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USE OF ZEOLITES AND INNOVATIVE NATURAL FILTERING MATERIALS IN DRINKING AND WASTEWATER TREATMENT TECHNOLOGIES

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Abstract
The article discusses methods for purifying natural and wastewater from heavy metals using zeolites and various filter materials. Heavy metals are characterized as priority pollutants of the aquatic environment, and the need for their removal from water is justified. The authors consider the physicochemical properties of zeolites, their ion exchange and sorption capacities, as well as the effectiveness of other loading materials, such as activated carbon. The main water purification technologies used to remove heavy metal ions, including filtration, sorption, and combined methods, are analyzed. The areas of application of these technologies in water treatment and wastewater treatment systems are considered. A comparative analysis of the effectiveness of various filter material is provided. Conclusions are made about the prospects for using zeolites and filter media to improve water purifications quality and ensure the environmental safety of water resources.
Key words: zeolites, heavy metals, water purifications, wastewater, filter materials, sorption, water treatment.

Introduction

The relentless expansion of industrial activity and urbanization are exerting increasing anthropogenic pressure on the natural environment, especially on water resources. The contamination of both natural and wastewater with heavy metal ions is one of the most important environmental problems facing modern society due to their toxicity, tendency to bioaccumulate, and long retention in ecosystems. This highlights the need to develop and implement advanced, cost-effective water treatment technologies capable of reducing heavy metal concentration to levels that meet regularity requirements.

Purifying water form heavy metal ions requires the use of advanced methods and materials that can ensure optimal removal of contaminants. One of the most promising areas in this regard is the use of zeolites and other adsorbent materials characterized by pronounced sorption and ion exchange properties. Natural zeolites, distinguished by their abundance, environmental safety, and regenerative capacity, are attracting considerable attention and are widely used in both drinking water treatment and wastewater treatment systems.

Contemporary water treatment technologies are meticulously designed to enhance process efficiently while simultaneously mitigating operational expenses and minimizing adverse environmental impacts. The integration of advanced filtration and sorption methodologies, utilizing zeolites, activated carbon, expanded clay, and quartz sand, significantly elevates the quality of treated water, thereby broadening its spectrum of practical applications. In the face of increasingly stringent environmental regulations and escalating volumes of wastewater, the relentless development and refinement of purification technologies represent a critical imperative for ensuring environmental safety and fostering sustainable development.

Main body

Contamination of drinking water sources with heavy metals (both natural and anthropogenic) poses a serious threat to human health.

Heavy metals are natural chemical elements characterized be high atomic mass and density. These elements possess the inherent potential for toxicity, particularly when their concentration in environmental matrices exceed critical threshold levels. The deleterious effects of heavy metals on human health are accentuated by their propensity for bioaccumulation and the cumulative nature of their toxicological profiles. The most important heavy metals in drinking water are cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and chromium (Cr). These metals can enter water sources in various ways, for example, through industrial wastewater, agricultural waste containing pesticides and chemical fertilizers, and as a result of corrosion of pipeline systems [Afzal I. et al., 2024].

The contamination of aqueous reservoirs, particularly groundwater and surface water, by heavy metals poses multifaceted and deleterious implications for human populations. The spread of urban landscapes, industrial development, and the use of chemical fertilizers n agriculture have led to a sharp increase in the amount of toxic metal pollutants in aquatic ecosystems through industrial wastewater, urban drainage networks, and stormwater management systems [Zhang P. et al., 2023]. The aquatic environment is of paramount importance for two primary reasons: first, it serves as a direct pathway of exposure for living organisms via consumption processes such as drinking and cooking; second, water operates as a ubiquitous transport medium, efficiently conveying dissolved and particulate forms of metals over substantial distances, thereby facilitating their participation in the intricate cycling of substances within the ecosystem.

The widespread utilization of toxic heavy metals, such as lead (Pb), thallium (Tl), cobalt (Co), cadmium (Cd), and antimony (Sb), in industrial processes underscores their significant impact as environmental pollutants. Thallium, characterized by its potent biological effects, is particularly noteworthy despite its relatively low natural abundance. Its toxicological profile is marked by its ability to induce alopecia in human subjects. The deleterious consequences of heavy metal exposure often outweigh any potential benefits. For instance, prolonged exposure to antimony and chromium has been causally linked to carcinogenic outcomes, while lead poisoning is associated with a spectrum of neurodevelopment disorders in children, including intellectual deficits. Mercury toxicity manifests in the form of Minamata disease, a severe neurological condition, whereas cadmium exposure is implicated in Itai-Itai disease, characterized by osteomalacia and skeletal pain. The cumulative evidence underscores the imperative for stringent regulatory measures and mitigation strategies to curtail the adverse health effects associated with heavy metal contamination. Heavy metals can also cause toxicity in specific organs of the human body, such as nephrotoxicity, neurotoxicity, hepatotoxicity, skin toxicity, and cardiovascular toxicity, among others [Mitra S. et al., 2022].

