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Research Article

Adsorption Behavior and Mechanistic Study of Arsenic Removal from Water Using Lanthanum Cobalt Ferrite Nano Composite Materials

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Abstract

The presence of arsenic in water bodies is one of the most important environmental and public health issues worldwide because of its persistence, toxicity, and cancer-causing properties. Water treatment technologies have been widely used have some drawbacks such as low efficiency, low selectivity, high water treatment cost and the loss of adsorbents. Lanthanum cobalt ferrite (LaCoFe) nanocomposite materials have been at the centre of much recent attention as potentially good adsorbent due to their high surface area, large number of active sites, magnetic separability and the good affinity for arsenic species. The present study is an in-depth study of the behaviour of adsorption and the mechanism of the removal of arsenic from an aquuous system using lanthanum cobalt ferrite nanocomposite material for its secondary research analysis. Literature search in scientific peer-reviewed journal from main scientific databases was conducted systematically to evaluate the effect of most operational parameters like solution pH, contact time, initial concentration of arsenic, adsorbent dosage, temperature, adsorption isotherm, adsorption kinetic and adsorption thermodynamic parameters. All of the studies reviewed demonstrated the good adsorption properties of lanthanum cobalt ferrite nanocomposites with optimization conditions that showed the adsorption mechanism was mainly monolayer adsorption and chemisorption according to the Langmuir isotherm and pseudo-second-order kinetic model. Furthermore, thermodynamic studies reported in the literature showed that the adsorption process is generally endothermic and spontaneous and mechanistic studies showed that the removal of arsenic is mainly attributed to electrostatic interactions, surface complexation, ligand exchange, ion exchange and pore diffusion. The magnetic property of the nanocomposite also supports the efficient separation and regeneration of the composite material and hence it is a potential material for water treatment application. Based on the results obtained, it can be concluded that lanthanum cobalt ferrite nanocomposites can be promising adsorbents for arsenic remediation that are sustainable and efficient. The review contributes to the existing knowledge by highlighting the current advancements in the mechanism of adsorption and suggesting future research directions, including application at the macro-scale, regeneration efficiency of the adsorbents, stability, and environmentally friendly synthesis methods of advanced nanocomposite adsorbents.

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1. INTRODUCTION

Safe and clean drinking water is a basic human right and an essential need for human well-being and sustainable development. However, pollution of water by toxic heavy metals and metalloids is recognized to be a serious worldwide environmental issue. Arsenic is well known to be one of the most toxic, persistent, mobile and bioaccumulative contaminants. Besides, the weathering of arsenic containing minerals and volcanic activities are the natural sources for arsenic contamination and its concentration in surface and groundwater has been enhanced significantly due to anthropogenic activities like mining, metallurgical industries, application of arsenic in pesticides, combustion of coal, and improper disposal of industrial effluents (Shaji et al., 2021; Smedley & Kinniburgh, 2002). The presence of arsenic in drinking water is a global public health problem, because millions of people in Bangladesh, India, China, Nepal, Vietnam, Argentina and other countries across South America are consuming water contaminated by arsenic.

As normally occurs in aquatic systems, it has two predominant inorganic oxidation states: arsenite (As (III)) and arsenate (As(V)). Of these, As (III) is more toxic, mobile and harder to remove due to its neutral molecular form in natural pH and conditions, while As(V) is mostly present in a negatively charged oxyanionic form, which is comparatively easier to be adsorbed by metal oxide-based adsorbents. Long-term arsenic exposure in drinking water has been associated with a variety of health effects including skin lesions, cardiovascular diseases, neurological diseases, diabetes, liver dysfunction, kidney damage and cancer (including skin, lungs, bladder, liver and kidney). Thus, World Health Organization (WHO) has recommended that drinking water should not contain more than 10 µg/L of arsenic to minimise adverse health effects.

There are lots of different technologies developed to remove arsenic from contaminated water, such as chemical precipitation, coagulation-flocculation, ion exchange, membrane filtration, electro coagulation, biological treatment and adsorption. Despite their different levels of success, these techniques are disadvantageous because of their high costs, production of sludge, fouling of the membrane, difficulty of maintenance and low efficiency when arsenic concentrations are low. In the treatment technologies that are available, adsorption has proven to be one of the more appealing, due to its simplicity, high removal efficiency, economic and environmental compatibility and ease of operation. If suitable adsorbent materials, which have high affinity and plenty of active site, are used, the adsorption process can effectively remove both arsenite and arsenate.

