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ADSORPTION OF COPPER AND ZINC IONS BY NATURAL ZEOLITES IN SOIL AND AQUATIC ECOSYSTEMS AND ASSESSMENT OF THEIR BIOLOGICAL AND ECOLOGICAL IMPACTS

In this research, the potential of modified natural zeolites obtained from the Aydag deposit in Azerbaijan to protect living organisms from the harmful effects of heavy metal ions in soil and aquatic environments was experimentally investigated. The results indicate that zeolites modified with monoethanolamine (MEA) can be used as a highly effective agent to mitigate the impact of copper and zinc ions on living organisms in soil and water ecosystems. The adsorption selectivity was determined as $Cu^{2+} > Zn^{2+}$. MEA-modified zeolites not only facilitate the removal of metal ions but also play a protective role for microorganisms, plants, and aquatic fauna by maintaining the biological and ecological stability of soil and water ecosystems. This sorbent enables the protection of soil microorganisms (Azotobacter, Pseudomonas, Bacillus), earthworms and other soil fauna, as well as aquatic plants and microorganisms (zooplankton, phytoplankton) from toxic metal ions. The binding of metal ions to the sorbent surface and their subsequent release reduce their toxic effects on living organisms, thereby contributing to the maintenance of ecosystem functions, including organic matter decomposition, nitrogen fixation, soil fertility, and the preservation of aquatic biogeography. Thus, MEA-modified Aydag zeolites present a promising approach for reducing heavy metal pollution, restoring soil and water environments, expanding biomonitoring capabilities, and supporting the sustainable management of ecosystems from both ecological and biological perspectives.

Keywords: ecology, soil and aquatic ecosystems, reduction of heavy metal toxicity, zeolite, adsorption, protection of microorganisms.

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Топырақ және су экожүйелерінде табиғи цеолиттер арқылы мыс пен мырыш иондарының адсорбциясы және олардың биологиялық және экологиялық әсерін бағалау

Бұл зерттеуде Әзірбайжандағы Айдағы кен орнынан алынған модификацияланған табиғи цеолиттердің топырақ және су орталарындағы ауыр металл иондарының зиянды әсерінен тірі ағзаларды қорғау әлеуеті тәжірибелік түрде зерттелді. Нәтижелер моноэтаноламинмен (MEA) модификацияланған цеолиттердің топырақ және су экожүйелеріндегі тірі ағзаларға мыс пен мырыш иондарының әсерін азайту үшін жоғары тиімді құрал ретінде қолданылуы мүмкін екенін көрсетті. Адсорбция селективтілігі $Cu^{2+} > Zn^{2+}$ тәртібімен анықталды. MEA-мен модификацияланған цеолиттер металл иондарын жоюға ғана емес, сонымен қатар топырақ және су экожүйелерінің биологиялық және экологиялық тұрақтылығын сақтай отырып, микроорганизмдерге, өсімдіктерге және су фаунасына қорғаныштық әсер етеді. Бұл сорбент топырақ микроорганизмдерін (Azotobacter, Pseudomonas, Bacillus), жауынқұрттарды және басқа да топырақ фаунасын, сондай-ақ су өсімдіктері мен микроорганизмдерін (зоопланктон, фитопланктон) улы металл иондарынан қорғауды қамтамасыз етеді. Металл иондарының сорбент бетімен байланысуы және олардың кейінгі босап шығуы тірі ағзаларға уытты әсерін төмендетеді, осылайша экожүйе функцияларының сақталуына, соның ішінде органикалық заттардың ыдырауына, азоттың фиксациясына, топырақ құнарлылығына және су биогеографиясының сақталуына ықпал етеді. Осылайша, MEA-мен модификацияланған Айдағ цеолиттері ауыр металдармен ластануды азайту, топырақ пен су орталарын қалпына келтіру, биомониторинг

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экологиялық және биологиялық тұрғыдан тұрақты басқаруды қамтамасыз ету үшін перспективалы тәсіл болып табылады.