Water quality is a global issue. The preservation of public health, food security, biodiversity, and additional ecosystem services is gradually being threatened by the intensification and escalation of freshwater pollution in both developed and developing countries [Singh V. et al., 2024]. Anthropogenic contamination of aquatic ecosystems represents a multifaceted challenge intricately linked to the socio-economic development of a region. Urbanization, intensification of agricultural production, industrial expansion, and energy sector growth are pivotal drivers exacerbating the influx of untreated wastewater into water bodies. Although extensive research has been conducted to evaluate water quality at a global scale, the magnitude and complexity of the issue persist as a subject of ongoing scientific inquiry. To formulate efficacious strategies for the preservation and enhancement of water quality, there is an imperative need for more granular and all-encompassing studies that comprehensively address the myriad interconnected factors contributing to this environmental concern.

In contemporary water treatment technologies, recent reviews underscore the active evolution of sorption and biosorption methodologies, encompassing the utilization of cutting-edge materials such as nanostructured and composite compounds. These advanced materials substantially enhance the selectivity and efficacy of metal ion extraction processes from aqueous solutions, thereby contributing to the augmentation of treated water quality and the mitigation of environmental impact.

Methods

Methods for removing heavy metals from natural and wastewater are a multifaceted field of research, including both traditional chemical and physicochemical approaches and modern adsorption, membrane, electrochemical, and biotechnological strategies. This diversity is due to the complexity of the tasks involved in removing toxic elements, as well as the specific nature of water treatment facilities.

The most common traditional methods are filtration, ion exchange, electrochemical treatment, chemical precipitation, solvent extraction, and adsorption. Adsorption is an important, economical, and practical alternative for water purification that is viable and most commonly used in filtration systems, mainly in developing countries [Rind I.K. et al., 2022].

Among modern technologies used to purify water from heavy metals, filtration methods using loading materials such as zeolites, activated carbon, quartz sand, etc. occupy a significant place. These technologies allow for the effective removal of dissolved metals from aqueous solutions. Adsorbents and filters demonstrate a high degree of purification from toxic elements such as mercury (Hg), lead (Pb) and cadmium (Cd).

A feed filter is usually understood to be a column (or pressure/non-pressure filter) filled with granular material (sand, anthracite, activated carbon, zeolite, biochar, etc.) through which water passes in a continuous mode [Propolsky D., Romanovski V., 2025]. In comparison with a laboratory batch, where the sorbent is mechanically mixed with the solution, the functioning of the filter in column is a more complex dynamic system. In this case, the filter function as a reactor with spatial distribution of concentrations along the vertical axis of the layer and in temporal dynamics. As a result, the key object of analysis becomes the breakthrough curves characterizing the kinetics of the sorption process, as well as the resource of the sorbent layer until the established standards are reached in the filtrate. These parameters play a critical role in optimizing the performance of the sorption column and ensuring the effectiveness of purification.

The most common scientifically and technologically significant areas, confirmed by reviews and applied articles in recent years, include:

1. Zeolites (natural and synthetic): function as highly efficient ion exchangers, but their effectiveness depends significantly on cation competition and the hydrochemical parameters of environment. Therefore, when using them, it is necessary to carefully select materials taking into account selectivity and operating conditions [Ola A., Walaa M.T., 2023].

2. Granular activated carbon and its composite materials: traditionally associated with organic sorbents, but when functionally modified, for example, by the introduction of hydroxide or oxide phases, they demonstrate the ability to extract ions through complexation and surface chemical reactions [Bakhta S. et al., 2024].

3. Biochar and its composite forms: these are promising low-cost sorbents that are actively developing in this field. Particular attention is paid to the transition from laboratory studies to real operating conditions and field tests, where the critical factors are the particle size distribution, mechanical strength, and stability of the physicochemical properties of materials [Raji Z. et al., 2023].

Zeolites, in particular clinoptilolite (Figure 1), as well as innovative natural filter materials, including biopolymers, biocoagulants, and mineral-based composites, have become the cornerstone of a new generation of water treatment technologies over the past five years. This has been made possible by their complex properties, including sorption and ion exchange capabilities, catalytic activity, and barrier functions. An additional advantage of these materials is the relative availability of raw materials, which makes them economically attractive for widespread use in drinking water and wastewater treatment processes [Fatemeh B., Ahad G., 2025].

Figure 1. Natural zeolite (clinoptilolite) (author's materials)

The natural structure of zeolite is an infinite lattice of three-dimensional tetrahedra consisting of Si and Al atoms connected by O atoms [Senila M., Cadar O., 2024]. It is this "structural charge" that makes zeolites cation exchangers: toxic cations (Pb^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, etc.) can replace the original cations in the channels and cavities, as well as attach themselves to the active centers of the surface.

