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Magnetic Nanocomposites for Removal of Arsenic from Water

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Abstract: Arsenic significantly impacts human health and the environment and its removal from wastewater is still difficult. Magnetic nanoparticles have come to light as a viable arsenic remediation technique, providing a fresh and long-lasting water purification method. This study investigates the use of magnetic nanoparticles to remove arsenic by concentrating on their adsorption mechanism, kinetics, potential for adsorption, recovery, and promising use of this method in the future. Due to the extensive surface area and variable surface chemistry of magnetic nanoparticles, they can effectively adsorb arsenic from water sources. Because their magnetic properties simplify separation and regeneration, they may be used again with little to no efficiency loss. As a result, they reduce trash output by providing an ecologically acceptable alternative to traditional adsorbents. The present study also examines the kinetics and adsorption process of magnetic nanoparticles, emphasising their improved selectivity and capacity for adsorption. Due to these characteristics, the authors were able to successfully remove arsenic from wastewater, resulting in better water quality and decreased health hazards after exposure to arsenic. Additionally, the potential applications of magnetic nanoparticles in removing arsenic have been highlighted. It is envisaged that advances in material science and nanotechnology will create unique magnetic nanoparticles with even better performance. Combining hybrid materials and surface alterations can increase their effectiveness in wastewater treatment settings.

Key words: Magnetic, nano-adsorbents, arsenic, removal, wastewater, water.

Introduction

Arsenic is found in two forms in water bodies, i.e., As(III) and As(V), with concentrations ranging from 1 to 10 g/L (Ahmaruzzaman, 2011; Brammer et al., 2009; Magalhaes, 2002). Around 150 million people around the world drink arsenic-contaminated water (Ahmaruzzaman, 2011). Arsenic contamination of ground water is tricky in many countries worldwide, including India. Arsenic-contaminated water continues to be a problem in several sections of the country. As a result, their removal from aquatic bodies is critical. Adsorption has been recognised to be among the most effective strategies for eradicating arsenic species from aqueous bodies in this context because it is an upfront, swift, cost-effective, and controllable process (Mishra et al., 2023a). Adsorbent efficiency is mostly determined by surface characteristics and discernment for a specific adsorbate (contaminant). Nano-adsorbents are currently highly recommended for removing different Arsenic types from water. Nano-adsorbents have unique qualities, like tiny size, large surface-to-volume ratio, and strong reactivity, which makes them ideal adsorbents for removing aqueous contaminants like arsenic and other inorganic contaminants (Mishra et al., 2023b). Collecting, separating, and replacing the depleted nano-adsorbents are challenging once contaminants have been eliminated. Adsorbent loss and filter clogging are potential consequences of the orthodox approach for extracting nano-adsorbents. Attention is being paid to magnetic nanocomposite-based adsorbents (effective sorbent), which address separation problems. Pollutants are effectively removed from wastewater as well as water using magnetic filtering. To create clean water and avoid subsequent contamination, it is crucial to properly reclaim or distinguish the depleted magnetic nano-adsorbents that have been loaded with arsenic. This will increase the viability of deploying magnetic nano-adsorbents in large-scale systems for filtering water. This study highlights the advancement of novel magnetic nano-adsorbents for removing arsenic from water.

Removal of Arsenic by Magnetic Nanocomposite Adsorbents

Recently, specialists from all around the world have successfully remedied arsenic pollutants from water by using a variety of nano-adsorbents. Akaneite (b-FeO(OH)), which was produced in an aqueous solution of Fe(III) chloride and ammonium carbonate, was demonstrated to be efficient in removing arsenic from the aqueous phase. According to Deliyanni et al. (2003), akageneite has the maximal adsorption capability, 120 mg As (V) per gram. A hybrid surfactant-akaganeite mixture enhanced the removal of arsenic from the water phase (Deliyanni et al., 2006).