Түйін сөздер: экология, топырақ және су экожүйелері, ауыр металдардың уыттылығын төмендету, цеолит, адсорбция, микроорганизмдерді қорғау.

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Адсорбция ионов меди и цинка природными цеолитами в почвенных и водных экосистемах и оценка их биологического и экологического воздействия

В данном исследовании экспериментально изучен потенциал модифицированных природных цеолитов, полученных из Айдагского месторождения в Азербайджане, в защите живых организмов от вредного воздействия ионов тяжёлых металлов в почвенных и водных средах. Полученные результаты показывают, что цеолиты, модифицированные моноэтаноламином (MEA), могут быть использованы в качестве высокоэффективного средства для снижения воздействия ионов меди и цинка на живые организмы в почвенных и водных экосистемах. Селективность адсорбции установлена в следующем порядке: $Cu^{2+} > Zn^{2+}$. Модифицированные MEA цеолиты не только способствуют удалению ионов металлов, но и выполняют защитную функцию для микроорганизмов, растений и водной фауны, поддерживая биологическую и экологическую стабильность почвенных и водных экосистем. Данный сорбент обеспечивает защиту почвенных микроорганизмов (Azotobacter, Pseudomonas, Bacillus), дождевых червей и другой почвенной фауны, а также водных растений и микроорганизмов (зоопланктон, фитопланктон) от токсичных ионов металлов. Связывание ионов металлов с поверхностью сорбента и их последующее высвобождение снижает их токсическое воздействие на живые организмы, способствуя сохранению функций экосистем, включая разложение органического вещества, фиксацию азота, плодородие почвы и сохранение водной биогеографии. Таким образом, цеолиты Айдагского месторождения, модифицированные MEA, представляют собой перспективный подход к снижению загрязнения тяжёлыми металлами, восстановлению почвенной и водной среды, расширению возможностей биомониторинга и обеспечению устойчивого управления экосистемами с экологической и биологической точек зрения.

Ключевые слова: экология, почвенные и водные экосистемы, снижение токсичности тяжёлых металлов, цеолит, адсорбция, защита микроорганизмов.

Introduction

The technologies employed in the processing industry do not ensure complete extraction of metals from raw materials and, in many cases, become a source of industrial pollution with significant ecological and biological impacts. Wastewaters discharged from chemical industry enterprises (Hajiyeva et al., 2020; Tang et al., 2016), mining activities (Miller, 2013), and battery manufacturing facilities (Gottesfeld & Cherry, 2011) are predominantly contaminated with heavy metal ions, which adversely affect aquatic ecosystems, soil microflora, and the life of plants and animals (Afandiyeva & Gadirova, 2025). Typically, high concentrations of metals such as Al, Ca, Fe, Si, Co, Cu, Zn, Mn, V, Ga, and others are observed in processing wastes and wastewaters, making them widespread environmental pollutants.

Typically, high concentrations of metals such as Al, Ca, Fe, Si, Co, Cu, Zn, Mn, V, Ga, and others are observed in processing wastes and the wastewaters generated during their washing, which are recognized as widespread environmental pollutants. These metals may exert adverse effects on soil microorganisms (e.g., *Azotobacter, Nitrosomonas,* and *Pseudomonas*) and soil microflora by disrupting their activity, thereby weakening key processes in soil ecosystems such as biological nitrogen fixation, decomposition of organic matter, and maintenance of soil structure (Hajiyeva et al., 2016). At the same time, heavy metals present in wastewater adversely affect plant root systems by hindering the uptake of water and mineral nutrients and inducing toxic effects in plant tissues and leaves, which in turn negatively impacts the vital activities of soil animals, such as earthworms and other soil invertebrates.

Such contamination disrupts the ecological balance of microorganisms, negatively affects the biogeography of soil and water ecosystems, and may even lead to the decline of certain species (Haciyeva et al., 2018). The recovery of valuable components

from processing wastes is not only economically significant but also of critical biological and ecological importance, as it contributes to the mitigation of environmental risks by preventing the migration of metals into ecosystems and living organisms under the influence of atmospheric factors. (GBD 2019 Colorectal Cancer Collaborators, 2022; Mushak, 1991).