In the context of engineering water treatment, it should be emphasized that cation exchange and surface complexation processes are characterized by high rates under favorable conditions. The incorporation of granular zeolite facilitates the formation of a filter bed with precisely controlled hydraulic characteristics, which is crucial for optimizing the performance of water treatment systems. At the same time, efficiency is determined not by the "name of the material", but by the specific type of zeolite (clinoptilolite or modified type), its particle size distribution, cation form (Na-form, Ca-form), and water composition [Dosa M. et al., 2022].

In the realm of advanced adsorption technologies, polymer adsorbents incorporating zeolite imidazolate frameworks (ZIFs) have garnered significant attention for their potential to effectively mitigate the presence of pollutants. These materials represent a cutting-edge development, leveraging the unique properties of their molecular architecture to achieve selective binding of diverse contaminant species. A comprehensive investigation has elucidated that the thickness of the filtration media is a critical parameter influencing the efficacy of pollutant removal. Specifically, a thick filter configuration, exemplified by a 16 cm layer, has demonstrated superior performance in eliminating a broad spectrum of pollutants, including oil, particulate matter, metal ions such as copper and zinc, surfactants, turbidity, and dissolved organic compounds. This empirical evidence underscores the potential of ZIF-based adsorbents as a robust and versatile solution for water purification applications. When this filter was used in the filtration process, many of the above contaminants were almost completely removed, which indicates its high filtering capacity and reliability in removing a wide range of pollutants [Mikilima T. et al., 2024].

Among the various methods for removing different particles in the final stages of treatment plants, physical adsorption stands out as one of the most effective approaches. Activated carbon (AC) is widely used as a modern adsorbent material, both in powered (PAC) and granular (GAC) forms [Cuomo M. et al., 2024]. The porous structure and large surface area of activated carbon give it high adsorption capacity, making it effective for removing microplastic particles from aquatic environments.

Traditional activated carbon adsorbents are carbonaceous materials whose adsorption efficiency is determined by their internal porous structure and surface chemical composition, without the integration of secondary functional phases [Chen H. et al., 2026]. High specific surface area, developed microporosity, and relatively low cost make these adsorbents preferable for use in drinking water and wastewater treatment technologies, especially in the context of organic pollutant removal.

Activated carbon occupies a preeminent position within the realm of adsorbents due to its exceptional performance characteristics. It is characterized by an extraordinarily high surface area, intricate porosity, robust mechanical strength, chemical inertness, and non-biodegradable precursors, offering a wide spectrum of applications across various industrial and environmental sectors. Recent studies have shown that activated carbon made from biodegradable waste has a number of advantages as it is more economical, reproductible, and sustainable compared to traditional methods [Pet I. et al., 2024]. The surface modification of activated carbon, including functionalization, markedly enhances its adsorption capacity, rendering it highly effective in wastewater treatment applications. Activated carbon, whether in granular or powdered forms, has been extensively employed for water decolorization, odor neutralization, metal extraction, and the adsorption of organic contaminants.

In the contemporary landscape of adsorption technology, a particularly promising avenue of research and application involves the synergistic utilization of zeolites in conjunction with other sorbents, such as activated carbon. This innovative approach has demonstrated remarkable efficacy in the removal of micropollutants from aqueous environments. Experimental findings indicate that hybrid systems incorporating zeolite and activated carbon can achieve adsorption efficiencies of up to 69% for micropollutants. It is noteworthy that this technological solution does not result in a substantial escalation in operational costs and does not compromise the quality of the final purified product.

Experimental part

The experimental segment is dedicated to the rigorous investigation of the efficacy of purifying aqueous solutions contaminated with heavy metal ions via a loading filter equipped with o composite sorption load comprising activated carbon and natural zeolite. The primary objective of this experiment was to systematically reduce the concentrations of various heavy metal ions, including Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+} and others, while simultaneously enhancing the organoleptic and physicochemical properties of the water. Additionally, the study sought to evaluate the feasibility and potential of water reuse, thereby contributing to the broader discourse on sustainable water management and environmental remediation.

The focus of this investigation is a model wastewater system designed to mimic industrial effluents containing heavy metal ions. The initial water matrix exhibited elevated concentrations of dissolved metal cations, absent suspended particulates, and a neutral to slightly acidic pH (ranging from 5.5 to 6.8). Sample collection was meticulously executed using chemically inert containers, with rigorous precautions to prevent secondary contamination. The samples were subsequently transported to the laboratory for detailed analysis.

Water purification was conducted using a batch-type laboratory unit, specifically a vertical filtration column tailored for adsorption and ion exchange processes in aqueous solutions. During this study, natural zeolite and activated carbon were employed as sorbent materials to remove heavy metal ions from the aqueous matrix. Both sorbents were pre-fractionated into particles measuring 1.25-2.5 mm in diameter. This particle size range is commonly utilized in water treatment systems, providing an optimal balance between hydraulic resistance and a high specific surface area, thereby enhancing sorption efficiency.

