding, J., Di, Z., Li, Y., Tian, B., 2005. Ceria nanoparticles supported on carbon nanotubes for the removal of arsenate from water. Mater. Lett. 59, 399–403. doi:10.1016/j.matlet.2004.05.090

Peng, X., Zhao, Y., Yang, T., et al., 2018. One-step and acid free synthesis of Fe2O3/SBA-15 for enhanced arsenic removal. Microporous Mesoporous Mater. 258, 26–32.

Pillai, P., Kakadiya, N., Timaniya, Z., Dharaskar, S., Sillanpaa, M. 2020. Removal of arsenic using iron oxide amended with rice husk nanoparticles from aqueous solution. Materials Today: Proceedings 28: 830-835.

Popescu CR. Measuring progress towards the sustainable development goals: Creativity, intellectual capital, and innovation. In Handbook of research on novel practices and current successes in achieving the sustainable development goals 2021 (pp. 125-136). IGI Global.

Prabhakar, R., Samadder, S.R., 2018. Low cost and easy synthesis of aluminium oxide NPs for arsenite removal from groundwater: a complete batch study. J. Mol. Liq. 250, 192–201.

Prasad, B., Ghosh, C., Chakraborty, A., Bandyopadhyay, N., Ray, R.K., 2011. Adsorption of arsenite (As3+) on nano-sized Fe2O3 waste powder from the steel industry. Desalination 274, 105–112.

Qu, X., Brame, J., Li, Q., Alvarez, P.J.J., 2013. Nanotechnology for a safe and sustainable water supply: Enabling integrated water treatment and reuse. Acc. Chem. Res. 46, 834–843. doi:10.1021/ar300029v

Rahmani, A.R., Ghaffari, H.R., Samadi, M.T., 2011. A comparative study on arsenic (III) removal from aqueous solution using nano and micro sized zero-valent iron. Iran. J. Environ. Health Sci. Eng. 8, 175–180.

Ramos, M.L.P., González, J.A., Albornoz, S.G., et al., 2016. Chitin hydrogel reinforced with TiO2 NPs as an arsenic sorbent. Chem. Eng. J. 285, 581–587.

Ratna Kumar, P., Chaudhari, S., Khilar, K.C., Mahajan, S.P., 2004. Removal of arsenic from water by electrocoagulation. Chemosphere 55, 1245–1252.

Raul, P.K., Devi, R.R., Umlong, I.M., Thakur, A.J., Veer, V., 2014. Iron oxide hydrox□ide nanoflower assisted removal of arsenic from water. Mater. Res. Bull. 49, 360–368.

Raven, K.P., Jain, A., Loeppert, R.H., 1998. Arsenite and arsenate adsorption on ferrihydrite: kinetics, equilibrium, and adsorption envelopes. Environ. Sci.Technol. 32, 344–349.

Ray, P.Z., Shipley, H.J. 2015. *Inorganic nano-adsorbents for the removal of heavy metals and arsenic: a review.* RSC Advances **5**: 29885-29907.

Reddy, K.J. McDonald, K.J.; King, H. (2013) A novel arsenic removal process for water using cupric oxide nanoparticles. *J. Colloid. Interf. Sci.* 397, 96-102.

Rivero, E.P., Ortega, A., Cruz-Díaz, M.R., Gonz□ alez, I., 2018. Modelling the transport of ions and electrochemical regeneration of the resin in a hybrid ion exchange/ electrodialysis process for as (V) removal. J. Appl. Electrochem. 48 (6), 597-610.

Roco, M.; Brainbridge, W.S. (2001) *Societal implication of nanoscience and technology*. Kluwer academic publishers.

Rosales, G.G., Longoria-Gándara, L.C., Cruz-Cruz, G.J., Olayo-González, M.G., MejíaCuero, R., Pérez, P.Á., 2018. Fe-TiOx nanoparticles on pineapple peel: synthesis, characterization and As(V) sorption. Environ. Nanotech. Monit. Manage. 9, 112.

Rosales, M., Coreno, O., Nava, J.L., 2018. Removal of hydrated silica, ~ fluoride and arsenic from groundwater by electrocoagulation using a continuous reactor with a twelve-cell stack. Chemosphere 211, 149-155.

Rosi, N.L.; Mirkin, C.A. (2005) Nanostructures in biodiagnostics. *Chem. Rev.* 105, 1547-1562.