Accumulation and inadequate extraction can be addressed through mesoporous magnetic nanostructures. As a consequence, scientists produced mesoporous Fe_2O_3 that was bigger than aggregated nanoparticles and had a surface area of 35.7 m^2/g and a maximum capacity for absorbing arsenic of 73.2 mg/g (Zeng et al., 2021). Magnetic bimetallic oxide manganese ferrite ($MnFe_2O_4$) and nickel ferrite nanoparticles ($NiFe_2O_4$) were used, respectively, for the eradication of As(V) and As(III) (Hu et al., 2017; Karakaş et al., 2017). Arsenic was concurrently eradicated from water using "mesoporous $CoFe_2O_4$@MIL-100(Fe) hybrid magnetic nanoparticles (MNPs) with core-shell and mesoporous structure (diameter 260 nm)" (Yang and Yin, 2017). In another investigation, waste biomass was used to create Fe_3O_4-loaded activated carbon, which was then used as an adsorbent to remove arsenate from water (Liu et al., 2010). The composite exhibited outstanding adsorption performance, with the highest adsorption capacity of 204.2 mg/g for eliminating arsenate at a pH of 8.0. Sahu et al. (2017) showed that arsenate was removed from wastewater using a Fe_3O_4-loaded activated carbon adsorbent produced from biomass (Fe_3O_4/CSAC). This composite material's wide surface area (575.6 m^2/g), small particle size (10 nm), and increased magnetic characteristics (10.77 emu/g) make it effective for removing arsenic, with absorption capacities of 80.99 mg/g for As (V) and 107.96 mg/g for As (III), respectively. The removal of arsenic from water was aided by the hydroxyl groups on the surface of Fe_3O_4/CSAC. The goal of a novel form of carbon fabric-reinforced magnetite multiwalled carbon nanotube (Fe_3O_4-MWNTs) nano-composite is to reduce significant arsenic concentrations and desalinate seawater (Mishra and Ramaprabhu, 2010). Arsenite and arsenate were removed from saltwater by using nano-composite. By immobilising zerovalent iron nanoparticles on oxidised multiwalled carbon nanotubes (MWCNT) and using EDTA as a complexing agent, zerovalent iron nanoparticles were utilised for the removal of arsenic from water (Sankararamakrishnan et al., 2014). Arsenic elimination from aqueous bodies has been successfully conducted using the Fe_3O_4-modified graphene/CNT hybrid composite (Park et al., 2016). For arsenic removal, cellulose@iron oxide composite nanomaterials were produced using a one-step co-precipitation process and demonstrated excellent arsenic absorption ability, with mono-layer adsorption capabilities of 23.16 mg/g for arsenate and arsenite, correspondingly (Yu et al., 2013). A nano zero-valent iron-impregnated chitosan-carboxymethyl-cyclodextrin was satisfactorily assessed for arsenic removal (Sikder et al., 2014). After 3 hours, equilibrium was attained, and the arsenic concentration dropped to 20 g/L, indicating that 99 percent of the arsenic had been removed. For As(V) and As(III), the highest adsorption capabilities were 13.51 and 18.51 mg/g, respectively.

Binary and ternary magnetic composites containing TiO_2 and GO were created and utilised to extract arsenic from an aqueous solution using a straightforward co-precipitation method (Ramos Guivar et al., 2018). All types of nano-composites, from bare to ternary, showed increased arsenic adsorption capacities, with As (III) and As(V) having the highest values (83.1–110.4) and (90.2–127.2) mg/g, respectively. An easy method was used to create new Fe_3O_4@TiO_2 nano-composites with significant surface area (89.4 m^2/g) and magnetic susceptibility (20.0 emu/g) for eliminating arsenic (Deng et al., 2019). Less residual arsenic was present than the required 10 g/L amount. Furthermore, the arsenic removal procedure showed that the created magnetic Fe_3O_4@TiO_2 nano-composites, with their unusual structure, would be an effective adsorbent for arsenic removal due to the relatively mild inhibiting properties on typical coexisting ions, with the notable exception of silicate and phosphate. Babu et al. (2016) used Fe_2O_3/TiO_2 nano-composites based on reduced graphene oxide for the removal of both As (III) and As (V) in water. The graphene in the Fe_3O_4 nano-composite altered the humic acid coating, which increased arsenic removal. Arsenic removal capacity nearly quadrupled after coating with humic acid at a pH value of 7 (Paul et al., 2015; Rashid et al., 2018) in order to boost the elimination of arsenic from water. Electrophilic interactions among the nucleophilic functional groups of humic acid and the electrophilic arsenic atom of As (V) may occur. The carboxylate groups of humic acid form an ester-type bond with As (III).