In recent years, the development of nanotechnology has revolutionized adsorption-based water treatment, by means of which the physicochemical properties of the nanostructure's adsorbents have been improved. Nanomaterials have extremely high specific surface area, high pore volume, tunable surface chemistry, large number of reactive functional groups, and better adsorption rate and adsorption kinetics than the traditional adsorbents. Their properties significantly improve removal of contaminants and shorten treatment time. Ferrite-based magnetic nanoparticles have been studied extensively owing to their remarkable adsorption efficiency, chemical stability, magnetizable feature and ability to be reused several times without causing significant secondary pollution.

The lanthanide cobalt ferrite (La-Co-Fe) nanocomposite class of magnetic materials is a novel and promising category of multifunctional magnetic arsenic remediating materials. Combination of lanthanum in cobalt ferrite structure increases surface hydroxyl groups and number of available adsorption sites due to its high affinity towards the arsenate ions. Cobalt ferrite provides high structural stability, magnetic property and mechanical strength, which is useful for effective separation of the treated water from the adsorbent using an external magnetic field. The synergic effect of lanthanum and cobalt ferrite increases the adsorption capacity, selectivity, and regeneration potential, and thereby makes the nanocomposites suitable for advanced applications in the area of water purification.

There are many possible physicochemical mechanisms such as electrostatic attraction, ligand exchange, ion exchange, inner-sphere surface complexation, hydrogen bonding, pore diffusion and surface precipitation that govern the arsenic adsorption onto lanthanum cobalt ferrite nanocomposites. Many operational parameters, including solution pH, contact time, dose of the adsorbent, initial arsenic concentration, temperature, competing ions, and physicochemical properties of the nanocomposite, affect the efficiency of the adsorption process. Knowing these adsorption processes is crucial to maximize treatment process parameters and to design and develop novel adsorbent materials.

During the last decade, a number of experimental studies have been conducted on the synthesis, characterization, adsorption performance, adsorption kinetics, adsorption isotherms, thermodynamics, and regeneration performance of lanthanum modified ferrite nanomaterials. These studies are, however, scattered and spread over scientific disciplines which make it cumbersome to come up with a complete knowledge of adsorption behavior and mechanistic pathways. A critical review of literature is thus imperative to review the current knowledge, to compare the adsorption performance with different experimental conditions, to find out common adsorption mechanisms and to identify the gaps for future research.

Hence, the present study will be of a secondary research type, which will involve a thorough review and critical analysis of published scientific literature. The study reviews the adsorption behaviour of arsenic onto lanthanide cobalt ferrite nanocomposite materials based on the literature review of the peer-reviewed articles indexed in respected scientific database journals. Special focus is given to the influence of operational parameters, adsorption kinetics, adsorption isotherms, thermodynamic property, regeneration capacity and mechanism involved in the arsenic removal process. This research aims to synthesize the results from various studies to achieve an overall understanding of the performance of lanthanum cobalt ferrite nanocomposites as a good candidate for the remediation of arsenic from water, as well as to point out the possible direction of future research for the development of sustainable, efficient, and scalable water treatment technologies for the remediation of arsenic from water.

2. LITERATURE REVIEW

Due to its toxicity, persistence, and detrimental human health effects, the contamination of arsenic is a major environmental issue worldwide. Adsorption has been the subject of many studies as a practical and environmentally friendly method of arsenic removal. With the recent development of nanotechnology, the production of magnetic nanocomposite adsorbents with better adsorption performance, such as La-modified ferrite materials, has been accelerated.

Smedley and Kinniburgh (2002) offered one of the first comprehensive reviews of arsenic occurrence in groundwater, showing that, in many countries, natural geological processes are the main source of contamination to groundwater. They paved the way for further arsenic remediation technology research.