The filtration system employed a two-layer composition of activated carbon and natural zeolite as the primary adsorbent matrix. Activated carbon was tasked with the sorption of dissolved organic compounds and selective removal of metal ions, thereby contributing to the overall contaminant reduction. Zeolite, on the other hand, facilitated highly efficient ion-exchange processes, specifically targeting the extraction of heavy metal cations from the aqueous solution. This synergetic combination significantly enhanced the purification efficacy of the system.

The filtration apparatus was meticulously constructed with a layer-by-layer loading technique, ensuring a uniform distribution of the materials along the vertical axis of the column. This strategic arrangement optimized the adsorption and ion exchange kinetics, thereby maximizing the water purification efficiency.

For a detailed and clear presentation of the experimental setup in this study, a diagram is provided (Figure 2). This illustrative material demonstrates the process of water filtration through a loading filter with combined sorption loading, which allows visualization of the key elements of the filtration system. The diagram clearly shows the raw water inlet, the filtration column, the layer-by-layer loading of activated carbon and zeolite, and the purified water outlet. This diagram allows for a comprehensive analysis of the flow direction and the mechanism of the filter's operation in the process of sorption and ion exchange purification of water from heavy metal ions, which is critical for understanding the effectiveness and applicability of this technology in conditions of high pollutant concentration.

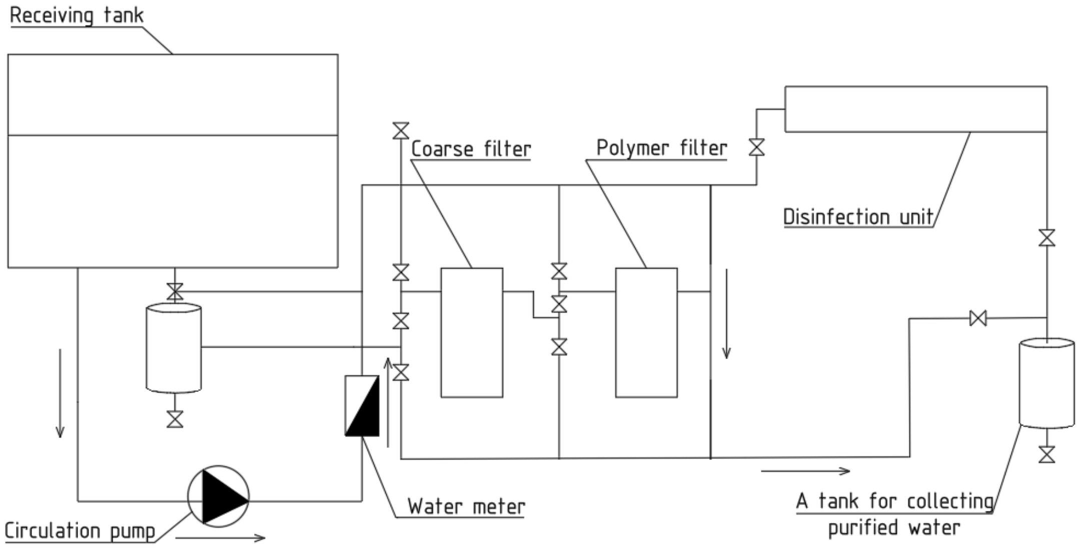

Figure 2. Technological diagram of purification

The filtration process of the investigated water environment was conducted in a downward flow configuration at a constant volumetric flow rate. As the water permeated through the loading filter, intricate sorption and ion exchange mechanisms were activated, facilitating the efficient retention of heavy metal ions within the activated carbon matrix and within the crystal lattice of the zeolite. Over the course of filter operation, a progressive saturation of the sorption layer was evident, concomitantly including alterations in the physicochemical parameters of the purified water.

Results

The effectiveness of the loading filter was assessed based on an analysis of the dynamics of heavy metal ion concentrations in the aqueous medium, as well as by monitoring changes in Ph values and transparency parameters. During the filtration process, a significant reduction in metal content was achieved, reaching values that met or approached regulatory standards. The purified water demonstrated a high degree of transparency, absence of turbidity, and stabilization of the acid-base balance in the pH range of 6.8-7.5, which indicates the high efficiency of the filtration process.

Through a meticulously designed and executed series of filtration experiments, it was conclusively demonstrated that the sorption media under scrutiny exhibited signs of partial saturation with respect to heavy metal ions. Notably, the zeolite component of the sorbent maintained its sorption capacity post-treatment with salt solutions or weak acids. Conversely, activated carbon necessitated thermal or chemical regeneration to reinstate its sorption properties. The deployment of regenerable materials notably enhances the operational longevity of the filtration system, thereby reducing lifecycle costs and fostering environmental sustainability. This approach not only ensures economic viability but also aligns with stringent ecological standards.