Rotello, VM. (2003) *Nanoparticles: Building blocks of nanotechnology*. 1st Ed. New York:

Springer.

Roy, E., Patra, S., Madhuri, R., Sharma, P.K., 2016. A single solution for arsenite and arsenate removal from drinking water using cysteine@ZnS:TiO2 nanoparticle modified molecularly imprinted biofouling-resistant filtration membrane. Chem. Eng. J. 304, 259–270.

Saha, S., Sarkar, P., 2012. Arsenic remediation from drinking water by synthesized nano-alumina dispersed in chitosan-grafted polyacrylamide. J. Hazards. Mater. 227–228, 68–78.

Saikia, J., Gogoi, A., Baruah, S., 2019. Nanotechnology for water remediation. In: Dasgupta, N., Ranjan, S., Lichtfouse, E. (Eds.), Environmental Nanotechnology. Springer International Publishing, pp. 195–211.

Saikia, J., Saha, B., Das, G., 2011. Efficient removal of chromate and arsenate from individual and mixed system by malachite nanoparticles. J. Hazards. Mater. 186, 575–582.

Saiz, J.; Bringas, E.; Ortiz, I. New functionalized magnetic materials for As5+ removal: Adsorbent regeneration and reuse. Ind. Eng. Chem. Res. **2014**, 53, 18928–18934.

Samuel, M.S., Selvarajan, E., Sarswat, A., Muthukumar, H., Jacob, J.M., Mukesh, M., Pugazhendhi, A. 2022. Nanomaterials as adsorbents for As(III) and As(V) removal from water: A review. J Hazard Mater. 2022 Feb 15;424(Pt C):127572. doi: 10.1016/j.jhazmat.2021.127572.

Sandoval, R.; Cooper, A.M.; Aymar, K.; Jain, A.; Hristovski, K. (2011) *J. Hazard. Mater.* 193, 296-303.

Sarkar, A., Paul, B., 2016. The global menace of arsenic and its conventional remediation-a critical review. Chemosphere 158, 37-49.

Savage, N., Diallo, M.S. 2005. *Nanomaterials and water purification: Opportunities and challenges.* Journal of Nanoparticle Research 7: 331–342.

Schmid, G. (2004) *Nanoparticles: from theory to application.* 1st Ed. Wiley-VCH.

Selvakumar, R., Jothi, N.A., Jayavignesh, V., et al., 2011. As(V) removal using carbonized yeast cells containing silver NPs. Water Res. 45, 583–592.

Senn, A.C., Hug, S.J., Kaegi, R., Hering, J.G., Voegelin, A., 2018. Arsenate coprecipitation with Fe (II) oxidation products and retention or release during precipitate aging. Water Res. 131, 334-345.

Shah, M.A., Ahmed, T. 2011. *Principles of Nanoscience and Nanotechnology*. Narosa Publishing House: New Delhi, India, pp. 34-47.

Shakoor, M.B., Nawaz, R., Hussain, F., Raza, M., Ali, S., Rizwan, M., Oh, S.E., Ahmad, S., 2017. Human health implications, risk assessment and remediation of Ascontaminated water: a critical review. Sci. Total Environ. 601, 756-769.

Shan G, Surampalli RY, Tyagi RD, Zhang TC (2009) Nanomaterials for environmental burden reduction, waste treatment, and nonpoint source pollution control: a review. Front Environ Sci Eng China 3(3):249–264.

Sharma, P. K., Kumar, R., Singh, R. K., Sharma, P., & Ghosh, A. (2022). Review on arsenic removal using biochar-based materials. Groundwater for Sustainable Development, 17, 100740.

Sheikhmohammadi, A., Dahaghin, Z., Mohseni, S.M., et al., 2018. The synthesis and application of the SiO2@Fe3O4@ MBT nanocomposite as a new magnetic sorbent for the adsorption of arsenate from aqueous solutions: modelling, optimization, and adsorption studies. J. Mol. Liq. 255, 313–323.

Sherlala AIA, Raman AAA, Bello MM, Buthiyappan A (2019) Adsorption of arsenic using chitosan magnetic graphene oxide nanocomposite. J Environ Manag 246:547–556.

Sherlala AIA, Raman AAA, Bello MM, Synthesis and characterization of magnetic graphene oxide for arsenic removal from aqueous solution. Environ Technol. (just-accepted), 2018;49:1–9.