According to Shaji et al. (2021), arsenic contamination is a problem for millions of people around the world, and adsorption is one of the simplest and most effective treatment techniques due to its operational ease, lower cost and high removal efficiency. They also noted the greater significance of the water purification with the use of adsorbents based on nanomaterials.

Koh, Yang and Chen (2022) comprehensively reviewed all lanthanides-based adsorbents and found that lanthanide compounds have high affinity to the inorganic anions, especially arsenate, owing to the strong Lewis acid property and the formation of the stable inner sphere complex. They noted that incorporation of lanthanum has a significant improvement in the adsorption activity than the conventional adsorbents.

The study of ferrite nanoparticles has shown that magnetic iron oxide nanoparticles possess high surface area, high adsorption rate, chemical stability, and easy magnetic separation. All these properties greatly decrease the operational costs and enhance the recyclability of the adsorbent.

Research into Co substituted Ferrite Nanoparticles has indicated significant enhancements in arsenic removal. It was found that the incorporation of cobalt leads to an improvement of surface chemistry and improves the number of adsorption sites, which explains the increase in adsorption capacity. The pseudo-second-order models were always best fitted to the kinetic analyses of arsenic adsorption, and both the Langmuir and Freundlich models were good fits to the equilibrium adsorption data.

The investigation on Al-substituted CoFe nano-adsorbent also showed that it has the adsorption capacity of As (III) and As (V) more than many conventional adsorbents. The spectroscopic analyses revealed that the ligand exchange reaction, the presence of surface hydroxyl groups, and the redox interaction are important mechanisms for arsenic adsorption. The study also verified that the pseudo-second-order equation is suitable to describe the adsorption process.

Lanthanum hydroxide has also been found to be an extremely good adsorbent for removal of arsenate. Experimental tests showed high adsorption capacities especially at mild acid conditions. The most prevalent adsorption process was determined to be ligand exchange (OH to as) and inner-sphere surface complexation, based on the XRD, FTIR, and XPS analyses.

García, Litter, and Sora, (2021) examined lanthanum ferrite ($LaFeO_3$) to assess its performances in the removal of arsenic and found good removal efficiencies especially for As (III) under photocatalytic conditions. Their results showed that the presence of iron active sites and lanthanum incorporation have beneficial effects on enhancing the arsenic removal efficiency.

The lanthanum modified adsorbents have been used to produce new products that continue to show excellent adsorption performance.Under alkaline conditions, lanthanum modified commercial adsorbents were able to remove over 98% of arsenic, as reported by Byun et al. (2026). It was shown from BET and FTIR analyses that lanthanum modification resulted in an increase of surface area and acid sites which improved the adsorption performance and gave good practical use in flow-through systems.

Similarly, to simultaneously remove arsenic and other contaminants, Yang et al. (2026) have generated lanthanum modified magnetic biochar. When they tried a mixture of magnetic particles and lanthanum, they found the synergy to be very effective, enhancing adsorption efficiency, reusability, and resistance to interfering ions.

The advanced ferrite-based nanocomposites have been further developed by incorporating 2-D materials. Recent study of MXene-functionalized CoFe2O4 revealed increased surface functional group, magnetic separation efficiency, adsorption capacity and reusability, which indicated that the adsorption property of MXene functionalized CoFe2O4 for arsenate is enhanced. The results indicate that the multifunctional nanocomposites are important in the field of water purification.

It is reported that solution pH, contact time, initial arsenic concentration, dosage of adsorbent, temperature, and competing ions affect the efficiency of adsorption in the literature. Most studies have reported maximum adsorption at neutral or slightly acidic pH values because the interaction between arsenic species and the surface hydroxyl groups is the strongest at these pH values. The adsorption equilibrium is basically reached in a short period of time due to the high specific surface area and large number of active adsorption sites of nanocomposite materials.

The majority of published investigations additionally reveal that the Langmuir isotherm is the most suitable adsorption isotherm for the model of adsorption equilibrium; therefore, it is suggested that the adsorption takes place as monolayer due to homogeneous active sites, while the adsorption kinetics are represented by the pseudo-second-order model, which corresponds to the adsorption mechanism of chemisorptions. Thermodynamic analysis of most of the studies generally shows negative Gibbs free energy values, thus confirming spontaneous adsorption, and positive enthalpy values that show endothermic adsorption processes.