The use of activated carbon and zeolite-based loading filters is a highly effective and environmentally safe method of removing heavy metals from water resources. The environmental safety of this approach is due to its ability to prevent the migration of toxic elements into surface and groundwater aquifers, which helps to preserve the ecological balance and minimize the risk to biodiversity. The economic feasibility of this method is confirmed by the availability of sorbents, the possibility of their multiple regeneration, and the absence of the need to use expensive and complex equipment, which reduces operating costs and makes the technological attractive for widespread use.

Through comprehensive multicomponent experimental investigations, the remarkable efficacy of a loading filter equipped with integrated sorption media, comprising activated carbon and zeolite, has been conclusively demonstrated in the realm of aquatic detoxification from heavy metal ions. The meticulously gathered data, subjected to rigorous analytical scrutiny and validation protocols, underscores the substantial potential of this technology. This empirical evidence not only corroborates the effectiveness of the system but also presents novel opportunities for its integration into both localized and industrial water treatment frameworks, thereby enhancing the sustainability and efficiency of environmental remediation strategies.

As part of this study, an experiment was conducted on water filtration using zeolite and activated carbon, with the aim of studying the adsorption properties of these materials in conditions of water pollution. During the experiment, significant changes in the structure and compositions of the sorbents were recorded, caused by their interaction with the polluting components of the water matrix. A detailed analysis of the solid phase before and after the filtration procedure allowed not only a qualitative but also a quantitative assessment of the accumulation of metal ions in the adsorption materials, which confirms the high efficiency of adsorption processes in this system (Figures 3).

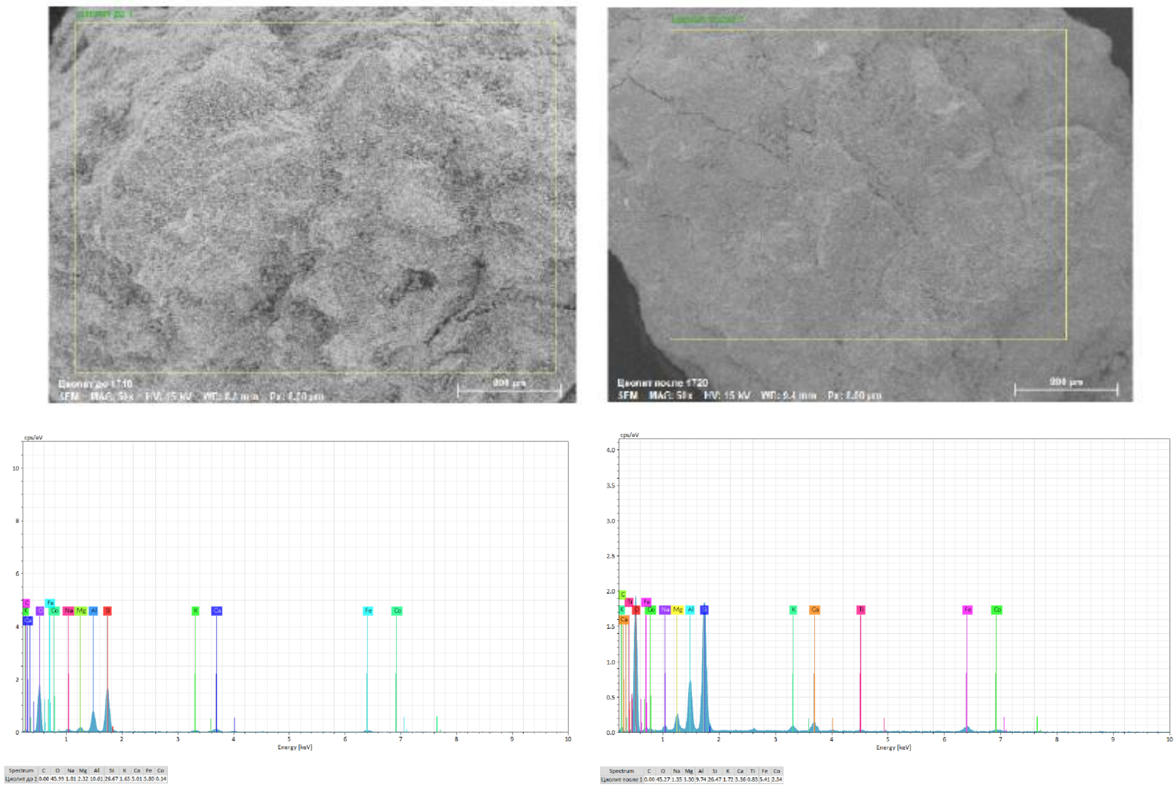

Figure 3. Zeolite before and after the experiment: SEM image showing metal concentration

Quantitative analysis revealed that the initial concentration of magnesium ions (Mg^{2+}) in the sorbents was 2.32. Upon contract with the solution through filtration, the magnesium concentration increased to 3.30, as illustrated in Figure 4. This observed increase signifies the active engagement of ion exchange processes characterized of zeolite materials. During these processes, Mg^{2+} ions not only undergo sorption from the solution but also exhibit a dynamic redistribution within the crystal lattice of the sorbent. This phenomenon underscores the intricate and dynamic nature of molecular interactions inherent in these materials.