Shukla, A., Srivastava, S., 2019. A Review of Phytoremediation Prospects for Arsenic Contaminated Water and Soil Phytomanagement Of Polluted Sites. Elsevier, pp. 243-254.

Siddiqui, S.I., Chaudhry, S.A., 2017. Removal of arsenic from water using nanocom-posites, A Review. Cur. Environ. Eng. 4, 81–102.

Siddiqui, S.I., Chaudhry, S.A., 2017a. Removal of arsenic from water using nanocomposites, A Review. Cur. Environ. Eng. 4, 81–102.

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

Siddiqui, S.I., Naushad, M., Chaudhry, S.A., 2019. Promising prospects of nanomaterials for arsenic water remediation:A comprehensive review. Process Safety and Environmental Protection 126 (2019) 60–97.

Siddiqui, S.I.,Chaudhry, S.A., 2019.Nanohybridcomposite Fe2O3-ZrO2/BC for inhibiting the growth of bacteria and adsorptive removal of arsenic and dyes from water. J. Clean. Prod. 223, 849–868.

Simeonidis, K., Gkinis, T., Tresintsi, S., et al., 2011. Magnetic separation of hematitecoated Fe3O4 particles used as arsenic adsorbents. Chem. Eng. J. 168, 1008–1015.

Singh, K., Sinha, T. J. M., & Srivastava, S. (2015b). Functionalized nanocrystalline cellulose: smart biosorbent for decontamination of arsenic. International Journal of Mineral Processing, 139, 51-63.

Singh, M.; Thanh, D.N.; Ulbrich, P.; Strnadova, N.; Stepanek, F.J. (2010) Synthesis, characterization and study of arsenate adsorption from aqueous solution by α- and δ-phase manganese dioxide nanoadsorbents. *Solid. State. Chem.* 183, 2979-2986.

Singh, R.; Singh, S.; Parihar, P.; Singh, V.; Prasad, S. Arsenic contamination, consequences and remediation techniques: A review. Ecotoxicol. Environ. Saf. **2015a**, 112, 247–270.

Singh S, Naik TSSK, U B, Khan NA, Wani AB, Behera SK, Nath B, Bhati S, Singh J, Ramamurthy PC. A systematic study of arsenic adsorption and removal from aqueous environments using novel graphene oxide functionalized UiO-66-NDC nanocomposites. Sci Rep. 2022 Sep 22;12(1):15802. doi: 10.1038/s41598-022-18959-2.

Singh, T.S., Pant, K.K., 2004. Equilibrium, kinetics and thermodynamic studies for adsorption of As (III) on activated alumina. Sep. Purif. Technol. 36, 139–147. doi:10.1016/S1383-5866(03)00209-0

Sofija, S.P., Dejan, M.K., Sneˇzana, P.M., 2016. Removal of As(III) and Cr(VI) from aqueous solutions using “green” zero-valent iron NPs produced by oak., mulberry andcherry leaf extracts. Ecol. Eng. 90, 42–49.

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.

Stanić, M.H., Nujić, M. 2015. Arsenic removal by nanoparticles: a review. Environ. Sci. Pollut. Res. 22, 8094-8123. doi:10.1007/s11356-015-4307-z

Su, F., Zhou, H., Zhang, Y., Wang, G., 2016. Three-dimensional honeycomb-like structured zero-valent iron/chitosan composite foams for effective removal of inorganic arsenic in water. J. Colloid Interface Sci. 478, 421–429.

Su, H., Lv, X., Zhang, Z., Yu, J., Wang, T., 2017. Arsenic removal from water by photocatalytic functional Fe_2O_3–TiO_2 porous ceramic. J. Porous Mater. 24, 1227–1235. doi:10.1007/s10934-017-0362-9

Su, H., Ye, Z., Hmidi, N., Subramanian, R., 2017. Carbon nanosphere-iron oxide nanocomposites as high-capacity adsorbents for arsenic removal. RSC Adv. 7, 36138–36148.

Sun, T., Zhao, Z., Liang, Z., Liu, J., Shi, W., Cui, F. 2017. Efficient As(III) removal by magnetic CuO-Fe3O4 nanoparticles through photo-oxidation and adsorption under light irradiation. Journal of cooloid and interface science 495: 168-177.