From the literature reviewed it can be concluded that the lanthanum modified ferrite nanocomposites have the adsorption capacity of lanthanide and magnetic recovery power of ferrite material and thus can be used as very effective adsorbents for arsenic removal. However, the majority of studies conducted are at the laboratory scale and there are relatively few studies that consider regeneration efficiency, long-term stability, pilot scale results, cost assessment, and environmental sustainability in a comprehensive way. The need to undertake the present secondary research study, in order to present a comprehensive understanding of the adsorption behavior and mechanistic pathways of arsenic removal using lanthanum cobalt ferrite nanocomposite materials, stems from these limitations.

3. Research Gap

In the past 20 years, water contamination by arsenic has been extensively explored, and a number of adsorbent materials (including activated carbon, metal oxides, biochar, zeolites, graphene composites and magnetic nanoparticles) have been developed. Lanthanum modified ferrite nano-composites have been proved to be good adsorbents due to their high adsorption capacity, magnetic recovering property, and chemical stability in recent years. There are several important research gaps that need to be addressed, though many experimental studies have shown promising results with respect to arsenic removal from water using lanthanum cobalt ferrite nanocomposites. Most of the research published so far is limited to laboratory-scale production of the adsorbents and to adsorption performance testing conditions. Full studies of adsorption mechanisms are still rare. The interaction of arsenic species with the active sites of the lanthanum cobalt ferrite nanocomposites have not been consistently reported and explained in the different reports and therefore the dominant adsorption mechanisms have been interpreted differently. The current studies are focused mainly on the individual adsorption parameters, such as pH, contact time, adsorbent dosage, or initial arsenic concentration. There is a lack of research that considers the operational variables together to study their influence on the efficiency of adsorption and the practical use of water treatment.

The present study aims to fill these gaps by performing an extensive secondary analysis of the published literature to obtain an integrated understanding of the arsenic adsorption using lanthanum cobalt ferrite nanocomposite materials and future research directions for achieving the sustainable water treatment technologies.

4. Statement of Problem

Groundwater contamination with arsenic is still a major environmental and public health problem in the world. Although the World Health Organisation (WHO) suggests arsenic should be present in drinking water at a maximum of 10 micrograms per litre, millions of people in developing countries, where groundwater is the predominant source of drinking water, are still at risk from consuming drinking water with arsenic concentrations above that recommended. The long-term effects of arsenic exposure are severe health effects including skin, heart, neurological and cancer issues.

5. RESEARCH OBJECTIVES

To achieve this, scientific literature was comprehensively analyzed to critically evaluate the adsorption behavior and removal mechanisms of arsenic from aquatic systems using lanthanum cobalt ferrite nanocomposite materials.

1. To assess the adsorption efficiency of lanthanum cobalt ferrite nanocomposite materials for the arsenic removal from water system at various operating conditions.
2. To understand the adsorption behavior and mechanism of arsenic removal by analyzing the adsorption isotherms, kinetic models and the thermodynamic characteristics reported in the literature.
3. To evaluate effectiveness, regeneration potential and future applicability of lanthanum cobalt ferrite nanocomposite materials as sustainable adsorbent for arsenic removal from water treatment.

6. RESEARCH METHODOLOGY

6.1 Research Design

This research is a qualitative secondary research that is obtained by studying and analyzing the scientific literature that has been published. The aim of this study is not to produce primary experimental data, but instead the results from previously published peer-reviewed research were compiled and analyzed to assess the adsorption behavior and removal mechanism for arsenic in the use of lanthanum cobalt ferrite nanocomposite materials.

The secondary research approach was chosen as it allows combining evidence from different studies which allows comparison of the adsorption performance and mechanisms, kinetic models, equilibrium isotherms, thermodynamic characteristics, and operational parameters reported by various researchers. This way, you can get a general idea of what current research is going on and see what are the gaps and opportunities for future research.

6.2 Data Sources

Secondary data was gathered from well-known scientific databases and digital libraries to ensure reliability, credibility and quality of the reviewed literature.