Arsenic Adsorption Mechanism and Kinetics

Electrostatic, inner-sphere complexation, and ion exchange mechanisms are involved in arsenic adsorption on magnetic nanomaterials (Ahmaruzzaman and Sharma, 2015; Hu et al., 2017; Yang and Yin, 2017; Mohanta and Ahmaruzzaman, 2018; Ramos Guivar et al., 2018; Tamaddoni Moghaddam et al., 2019). FT-IR, zeta potential, X-ray photoelectron spectroscopy (XPS), and X-ray absorption spectroscopy (XAS) are used to examine the arsenic adsorption process. According to Hao et al. (2018), "bidentate binuclear corner-sharing complexes (2C) with an interatomic Fe-As distance of 3.35-3.39" develop after adsorption of As(V) on MNPs. According to Farideh et al. (2018), "bidentate binuclear corner-sharing complexes (2C) for As(V) and tridentate hexanuclear corner-sharing complexes (3C) for As(III)" were reported on MNP surfaces through extended X-ray absorption fine structure (EXAFS) spectra.

Adsorption kinetics is essential because it controls the process efficiency. Numerous kinetic models based on the solution concentration have been published (Redlich and Peterson, 1959; Sips, 1948; Vijayaraghavan et al., 2006) to characterise the adsorption systems' reaction sequence. Lagergren's first-order equation (Sips, 1948) and the pseudo-second-order (PSO) equation are the two most often used kinetic models for explaining the adsorption of a solute from a liquid solution. A significant amount of literature (Ahmaruzzaman and Gayatri, 2010a; Ahmaruzzaman and Gayatri, 2010b; Ahmed et al., 2014; Ahmed and Ahmaruzzaman, 2015; Ahmed and Ahmaruzzaman, 2016; Ahmaruzzaman et al., 2019) has used the PSO model, which fits the adsorption data very well. The pseudo-second-order equation was employed to illustrate chemisorption, which includes covalent forces between the adsorbent and adsorbate and valency forces via allocation of electrons or ion exchange. Arsenic adsorption from water has lately been widely researched, employing the PSO rate expression (Sips, 1948). The PSO kinetic model has also been used to define the adsorption of As (III)/As(V) on CDs-GO@Fe_3O_4 NPs (Kumar and Jiang, 2017). In most of the published research, As (III)/As (V) adsorption on several nano-adsorbents obeyed PSO kinetics.

Adsorption Potential and Recovery of Magnetic Nanocomposites

Arsenic elimination from wastewater has been researched by utilising a variety of traditional adsorbents. Surface area, pore size and volume, and physical strength are all distinctive physico-chemical features of adsorbents, in addition to inherent assistances and downsides in wastewater remediation. However, nano-adsorbents have shown promise in removing arsenic from aqueous solutions in recent years. For their maximal removal capacity and adsorption rate, magnetic nano-adsorbents have lately shown promise in eradicating As (III)/ As(V) from contaminated water. Sawdust/$MnFe_2O_4$ composite (506 mg/g), GO-$MnFe_2O_4$ (146 mg/g), and mesoporous $CoFe_2O_4$@MIL-100(Fe) (143.6 mg/g) are magnetic nano-adsorbents that stand out for significant adsorption capabilities for removing As(III) from polluted water. It has been reported that several magnetic nano-adsorbents, such as sawdust/$MnFe_2O_4$ composite (545 mg/g), GO-$MnFe_2O_4$ (207 mg/g), mesoporous $CoFe_2O_4$@MIL-100(Fe) (114.6 mg/g), and γ-Fe_2O_3-TiO_2-GO NPs (127.2 mg/g), also demonstrated excellent adsorption capabilities for As(V) removal from water.

The most significant benefits are the effective recovery of used-up nanomaterials and pollutant recovery following adsorption. To make the adsorption process less expensive and viable, it is critical to renew the exhausted adsorbent. Karakaş et al. (2017) showed that nickel ferrite nanoparticles were recovered using a 5 (N) NaOH solution after the adsorption of As(III). Using 0.1(M) NaOH, Arsenic was desorbed from AC loaded with zerovalent iron (Zhu et al., 2009). The results indicated that magnetic nano-adsorbents can be restored and employed to clean water.