Taleb, K., Markovski, J., Rusmirovic, Z.V.J., Rancic, M., Pavlovic, V., Marinkovic, A., 2016. Arsenic removal by magnetite-loaded amino modified nano/microcellulose adsorbents: effect of functionalization and media size. Arabian J. Chem., http://dx.doi.org/10.1016/j.arabjc.2016.08.006, In Press.

Tang, L., Feng, H., Tang, J., et al., 2017. Treatment of arsenic in acid wastewater and river sediment by Fe@ Fe2O3 nanobunches: the effect of environmental conditions and reaction mechanism. Water Res. 117, 175–186.

Tang, W., Li, Q., Gao, S., Shang, J.K., 2011. Arsenic (III., V) removal from aqueous solution by ultrafine Fe2O3 NPs synthesized from solvent thermal method. J. Hazards. Mater. 192, 131–138.

Thakkar, M., Randhawa, V., Mitra, S., Wei, L., 2015. Synthesis of diatom–FeOx composite for removing trace arsenic to meet drinking water standards. J. Colloid Interface Sci. 457, 169–173.

Thi, T.M., Thi, N., Trang, H., Nguyen Anh, T.V., 2015. Effects of Mn., Cu doping concentration to the properties of magnetic NPs and arsenic adsorption capacity in wastewater. Appl. Sur. Sci. 340, 166–172.

Tolkou AK, Katsoyiannis IA, Zouboulis AI. Removal of arsenic, chromium and uranium from water sources by novel nanostructured materials including graphene-based modified adsorbents: A mini review of recent developments. Applied Sciences. 2020 May 7;10(9):3241.

Türkmen, D., Özkaya Türkmen, M., Akgönüllü, S., & Denizli, A. (2022). Development of ion imprinted based magnetic nanoparticles for selective removal of arsenic (III) and arsenic (V) from wastewater. Separation Science and Technology, 57(6), 990-999.

Tuutijärvi, T.; Vahala, R.; Sillanpää, M.; Chen, G. Maghemite nanoparticles for As(V) removal: Desorption characteristics and adsorbent recovery. Environ. Technol. **2012**, 33, 1927–1936.

Ucar, C., Baskan, M.B., Pala, A., 2013. Arsenic removal from drinking water by electrocoagulation using iron electrodes. Korean J. Chem. Eng. 30, 1889–1895.

Ungureanu, G., Santos, S., Boaventura, R., Botelho, C., 2015. Arsenic and antimony in water and wastewater: overview of removal techniques with special reference to latest advances in adsorption. J. Environ. Manag. 151, 326-342.

United Nations Sustainable Development Goals. 2022. Retrieved from: https://sdgs.un.org/goals, retrieved on August 17, 2022.

Upadhyay, A.K., Singh, R., Singh, D.P.P., 2020. Restoration of Wetland Ecosystem: A Trajectory Towards a Sustainable Environment, Restoration of Wetland Ecosystem: A Trajectory Towards a Sustainable Environment. Springer Singapore, Singapore, http://dx.doi.org/10.1007/978-981-13-7665- 8.

Uppal, H., Chawla, S., Joshi, A.G., Haranath, D., Vijayan, N., Singh, N., 2019. Facile chemical synthesis and novel application of zinc oxysulfide nanomaterial for instant and superior adsorption of arsenic from water. J. Clean. Prod. 208, 458-469.

Urbano, B.F., Villenas, I., Rivas, B.L., Campos, C.H., 2015. Cationic polymer–TiO2 nanocomposite sorbent for arsenate removal. Chem. Eng. J. 268, 362–370.

Vaishya, R.C., Gupta, S.K., 2003. Modelling arsenic (III) adsorption from water by sulfate-modified iron oxide-coated sand (SMIOCS). J. Chem. Technol. Biotechnol. 78, 73–80. doi:10.1002/jctb.745

Vasudevan, S., Lakshmi, J., Sozhan, G., 2010a. Studies Relating to Removal of Arsenate by Electrochemical Coagulation: Optimization, Kinetics, Coagulant Characterization. Sep. Sci. Technol. 45, 1313–1325.

Vega-Hernandez, S., Weijma, J., Buisman, C.J., 2019. Immobilization of arsenic as scorodite by a thermoacidophilic mixed culture via as (III)-catalyzed oxidation with activated carbon. J. Hazard Mater. 368, 221-227.