7. DISCUSSION AND ANALYSIS

7.1 Adsorption Capacity Comparison

Published literature analysis shows that lanthanum cobalt ferrite (LaCoFe) nanocomposite material has excellent adsorption performance for the removal of arsenic from aqueous systems. The improvement in adsorption efficiency is mainly due to the synergistic effect of lanthanum and cobalt ferrite, in which lanthanum has high affinity towards arsenic oxyanion and cobalt ferrite has magnetic recoverability, structural stability and high density of active surface sites.

These properties of lanthanum cobalt ferrite nanocomposites are found consistently to be superior to traditional adsorbents like activated carbon, natural clays, zeolites and unmodified iron oxides.

From the reviewed studies, the following physicochemical properties of the nanocomposite were found to be affecting the adsorption capacity: specific surface area, pore volume, particle size, crystallinity, magnetic properties, and the presence of surface hydroxyl groups. Hydrothermal and sol–gel processes yield smaller particle size and higher surface area for the nanoparticles than conventional ceramic processes and thus are able to show higher adsorption capacities.

Some works have shown that the addition of lanthanum to CoFe significantly enhances the number of active adsorption sites that are involved in the arsenic uptake process. Lanthanide ions have a high positive charge density and can readily form stable inner-sphere complexes with arsenate species and have strong chemical affinity for these species. At the same time, the cobalt ferrite provides better structural stability and for magnetic separation after adsorption can be quickly removed from the nanocomposite, which makes it applicable in repeated use. Comparative analyses also demonstrate that the magnetic lanthanum modified ferrite materials have better performance than most of the conventional adsorbents, such as activated carbon, activated alumina, molecular sieves, and zeolites, which have lower adsorption capacities and are not so easily recycled. Magnetic nanocomposites can be easily removed from the treated water with the help of external magnetic field, which helps in reduction of operational cost and secondary waste generation, unlike activated carbon and some mineral adsorbents, which require the complicated process of filtration after absorption.

Literature further shows that the capacity for arsenic adsorption is dependent on the nature of arsenic species. The removal efficiencies for arsenate [As(V)] are generally higher than arsenite [As (III)] due to the predominance of negatively charged oxyanions in solution which are easily attracted to the positively charged lanthanum active sites and undergo ligand exchange. Conversely, under close to neutral pH conditions, the arsenite species may be neutral (H_3AsO_3), with relatively weak interaction with surface of the adsorbent.

Variations in adsorption capacity observed in different studies have been primarily attributed to the differences in the synthesis procedure, the calcination temperature, the particle morphology, the solution chemistry, and operating conditions. The pH, competition ions, contact time, amount of adsorbent, initial concentration of arsenic, and others are important parameters affecting adsorption performance. It should be noted then that the numbers given for adsorption capacities in the various studies cannot be compared directly, as the conditions under which the experiments are carried out seldom are identical.

The overall literature review shows that Lanthanum cobalt ferrite nanocomposite materials have better adsorption capability than a lot of traditional adsorbents. These nanocomposites are also highly promising for the use in advanced arsenic remediation technologies due to their high adsorption efficiency, fast adsorption rate, magnetic separability, chemical stability, and regeneration.

Table 7.1 Comparison of Adsorption Performance Reported in the Literature

Adsorbent Material	Major Characteristics	Relative Adsorption Performance	Key Observations
Activated Carbon	High surface area	Moderate	Limited selectivity toward arsenic; regeneration may reduce efficiency.
Iron Oxide Nanoparticles	Strong affinity for arsenic	High	Effective adsorption but difficult separation without magnetic modification.
Cobalt Ferrite Nanoparticles	Magnetic and chemically stable	High	Good adsorption performance with easy magnetic recovery.
Lanthanum-Based Adsorbents	High affinity for arsenate	Very High	Excellent adsorption due to surface complexation and ligand exchange.
Lanthanum Cobalt Ferrite Nanocomposites	Magnetic, high surface area, abundant active sites	Excellent	Superior adsorption efficiency, rapid equilibrium, easy magnetic separation, and good regeneration potential.