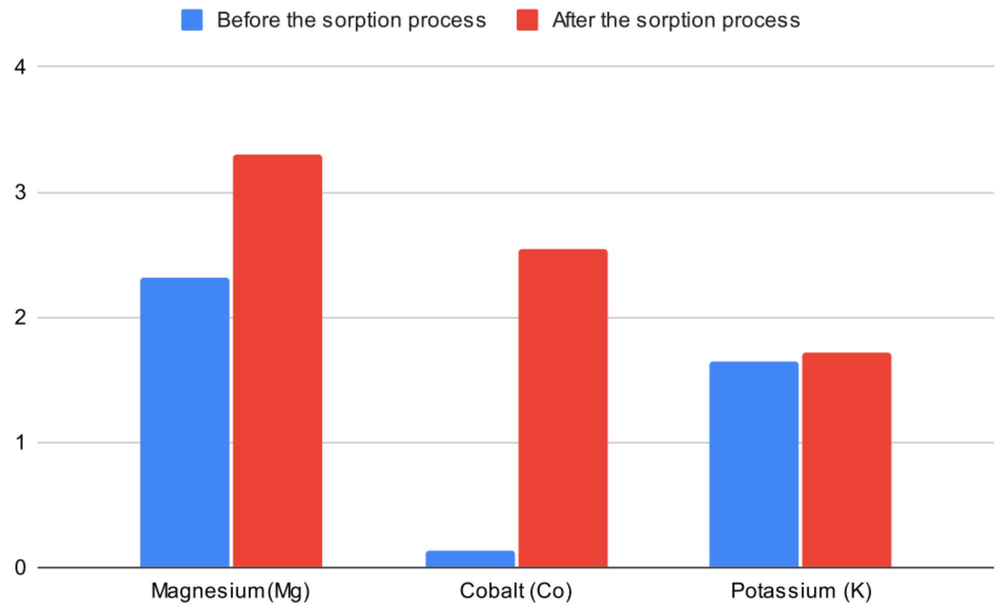

Figure 4. Results of the sorption process

The most substantial transformations were observed for cobalt ions. The initial concentration of Co^{2+} ions in the feed materials prior to the experimental procedure was 0.14, whereas post-filtration, it escalated to 2.54. Consequently, the cobalt concentration increased by more than 18-fold, compellingly demonstrating the high sorption capacity of the investigated materials in relation to heavy metal ion. This outcome underscores the efficacy of both zeolite and activated carbon in the extraction of cobalt ions from aqueous solutions and reveals an intensive cumulative accumulation of Co^{2+} ions within the solid phase.

In contrast, changes in the potassium (K^{+}) concentration in thee studied sorbents were less significant. The initial potassium concentrated in the sorption materials was 1.65, which increased to 1.72 following filtration. This modest elevation in K^{+} concentration can be attributed to ion exchange processes involving cations embedded within the crystal structure of zeolite and ions present in the aqueous solution. The consistency potassium level suggests that the structural integrity of the sorption material was preserved throughout the experimental procedure corroborating its resistance to the impact of the filtered medium.

The empirical evidence amassed in this study unequivocally demonstrates that during the filtration process, heavy metals, primarily cobalt, undergo significant accumulation within the structure of the loading materials employed. This phenomenon is concurrent with the redistribution of alkaline earth and alkali cations, underscoring the paramount importance of ion exchange and adsorption mechanisms in facilitating the efficacy of water purification.

A thorough examination of the solid phase corroborates the findings of the aqueous phase analysis, attesting to the high efficiency of utilizing zeolite and activated carbon as loading materials for the purification of aqueous solution from heavy metal ions. Notably, these materials exhibit a pronounced capacity to accumulate cobalt, rendering them highly promising for applications in water purification systems. These systems are designed to mitigate the adverse environmental and health impacts associated with toxic metal pollutants.

Discussion

The results obtained in this study strongly support the growing consensus that zeolites represent an efficient and sustainable solution for heavy metal removal from aqueous systems. The significant increase in cobalt concentration within the solid phase, alongside changes in magnesium and potassium content, clearly indicates that ion exchange plays a dominant role in the sorption process. This observation is consistent with the findings of Raji Z. et al. (2023), who identified ion exchange and surface complexation as key mechanisms governing heavy metal adsorption in mineral-based sorbents [Raji Z. et al., 2023].

The demonstrated effectiveness of zeolites can also be explained by their structural and chemical properties. As reported by Ola A. and Walaa M.T., and Senila M. and Cadar O., the negatively charged aluminosilicate framework of natural zeolites enables selective binding of metal cations, particularly lead, cadmium, and zinc [Ola A., Walaa M.T., 2023; Senila M., Cadar O., 2024]. The observed increase in divalent cations such as magnesium further confirms that exchange reactions between solution-phase ions and zeolite lattice cations are actively occurring, reinforcing the mechanistic interpretation of the results.