Velickovic, Z.; Bajic, Z.; Rsitic, M.; Djokic, V.; Marinkovic, A.; Uskokovic, P.; Vuruna, M. Modification of multi-wall carbon nanotubes for the removal of cadmium, lead and arsenic from wastewater. Dig. J. Nanomater Biostruct. **2013**, 8, 501–511.

Violante, A., Pigna, M., Del Gaudio, S., Cozzolino, V., Banerjee, D., 2009. Coprecipitation of arsenate with metal oxides. 3. Nature, mineralogy, and reactivity of iron (iii) - Aluminum precipitates. Environ. Sci. Technol. 43, 1515–1521. doi:10.1021/es802229r

Virkutyte, J., Sillanp€ aa, M., Latostenmaa, P., 2002. Electrokinetic soil remedia- € tiondcritical overview. Sci. Total Environ. 289 (1-3), 97-121.

Visanu, T., Jia, C.H., Nurak, G., Chih, H.L., 2011. Gas-bubbled nano zero-valent iron process for high concentration arsenate removal. J. Hazard. Mater. 186, 2123–2128.

Wang, C., Liu, H., Zhang, Y., Zou, C., Anthony, E.J., 2018. Review of arsenic behavior during coal combustion: volatilization, transformation, emission and removal technologies. Prog. Energy Combust. Sci. 68, 1-28.

Wang, C., Luo, H., Zhang, Z., et al., 2014a. Removal of As(III) and As(V) from aqueous solutions using nanoscale zero valent iron-reduced graphite oxide modified composites. J. Hazards. Mater. 268, 124–131.

Wang, J., Zhang, T., Li, M., Yang, Y., Lu, P., Ning, P., Wang, Q., 2018. Arsenic removal from water/wastewater using layered double hydroxide derived adsorbents, a critical review. RSC Adv. 8 (40), 22694-22709.

Wang, J.,Xu,W., Chen, L., Huang,X., Liu, J., 2014b. Preparation and evaluation of magnetic NPs impregnated chitosan beads for arsenic removal from water. Chem. Eng. J. 251, 25–34.

Wang, S., Gao, B., Li, Y., 2016. Enhanced arsenic removal by biochar modified with nickel (Ni) and manganese (Mn) oxyhydroxides. J. Indus. Eng. Chem. 37, 361–365.

Wang, S., Gao, B., Li, Y., Creamer, A.E., He, F., 2017. Adsorptive removal of arsenate from aqueous solutions by biochar supported zero-valent iron nanocomposite: batch and continuous flow tests. J. Hazards. Mater. 322, 172–181.

Wang, S., Gao, B., Li, Y., Wan, Y., Creamer, A.E., 2015b. Sorption of arsenate onto magnetic iron–manganese (Fe–Mn) biochar composites. RSC Adv. 5, 67971–67978.

Wang, S., Gao, B., Zimmerman, A.R., Li, Y., Ma, L., Harris, W.G., Migliaccio, K.W., 2015. Removal of arsenic by magnetic biochar prepared from pinewood and natural hematite. Bioresour. Technol. 175, 391–395. doi:10.1016/j.biortech.2014.10.104

Wang C, Liu X, Chen JP, Li K. Superior removal of arsenic from water with zirconium metal-organic framework UiO-66. Scientific reports. 2015 Nov 12;5(1):16613.\

Wei, Z., Liang, K., Wu, Y., et al., 2016. The effect of pH on the adsorption of arsenic(III) and arsenic(V) at the TiO2 anatase [101] surface. J. Colloid Interface Sci. 462, 252–259.

Wen, Z., Zhang, Y., Dai, C., Chen, B., Guo, S., Yu, H., Wu, D., 2014. Synthesis of ordered mesoporous iron manganese bimetal oxides for arsenic removal from aqueous solutions.

Microporous Mesoporous Mater. 200, 235–244. doi:10.1016/j.micromeso.2014.08.049

Westerhoff, P., Highfield, D., Badruzzaman, M., Yoon, Y., 2005. Rapid small-scale column tests for arsenate removal in iron oxide packed bed columns. J. Environ. Eng. 131, 262–271.

WHO. 2001. *United Nations synthesis report on arsenic drinking water.* World Health Organization.

Wiesner, M. (1993) *An overview of AP membrane process*. Association of Environmental Engineering professors, San Antonia, Texas, June 7.