Future Prospective

An inexpensive water purification technology is critical for meeting the needs of millions of people who require drinkable water. Various new nanomaterials with high adsorption capabilities have been developed in this regard. However, the costs associated with creating these materials varied widely, and only a small number of materials could be made for less money. As a result, the development of magnetic nano-composite materials depends on accessible, affordable, and practical arsenic removal processes. Arsenic removal from water has recently been accomplished using nanomaterials. These nanostructured materials lose some of their adsorption capacity when they are aggregated. The aggregation of pure magnetic nano-adsorbents decreases the efficacy of adsorption and elimination. To address these issues, nanoparticles are loaded with appropriate moieties, such as AC, biomass, charcoal, CNTs, and graphene oxide, improving adsorption characteristics and stability while increasing selectivity towards a specific metal. However, the cost of functionalising magnetic nano-adsorbents could be prohibitive, limiting their use in industrial wastewater treatment. More research is needed to create magnetic nanocomposites-based techniques for long-term filtration of arsenic-contaminated water. Secondary pollution (caused by using magnetic nanoparticles) needs to be controlled in an ecologically responsible way to preserve a healthy ecosystem. The magnetic nano-adsorbents synthetic technique is proposed to be re-engineered into a more benign procedure. After removing arsenic from nanoparticles, proper standards are required for their disposal, and recycling may be one of the options.

Conclusion

In conclusion, using magnetic nanoparticles to remove arsenic from wastewater has enormous potential as a cost-effective and long-term solution to the urgent problem of arsenic pollution in water sources. We have examined this developing technology's many facets in this study, demonstrating its promise as an effective remedial technique. The adsorption mechanism and kinetics of magnetic nanoparticles provide high surface area and active sites for effective arsenic removal. Magnetic nanoparticles are a desirable substitute for traditional adsorbents due to their greater adsorption capacity and selectivity, resulting in better water quality and decreased health concerns from arsenic exposure. Furthermore, recovering magnetic nanoparticles reduces environmental effects while improving economic feasibility. Because of their magnetic properties, which simplify separation and regeneration after adsorption, they may be used again with little to no efficiency loss. This feature promotes a sustainable approach to water treatment by addressing issues with the disposal of used adsorbents. Future applications of magnetic nanoparticles in the elimination of arsenic look promising. Nanotechnology and material science developments will probably result in the creation of brand-new, high-performance magnetic nanoparticles with improved selectivity and adsorption capability. They can perform even better in wastewater treatment settings by investigating hybrid materials and surface alterations. However, further investigation is required to improve their synthesis, comprehend their long-term stability, and assess their environmental effect before magnetic nanoparticles ultimately realise their promise. Scale-up studies and cost-effectiveness analyses are also necessary to evaluate their practical application in large-scale water treatment plants. In summary, magnetic nanoparticles present a fascinating and promising method for removing arsenic from wastewater. Future water treatment systems would benefit from their distinctive qualities, effective adsorption processes, and simplicity of recovery. By guaranteeing that people worldwide have access to safe and clean water, magnetic nanoparticles can significantly reduce the negative impacts of arsenic poisoning on human health and the environment with further study and development.

References

Ahmaruzzaman, M. and D.K. Sharma (2005). Adsorption of phenols from wastewater. *Journal of Colloid and Interface Science*, **287(1):** 14-24.

Ahmaruzzaman, M. and S.L. Gayatri (2010a). Batch adsorption of 4-nitrophenol by acid activated jute stick char: Equilibrium, kinetic and thermodynamic studies. *Chemical Engineering Journal*, **158(2):** 173-180.

Ahmaruzzaman, M. and S.L. Gayatri (2010b). Activated tea waste as a potential low-cost adsorbent for the removal of p-nitrophenol from wastewater. *Journal of Chemical & Engineering Data*, **55(11):** 4614-4623.

Ahmaruzzaman, M. (2011). Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals. *Advances in Colloid and Interface Science*, **166 (1-2):** 36-59.

Ahmaruzzaman, M., Mohanta, D. and A. Nath (2019). Environmentally benign fabrication of SnO_2-CNT nanohybrids and their multifunctional efficiency as an adsorbent, catalyst and antimicrobial agent for water decontamination. *Scientific Reports*, **9(1):** 1-19.

Ahmed, M.J.K., Ahmaruzzaman, M. and R.A. Reza (2014). Lignocellulosic-derived modified agricultural waste: Development, characterization and implementation in sequestering pyridine from aqueous solutions. *Journal of Colloid and Interface Science*, **428:** 222-234.

Ahmed, M.J.K. and M. Ahmaruzzaman (2015) A facile synthesis of Fe_3O_4-charcoal composite for the sorption of a hazardous dye from aquatic environment. *Journal of Environmental Management*, **163:** 163-173.