In comparison with other adsorbents, the combined use of zeolites and activated carbon appears particularly advantageous. While activated carbon is widely recognized for its high surface area and adsorption capacity [Chen H. et al., 2026; Pet I. et al., 2024], its efficiency may decrease in complex wastewater matrices due to competition with organic compounds. The present findings support the conclusions of Cuomo M. et al., who demonstrated that integrating zeolites with activated carbon can enhance overall treatment performance and reduce reliance on single-component systems [Cuomo M. et al., 2024]. This synergistic effect is evident in the improved stability and broader contaminant removal observed in this study.

The environmental and economic implications of using natural zeolites further strengthen their applicability. According to Mitra S. and Zhang P., heavy metal contamination poses severe risks to ecosystems and human health, necessitating cost-effective and scalable remediation technologies [Mitra S. et al., 2022; Zhang P. et al., 2023]. Zeolites, being naturally abundant and non-toxic, offer a clear advantage over synthetic alternatives. Additionally, their potential for reuse and safe disposal aligns with principles of sustainable resource management, as also highlighted by Fatemeh and Ahad [Fatemeh B., Ahad G., 2025].

However, despite these promising results, certain limitations should be considered. Previous studies [Propolsky D., Romanovski V., 2025; Rind I.K. et al., 2022] indicate that long-term performance, regeneration efficiency, and scalability remain critical challenges for sorbent-based systems. Therefore, further research is required to optimize operational parameters, improve material modification techniques, and evaluate performance under real industrial conditions.

Overall, the findings of this study are in strong agreement with existing literature and confirm that zeolite-based and hybrid filtration systems represent a highly effective strategy for heavy metal removal. Their integration into modern water treatment technologies offers significant potential for improving water quality while maintaining environmental sustainability.

Conclusion

Contemporary scientific inquiry underscores zeolites as a highly promising natural sorbent for the effective removal of heavy metal ions from aqueous solutions. The distinctive crystalline architecture of zeolites, characterized by a system of nanoscale channels and cavities, confers superior ion exchange capacity and selective affinity for metal cations. The negatively charged aluminiosilicate framework of these materials facilitates the binding of lead, cadmium, copper and zinc ions by displacing sodium, calcium, or potassium ions from their structural lattice. The inherent stability of zeolites across a broad spectrum of pH and temperature conditions sets them apart from many synthetic sorbents. In contrast to activated carbon, which exhibits variable sorption performance contingent upon the chemical composition of the water and competitive interactions with organic species, zeolites demonstrate consistent efficacy in complex, multicomponent aqueous systems. This resilience renders them indispensable for the remediation of industrial wastewater, particularly in metallurgical, mining and chemical processing facilities.

From an environmental perspective, the utilization of zeolites in water treatment systems represents a safe and sustainable approach. Zeolites, as natural mineral aluminosilicates, exhibit a unique chemical composition and structural properties that render them non-toxic and free of secondary pollutant generation during operational processes. The adsorption of locally sourced zeolite deposits further diminishes the carbon footprint associated with water treatment technologies, thereby promoting the rational utilization of natural resources and mitigating environmental impact. Additionally, saturated zeolites, particularly when appropriately stabilized, can be repurposed as secondary materials or managed through controlled disposal methods, thereby enhancing the circularity of resource use.

Experimental characterization of the solid phase in sorbent systems has revealed a significant accumulation of metal ions within the loading materials. Specifically, the concentration of cobalt ions increased from 0.14 to 2.54, signifying an augmentation of more than 18-fold. This finding underscores the high sorption capacity of the materials in relation to heavy metals, attesting to the efficacy of adsorption and ion exchange processes within the filter layer. This observation provides compelling evidence of the materials ability to efficiently sequester contaminants, thereby contributing to the purification and safeguarding of water resources.

Analysis of the cationic composition revealed significant alterations in the content of alkaline earth and alkaline cations. Specifically, the magnesium concentration exhibited a notable increase from 2.32 to 3.30, corroborating the active involvement of ion exchange mechanisms in the filtration process. The potassium content demonstrated a minor increment from 1.65 to 1.72, suggesting the maintenance of structural integrity and stability of the sorbent throughout the experimental period.

Consequently, the filtration technique employing zeolite and activated carbon-based sorbents emerges as a highly effective methodology for the removal of heavy metal ions from aqueous solutions. Zeolite, characterized by its unique crystal structure and exceptional ion exchange capacity, demonstrates superior efficiency in this context.

The most promising approach in the field of water purification is the integrated utilization of zeolites and activated carbon within filtration systems. This synergistic combination leverages the ion-exchange capabilities of zeolites and the adsorption properties of activated carbon, resulting in a multifaceted enhancement of water purification processes. The resultant synergistic effect manifests as deeper purification, a broader spectrum of contaminant removal and an increased resistance of the filtration systems to variations in wastewater composition.