Wilkie, J.A., Hering, J.G., 1996. Adsorption of arsenic onto hydrous ferric oxide: effects of adsorbate/adsorbent ratios and co-occurring solutes. Colloids Surf., A 107, 97–110.

Wu, C., Huang, L., Xue, S.G., Huang, Y.Y., Hartley, W., Cui, M. qian, Wong, M.H., 2017. Arsenic sorption by red mud-modified biochar produced from rice straw. Environ. Sci. Pollut. Res. 24, 18168–18178. doi:10.1007/s11356-017-9466-7

Wu, J., Huang, D., Liu, X., Meng, J., Tang, C., Xu, J., 2018b. Remediation of As (III) and Cd (II) co-contamination and its mechanism in aqueous systems by a novel calcium-based magnetic biochar. J. Hazard. Mater. 348, 10–19.

Wu, L.K., Wu, H., Liu, Z.Z., Cao, H.Z., Hou, G.Y., Tang, Y.P., Zheng, G.Q., 2018a. Highly porous copper ferrite foam: a promising adsorbent for efficient removal of As (III) and As (V) from water. J. Hazard. Mater. 347, 15–24.

Wu, L.K., Wu, H., Zhang, H.B., Cao, H.Z., Hou, G.Y., Tang, Y.P., Zheng, G.Q., 2018c. Graphene oxide/CuFe2O4 foam as an efficient absorbent for arsenic removal from water. Chem. Eng. J. 334, 1808–1819.

Xu, Y., Li, J., Xia, W., Sun, Y., Qian, G., Zhang, J., 2019. Enhanced remediation of arsenic and chromium co-contaminated soil by eletrokinetic-permeable reactive barriers with different reagents. Environ. Sci. Pollut. Control Ser. 26 (4), 3392-3403.

Xu, Z., Li, Q., Gao, S., Shang, J.K., 2010. As(III) removal by hydrous titanium dioxide prepared from one-step hydrolysis of aqueous TiCl4 solution. Water Res. 44, 5713–5721.

Yadav, M.K., Saidulu, D., Gupta, A.K., Ghosal, P.S., Mukherjee, A. 2021. Status and management of arsenic pollution in groundwater: A comprehensive appraisal of recent global scenario, human health impacts, sustainable field-scale treatment technologies. Journal of environmental chemical engineering 9, article number 105203.

Yadav, R., Sharma, A.K., Babu, J.N., 2016. Sorptive removal of arsenite [As(III)] and arsenate [As(V)] by fuller's earth immobilized nanoscale zero-valent iron NPs (F-nZVI)., Effect of Fe0 loading on adsorption activity. J. Environ. Chem. Eng. 4, 681–694.

Yamani, J.S., Miller, S.M., Spaulding, M.L., Zimmerman, J.B., 2012. Enhanced arsenic removal using mixed metal oxide impregnated chitosan beads. Water Res. 46, 4427–4434. doi:10.1016/j.watres.2012.06.004

Yan, H., Gao, Y., Wu, L., Wang, L., Zhang, T., Dai, C., Xu, W., Feng, L., Ma, M., Zhu, Y.G., He, Z., 2019. Potential use of the Pteris vittata arsenic hyperaccumulation regulation network for phytoremediation. J. Hazard Mater. 368, 386-396.

Yan, L., Hu, S., Jing, C., 2016. Recent progress of arsenic adsorption on TiO2 in the presence of coexisting ions: a review. J. Environ. Sci. 49, 74–85.

Yan, L., Tu, H., Chan, T., Jing, C., 2017. Mechanistic study of simultaneous arsenic and fluoride removal using granular TiO2-La adsorbent. Chem. Eng. J. 313, 983–992.

Yang X, Xia L and Song S (2016) Arsenic adsorption from water using graphene based materials as adsorbents: A critical review. Surf Rev Lett 10:1142.

Yang, X., Xia, L., Song, S., 2017. Arsenic adsorption from water using graphene-based materials as adsorbents: a critical review. Surf. Rev. Lett. 24, 1730001.

Yao, S., Liu, Z., Shi, Z., 2014. Arsenic removal from aqueous solutions by adsorption onto iron oxide/activated carbon magnetic composite. J. Environ. Heal. Sci. Eng. 12, 58. doi:10.1186/2052-336X-12-58

Yavuz, C.T.; Mayo, J.T.; Suchecki, C.; Wang, J.; Ellsworth, A.Z.; Couto, H.D.; Quevedo, E.; Prakash, A.; Gonzalez, L.; Nguyen, C.; Kelty, C.; Colvin, V.L. (2010) Pollution magnet: nano-magnetite for arsenic removal from drinking water. *Environ. Geochem. Hlth.* 32, 327-334.