The overall results show that lanthanum cobalt ferrite nanocomposites are a promising development of the adsorption water treatment technologies. The enhanced performance can be attributed to the synergistic effect between lanthanum and cobalt ferrite that improves the adsorption capacity and the practical use of this material. Lanthanum supports chemically active adsorption sites that can form strong complexes with arsenic species and cobalt ferrite provides magnetic recoverability and structural durability. Moreover, the studies reviewed all indicate that the efficiency of adsorption is not only dependent on the intrinsic properties of the nanocomposite but also on factors such as solution pH, amount of adsorbent, contact time and initial concentration of arsenic. Therefore, optimization of these parameters is crucial to improve the adsorption capacity in practical water treatment applications. The results indicate that further research and development efforts in the transition of lanthanum cobalt ferrite nanocomposites from laboratory settings to large-scale water purification applications should be directed at scalable synthesis methods, long-term regeneration studies and pilot-scale applications.

7.2 Effect of Initial Arsenic Concentration

Amongst all the factors, the initial concentration of arsenic in the aqueous solution is one of the most important factors which affect the adsorption efficiency of lanthanum cobalt ferrite nanocomposite material. The literature indicates that the higher the concentration of arsenic at the start of the process, the more the adsorbent can be expected to have an increased adsorptive capacity, and the percentage efficiency of removal may drop after a certain concentration of the arsenic.

In the lower concentration range, there are many more active adsorption sites on the surface of the nanocomposite that are not occupied, enabling the rapid adsorption of arsenic species by electrostatic attraction and ligand exchange as well as surface complexation. The higher the concentration of arsenic, the bigger the concentration gradient between the aqueous and adsorbent surface, the more mass transfer occurs, and then the more arsenic is adsorbed per mass of adsorbent.

At higher arsenic concentrations the number of active sites will slowly become saturated and the percentage removal efficiency will decrease. This phenomenon is due to the fact that the number of arsenic ions in solution is larger than the adsorption sites on the surface of the nanocomposite. Thus, the adsorption capacity (mg/g) is proportional to the initial concentration; however, the adsorption percentage tends to decrease with increasing initial concentration.

The analysis of the literature suggests that lanthanum cobalt ferrite nanocomposites are capable of effectively removing arsenic even at high concentration of arsenic because of the presence of large number of active sites such as hydroxyl groups on the surface of the nanocomposites. The improved adsorption performance is due to the strong interaction between lanthanum centers and the arsenic oxyanions, compared to the conventional iron oxide materials.Effect of initial concentration is also important and it gives info about the adsorption mechanism. A rapid increase in adsorption capacity at higher concentrations suggests that surface diffusion and chemical interaction between arsenic species and active sites play important roles in the adsorption process.

7.3 Effect of Temperature

Temperature is one of the factors that can affect the efficiency of arsenic adsorption, as it can affect the interactions between the surfaces, the rate of diffusion, and the interactions between arsenic species and the surfaces of the adsorbent. The literature studies of lanthanum cobalt ferrite and related ferrite nanocomposites showed that the adsorption capacity typically increases with increasing temperatures, which implies that in most cases the adsorption of arsenic is an endothermic process.

The mobility of arsenic ions in solution increases with increasing temperature and the mobility of arsenic ions to the active adsorption sites increases. Increased availability of reactive surface sites can also be achieved by modifying the interactions at surfaces and by promoting ligand exchange reactions with higher temperatures.

The enthalpy changes for adsorption ($\Delta H°$) from thermodynamic investigations reported in previous studies show the values are usually positive, meaning that energy is absorbed during the adsorption process. The behavior indicates that both inner-sphere complex formation and surface bonding play an important role in the uptake of arsenic. But if the increase of temperature is too high, it can adversely impact the adsorption efficiency because of changes in the structure of nanocomposites or reduction in the surface interactions. Thus, moderate temperatures are likely to be optimal for practical arsenic treatment applications. An advantage of lanthanum cobalt ferrite nanocomposites is their magnetic stability over a broad temperature range which may enable potential re-use and regeneration of the material.

In conclusion, lanthanum cobalt ferrite nanocomposites are a promising strategy for developing efficient, sustainable, and scalable technologies for arsenic removal. Further study incorporating material science, environmental engineering and application studies will be necessary for the successful implementation.

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