Extensive analytical studies have demonstrated that zeolites constitute a highly effective, economically viable and environmentally benign sorption material for the removal of heavy metal ions from aqueous solutions. Continued research efforts focused on zeolite modification, optimization of filtration parameters and the integration of zeolites into complex technological frameworks hold the potential to significantly augment the efficiency of water treatment systems and expand their practical applicability. A comparison with data from the literature shows that in most studies, the degree of heavy metal removal by natural sorbents varies widely - from 10 to 90% - depending on experimental conditions (pH, contact time, initial concentration, particle size) [Zhang P. et al., 2023; Ola A., Walaa M.T., 2023]. At the same time, for low concentrations and static conditions similar to those in the present study, efficiency values often range from 10–20%, which is comparable to the results obtained. Unlike a number of studies [Zhang P. et al., 2023; Senila M., Cadar O., 2024], where the main focus is solely on reducing the metal concentration in the solution, this study employed a dual sorption control - by analyzing both the liquid and solid phases. This allows for a more reliable assessment of the sorption capacity of the materials and eliminates possible errors associated with the redistribution of the substance within the system.

Furthermore, the novelty of this work lies in the use of sorbents with comparable particle size distributions (1.25-2.5 mm), which allowed for a proper comparison of their effectiveness. In a number of studies, such a comparison is difficult due to differences in particle size and experimental conditions.

Thus, the results obtained not only confirm the findings in the literature regarding the ability of zeolites and activated carbon to adsorb heavy metals, but also supplement them with a quantitative assessment of cobalt accumulation within the sorbent structure. This provides a deeper understanding of the mechanism underlying the process and supports the potential of these materials for water purification.

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Табиғи су көздері мен сарқынды суларды тазарту технологияларында цеолиттер мен инновациялық табиғи сүзгі материалдарын пайдалану

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Аңдатпа
Мақалада цеолиттер мен әртүрлі сүзгі материалдарын пайдалана отырып, табиғи және тұрмыстық ағынды суларды ауыр металдардан тазарту әдістері қарастырылған. Ауыр металдар су ортасының басты ластаушылары болып табылады, сондықтан оларды судан шығару қажеттілігі негізделген. Авторлар цеолиттердің физика-химиялық қасиеттерін, олардың ион алмасу және адсорбциялық сыйымдылықтарын, сондай-ақ белсендірілген көмір сияқты басқа толтыру тиімділігін қарастырады. Ауыр металл иондарын кетіруге арналған негізгі су тазарту технологиялары, соның ішінде сүзу, сіңіру және аралас әдістер талданады. Бұл технологиялардың су өңдеу және сарқынды суларды тазарту жүйелеріндегі қолдану салалары қарастырылады. Әртүрлі сүзгі материалдарының тиімділігінің салыстырмалы талдауы ұсынылған. Су тазарту сапасын жақсарту және су ресурстарының экологиялық қауіпсіздігін қамтамасыз ету мақсатында цеолиттер мен сүзгі орталарын қолдану перспективалары туралы қорытындылар жасалған.
Түйін сөздер: цеолиттер, ауыр металдар, су тазарту, сарқынды сулар, сүзгі материалдары, сорбция, су тазарту.

Использование цеолитов и инновационных природных фильтрующих материалов в технологиях очистки природной и сточной воды

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Аннотация
В статье рассматриваются методы очистки природных и сточных вод от тяжелых металлов с использованием цеолитов и различных фильтрующих материалов. Дается характеристика тяжелых металлов как приоритетных загрязнителей водной среды и обосновывается необходимость их удаления из воды. Авторы рассматривают физико-химические свойства цеолитов, их ионообменные и сорбционные способности, а также эффективность применения других загрузочных материалов, таких как активированный уголь. Проанализированы основные технологии очистки воды, применяемые для удаления ионов тяжелых металлов, включая фильтрационные, сорбционные и комбинированные методы. Рассмотрены области применения данных технологий в системах водоподготовки и очистки сточных вод. Приводится сравнительный анализ эффективности различных фильтрующих материалов. Сделаны выводы о перспективности использования цеолитов и фильтрующих загрузок для повышения качества очистки воды и обеспечения экологической безопасности водных ресурсов.
Ключевые слова: цеолиты, тяжелые металлы, очистка воды, сточные воды, фильтрующие материалы, сорбция, водоподготовка.

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WATER SCARCITY AND WAYS TO OVERCOME IT IN AFRICA

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Abstract
Water is the main source of life. Consequently, water scarcity leads to critical indicators in socio-economic aspects, the ecological situation and deterioration in public health. Water scarcity in developing countries in Africa is the result of natural factors, management issues, socioeconomic causes. The main area of water deficit is located in the arid and semi-arid (ASALs) zones of developing countries in Africa. For the sustainable