Ahmed, M.J.K. and M. Ahmaruzzaman (2016) A review on potential usage of industrial waste materials for binding heavy metal ions from aqueous solutions. *Journal of Water Process Engineering*, **10:** 39-47.

Babu, C.M., Vinodh, R., Sundaravel, B., Abidov, A., Peng, M.M., Cha, W.S. and H.T. Jang (2016). Characterization of reduced graphene oxide supported mesoporous Fe_2O_3/TiO_2 nanoparticles and adsorption of As(III) and As(V) from potable water. *Journal of Taiwan Institute of Chemical* Engineering, **62:** 199-208.

Brammer, H. and P. Ravenscroft (2009). Arsenic in groundwater: A threat to sustainable agriculture in South and South-East Asia. *Environmental International*, **35(3):** 647-654.

Deliyanni, E.A., Bakoyannnnakis, D.N., Zouboulis, A.I. and K.A. Matis (2003). Sorption of As(V) ions by akaganeite-type nanocrystals. *Chemosphere*, **50:** 155-163.

Deliyanni, E.A., Nalbandian, L.K. and A. Matis (2006). Adsorptive removal of arsenites by a nanocrystalline hybrid surfactant–akaganeite sorbent. *Journal of Colloid and Interface Science*, **302(2):** 458-466.

Deng, M., Wu, X., Zhu, A., Zhang, Q. and Q. Liu (2019). Well-dispersed TiO_2 nanoparticles anchored on Fe_3O_4 magnetic nanosheets for efficient arsenic removal. *Journal of Environmental Management*, **237:** 63-74.

Farideh, J.B., Najafpoor, A.A., Davoudi, M., et al. (2018). Adsorptive removal of arsenic from aqueous solutions using magnetite nanoparticles and silica-coated magnetite nanoparticles. *Environ. Prog. Sustainable Energy*, **37:** 951-960.

Gayatri, S.L. and M. Ahmaruzzaman (2010). Adsorption technique for the removal of phenolic compounds from wastewater using low-cost natural adsorbents. *Journal of Science and Technology*, **5(2):** 156-166.

Hao, L., Liu, M., Wang, N. and G. Li (2018). A critical review on arsenic removal from water using iron-based adsorbents. *RSC Adv.,* **8:** 39545-39560.

Hu, Q., Liu, Y., Gu, X. and Y. Zhao (2017). Adsorption behavior and mechanism of different arsenic species on mesoporous $MnFe_2O_4$ magnetic nanoparticles. *Chemosphere*, **181:** 328-336.

Karakaş, Z.K., Boncukcuoğlu, R. and I.H. Karakaş (2017). Adsorptive properties of As (III) from aqueous solution using magnetic nickel ferrite ($NiFe_2O_4$) nanoparticles: Isotherm and kinetic studies. *Separation Science and Technology*, **52(1):** 21-34.

Kumar, A.S.K. and S.J. Jiang (2017). Synthesis of magnetically separable and recyclable magnetic nanoparticles decorated with β-cyclodextrin functionalized graphene oxide an excellent adsorption of As(V)/(III). *Journal of Molecular Liquids*, **237:** 387-401.

Liu, Z., Zhang, F.S. and R. Sasai (2010). Arsenate removal from water using Fe_3O_4-loaded activated carbon prepared from waste biomass. *Chemical Engineering Journal*, **160(1):** 57-62.

Magalhaes, M.C.F. (2002) Arsenic: An environmental problem limited by solubility. *Pure and Applied Chemistry*, **74(10):** 1843-1850.

Mishra, A.K. and S. Ramaprabhu (2010). Magnetite decorated multiwalled carbon nanotube based supercapacitor for arsenic removal and desalination of seawater. *Journal of Physical Chemistry C*, **114:** 2583-2590.

Mishra, S.R., Gadore, V. and M. Ahmaruzzaman (2023). Novel 3D sphere-like β-In2S3/Biochar nanoflowers for remediation of dyes in single and binary systems and interpretation using statistical physical modeling. *Environmental Nanotechnology, Monitoring & Management*, **20:** 100807.

Mishra, S.R., Gadore, V. and M. Ahmaruzzaman (2023b). Development of high-performance bi-functional novel CdSnS2 atom clusters for adsorption of rose Bengal and AOP-assisted degradation of methylene blue. *Environmental Science: Water Research & Technology*, **9(2):** 586-602.