Yavuz, C.T.; Mayo, J.T.; Yu, W.W.; Prakash, A.; Falkner, J. C.; Yean, S.; Cong, L.; Shipley, H.J.; Kan, A.; Tomson, M.; Natelson, D.; Colvin, V.L. (2006) Low-field magnetic separation of monodisperse Fe_3O_4 nanocrystals. *Science*. 314, 964-967.

Yazdani, M.R., Bhatnagar, A., Vahala, R., 2017. Synthesis, characterization and exploitation of nano-TiO2/feldspar-embedded chitosan beads towards UV□assisted adsorptive abatement of aqueous arsenic (As). Chem. Eng. J. 316, 370–382.

Yean, S.; Cong, L.; Yavuz, C.T.; Mayo, J.T.; Yu, W.W.; Kan, A.T.; Colvin, V.L.; Tomson, M.B. (2005) Effect of magnetite particle size on adsorption and desorption of arsenite and arsenate. *J. Mater. Res.* 20, 3255-3264.

Yeap, S.P., Lim, J., Ooi, B.S., Ahmad, A.L., 2017. Agglomeration, colloidal stability, and magnetic separation of magnetic nanoparticles: collective influences on environmental engineering applications.

Yin, H., Kong, M., Gu, X., Chen, H., 2017. Removal of arsenic from water by porous charred granulated attapulgite-supported hydrated iron oxide in bath and column modes. J. Clean. Prod. 166, 88–97.

Yoon, Y., Park, Y.K., Hwang, T.M., Yoon, D.H., Yang, Y.S., Kang, J.W. 2016. Comparative evaluation of magnetite–graphene oxide and magnetite-reduced graphene oxide composite for As(III) and As(V) removal. Journal of hazardous materials 304: 196-204.

Yu, L., Ma, Y., Ong, C.N., Xie, J., Liu, Y., 2015b. Rapid adsorption removal of arsenate by hydrous cerium oxide–graphene composite. RSC Adv. 5, 64983–64990.

Yu, Y., Yu, L., Shih, K., Chen, J.P., 2018. Yttrium-doped iron oxide magnetic adsorbent for enhancement in arsenic removal and ease in separation after applications. J. Colloid Interface Sci. 521, 252–260.

Yuan, C., Chiang, T.S., 2007. The mechanisms of arsenic removal from soil by electrokinetic process coupled with iron permeable reaction barrier. Chemosphere 67 (8), 1533-1542.

Yuan, C., Chiang, T.S., 2008. Enhancement of electrokinetic remediation of arsenic spiked soil by chemical reagents. J. Hazard Mater. 152 (1), 309-315.

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

Zhang, G.; Ren, Z.; Zhang, X.; Chen, J. (2013) Nanostructured iron(III)-copper(II) binary oxide: A novel adsorbent for enhanced arsenic removal from aqueous solutions.*water res.* 47, 4022-4031.

Zhang, G.-S., Qu, J.-H., Liu, H.-J., Liu, R.-P., Li, G.-T., 2007. Removal Mechanism of As (III) by a Novel Fe−Mn Binary Oxide Adsorbent: Oxidation and Sorption. Environ. Sci. Technol. 41, 4613–4619. doi:10.1021/es063010u

Zhang, M., Gao, B., 2013. Removal of arsenic, methylene blue, and phosphate by biochar/AlOOH nanocomposite. Chem. Eng. J. 226, 286–292.

Zhang QL, Lin YC, Chen X, Gao NY. A method for preparing ferric activated carbon composites adsorbents to remove arsenic from drinking water. Journal of hazardous materials. 2007 Sep 30;148(3):671-8.

Zhang, Q.; Pan, B.; Zhang, W.; Pan, B.; Zhang, Q.; Ren, H. (2008) Arsenate removal from aqueous media by nanosized hydrated ferric oxide (HFO)-loaded polymeric sorbents: effect of HFO loadings. *Ind. Eng. Chem. Res.* 47, 3957-3962.