Mohanta, D. and M. Ahmaruzzaman (2018). Bio-inspired adsorption of arsenite and fluoride from aqueous solutions using activated carbon@SnO_2 nano-composites: Isotherms, kinetics, thermodynamics, cost estimation and regeneration studies. *Journal of Environmental Chemical Engineering*, **6(1):** 356-366.

Park, W.K., Yoon, Y.J., Kim, S., Yoo, S., Do, Y., Kang, J.W., Yoon, D.H. and W.S. Yang (2016). Feasible water flow filter with facilely functionalized Fe_3O_4-non-oxidative graphene/ CNT composites for arsenic removal. *Journal of Environmental Chemical Engineering*, **4:** 3246-3252.

Paul, B., Parashar, V. and A. Mishra (2015). Graphene in the Fe_3O_4 nano-composite switching the negative influence of humic acid coating into an enhancing effect in the removal of arsenic from water. *Environmental Science: Water Research and Technology*, **1:** 77-83.

Ramos Guivar, J.A., Bustamante D. A., Gonzalez, J.C., Sanches, E.A., Morales, M.A., Raez, J.M., López-Muñoz, M.J. and A. Arencibia (2018) Adsorption of arsenite and arsenate on binary and ternary magnetic nano-composites with high iron oxide content. *Applied Surface Science*, **454:** 87-100.

Rashid, M., Sterbinsky, G.E., Pinilla, M.Á.G., Cai, Y. and K.E. O'Shea (2018). Kinetic and mechanistic evaluation of inorganic arsenic species adsorption onto humic acid grafted magnetite nanoparticles. *Journal of Physical Chemistry C*, **122(25):** 13540-13547.

Redlich, O. and D.I. Peterson (1959). A useful adsorption isotherm. *Journal of Physical Chemistry*, **63:** 1024-1026.

Sahu, U.K., Sahu, S., Mahapatra, S.S. and R.K. Patel (2017). Cigarette soot activated carbon modified with

Fe_3O_4 nanoparticles as an effective adsorbent for As(III) and As(V): material preparation, characterization and adsorption mechanism study. *Journal of Molecular Liquids*, **243:** 395-405.

Sankararamakrishnan, N., Gupta, A. and S.R. Vidyarthi (2014). Enhanced arsenic removal at neutral pH using functionalized multiwalled carbon nanotubes. *Journal of Environmental Chemical Engineering*, **2:** 802-810.

Sikder, M.T., Tanaka, S., Saito, T. and M. Kurasaki (2014). Application of zero-valent iron impregnated chitosan-caboxymethyl β-cyclodextrin composite beads as arsenic sorbent. *Journal of Environmental Chemical Engineering*, **2:** 370-376.

Sips, R. (1948). The structure of a catalyst surface. *Journal of Physical Chemistry*, **16:** 490-495.

Tamaddoni Moghaddam, S., Naimi-Jamal, M.R., Rohlwing, A., Hussein, F.B. and N. Abu-Zahra (2019). High removal capacity of arsenic from drinking water using modified magnetic polyurethane foam nano-composites. *Journal of Polymers and the Environment*, **27(7):** 1497-1504.

Vijayaraghavan, K., Padmesh, T.V.N., Palanivelu, K. and M. Velan (2006). Biosorption of nickel(II) ions onto *Sargassum wightii*: Application of two-parameter and three-parameter isotherm models. *Journal of Hazardous Materials*, **133(1-3):** 304-308.

Yang, J.C. and X.B. Yin (2017). $CoFe_2O_4$@MIL-100(Fe) hybrid magnetic nanoparticles exhibit fast and selective adsorption of arsenic with high adsorption capacity. *Scientific Reports*, **7:** 40955.

Yu, X., Tong, S., Ge, M., Zuo, J., Cao, C., and W. Song (2013). One-step synthesis of magnetic composites of cellulose@iron oxide nanoparticles for arsenic removal. *Journal of Materials Chemistry A*, **1:** 959-965.

Zeng, H., Zhai, L., Zhang, J. and D. Li (2021). As(V) adsorption by a novel core-shell magnetic nanoparticles prepared with Iron-containing water treatment residuals. *Science of the Total Environment*, **753:** 142002.

Zhu, H., Jia, Y., Wu, X. and H. Wang (2009). Removal of arsenic from water by supported nano zero-valent iron on activated carbon. *Journal of Hazardous Materials*, **172:** 1591-1596.