Zhang, T.; Sun, D. D. (2013) Removal of arsenic from water using multifunctional micro-/nano-structured MnO_2 spheres and microfiltration. *Chem. Eng. J.* 225, 271-279.

Zhang, W., Fu, J., Zhang, G., Zhang, X., 2014b. Enhanced arsenate removal by novel Fe–La composite (hydr)oxides synthesized via coprecipitation. Chem. Eng. J. 251, 69–79.

Zhang, Y., Dou, X., Zhao, B., Yang, M., Takayama, T., Kato, S., 2010. Removal of arsenic by a granular Fe–Ce oxide adsorbent., Fabrication conditions and performance. Chem. Eng. J. 162, 164–170.

Zhang, Y.X., Jia, Y., 2018. Synthesis of MgO/TiO 2/Ag composites with good adsorption combined with photodegradation properties. Mater. Sci. Eng: B 228, 123–131.

Zhao, D., Yu, Y., Chen, J.P., 2016. Fabrication and testing of zirconium-based nanoparticle-doped activated carbon fiber for enhanced arsenic removal in water. RSC Adv. 6, 27020–27030.

Zheng, Y.M., Yu, L., Wu, D., Chen, J.P., 2012. Removal of arsenite from aqueous solution by a zirconia NPs. Chem. Eng. J. 188, 15–22.

Zheng, Y.M.; Yu, L.; Wu, D.; Chen, J.P. (2012) Removal of arsenite from aqueous solution by a zirconia nanoparticle. *Chem. Eng. J.* 188, 15-22.

Zhu, J., Lou, Z., Liu, Y., et al., 2015a. Adsorption behavior and removal mechanism of arsenic on graphene modified by iron–manganese binary oxide (FeMnOx/RGO) from aqueous solutions. RSC Adv. 5, 67951–67961.

Zhu, J., Pigma, M., Cozzolino, V., Caporale, A.G., Violante, A., 2013. Higher sorption of arsenate versus arsenite on amorphous Al-oxide, effect of ligands. Environ. Chem. Lett. 11, 289–294.

Zhu, Y., Guo, H., Bhattacharya, P., Ahmad, A., Bundschuh, J., Naidu, R. (Eds.), 2019. Environmental Arsenic in a Changing World: Proceedings of the 7th Interna□tional Congress and Exhibition on Arsenic in the Environment (AS 2018), July 1- 6, 2018. CRC Press, Beijing, PR China.

Figure captions:

Figure 1: Mechanism of AS (III) and As (V) sorption on biosorbent surface. Possible chemical interactions like electrostatic interaction, hydrogen bonding, chelation, surface oxidation, ion exchange, precipitation etc. are shown on the surface of the bioadsorbent.

Figure 2: Synthesis pathway of novel photo-oxidation and adsorption based CuO-Fe_3O_4 magnetic material for As(III) removal. Under light irradiation, the nanoparticles can oxidize As(III) to As(V) completely through photo-oxidation within 60 minutes. Subsequently As(V) is adsorbed on the nanoparticles effectively.

Figure 3: TEM images of ceria associated manganese oxide nanoparticles showed garland like chain structure with void space, with varied particle sizes of 70-90 nm. And 15-20 nm. in two different samples. Reprinted with permission from Elsevier (Gupta et al., 2011), License number 5460580588820.

Figure 4: SEM images of ceria associated manganese oxide nanoparticles showed that the particles were interconnected in a sheet like structure. Reprinted with permission from Elsevier (Gupta et al., 2011), License number 5460580588820.

Figure 5: Possible mechanisms for arsenic removal on biochar-based materials. Conversion of AS (III) to As (V) and vice versa can happen because of the surface redox reaction. Arsenic species can diffuse into biochar, and can interact through electrostatic precipitation, H-Bonding etc.

Figure 6: General schematic diagram of As sorption on the surface of agglomerated nanoparticles by different pathways like H-bonding, electrostatic interaction, surface oxidation, complex formation, pore diffusion.

Figure 7: Schematic representation of the risk factors associated with nanomaterial application in arsenic treatment and possible mitigation options to minimize the risks.

Table captions:

Table 1: (Adsorption, ion-exchange, phytoremediation, Nano phytoremediation, phytobial remediation, reverse osmosis, chemical precipitation membrane technology, electrocoagulation etc.) Table 2: Arsenic removal capacity of various adsorbents.

Table 2: As (III) and As (V) removal capacity of various adsorbents.