The long-term effects of such contamination degrade the quality of the soil humus layer, reduce microbial diversity, and may disrupt plant life cycles. In addition, metals can migrate into water bodies, exerting toxic effects on fish, zooplankton, and aquatic plants, thereby weakening the stability of aquatic ecosystems.

Currently, large volumes of technical waste that contaminate the environment and local biogeography have accumulated in the area of the Dashkasan Ore Processing and Enrichment Plant in Azerbaijan. These wastes lead to the accumulation of heavy metal ions in soil layers and groundwater sources, which adversely affects the physiological activity and reproduction of soil microorganisms (e.g., *Azotobacter, Pseudomonas,* and *Bacillus*), earthworms, scorpions, and other soil invertebrates, as well as disrupts the life cycles of aquatic plants and organisms, thereby weakening the biological balance of the ecosystem. The accumulation of heavy metals reduces the microbiological activity of soil, slows the decomposition of organic matter, and limits nitrogen fixation, thereby negatively affecting soil fertility and the sustainability of plant life. (Linnik & Nabivanets, 1986).

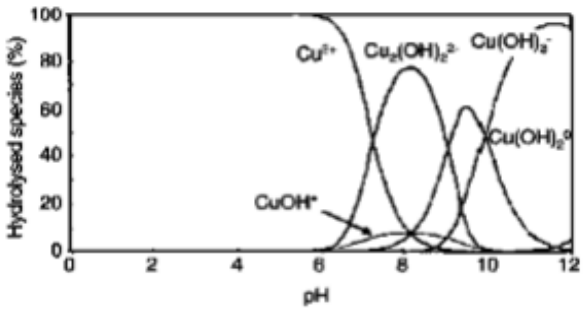
At the same time, these wastes provide potential raw materials for the recovery of certain valuable metals and offer opportunities for ecological and biological remediation. (Hasanova et al., 2025). In our previous studies, we demonstrated the feasibility of recovering metals such as Cu and Zn from iron concentrate wastes using heap leaching with diluted sulfuric acid. This approach is not only economically efficient but also enables the restoration of soil and aquatic ecosystems, the protection of microorganisms and soil fauna, and the safeguarding of aquatic plants and life from toxic metals. (Albayrak et al., 2023). At the highest level of the ecosystem, human health benefits, particularly by providing conditions that support the normalization of cardiovascular system functions, which is especially relevant in the 21st century (Abou Ghayda et al., 2021). Thus, this method contributes to ensuring biological safety and maintaining the functional stability of ecosystems (Geydarov et al., 2016).

İn the solution, the prevailing form of copper primarily depends on hydrolysis processes, the absence of complex formation, and the pH of the medium. These factors play a crucial role in selecting optimal adsorption conditions and in the remediation of contaminated soil and water environments. The distribution of copper ionic forms depending on pH is shown in Figure 1 (Wang & Qin, 2005), which is significant for ecological monitoring and biological safety measures.

In solution, the prevailing form of copper primarily depends on hydrolysis processes, complex formation, and the pH of the medium. These factors play a crucial role not only in selecting optimal adsorption conditions but also in the remediation of contaminated soil and water environments, as well as in preserving the physiological activity of microorganisms (*Azotobacter, Pseudomonas, Bacillus*) and soil fauna.

The distribution of copper ionic forms depending on pH is shown in Figure 1 (Wang & Qin, 2005), and this information is important for ecological monitoring, pollution assessment, and the planning of biological safety measures. As the pH changes, the bioavailability and toxic effects of copper ions on soil microflora, plants, and aquatic organisms also vary, directly influencing ecosystem functional stability and the life cycles of living organisms.

Figure 1
Percentage distribution of copper in ionic forms in solution as a function of pH



In the pH range of 1.5–6.5, copper in solution predominantly exists as Cu^{2+} ions. As a result of hydrolysis, the following aquahydroxo complexes are formed: $[Cu(OH)]^{+}$, $[Cu(OH)_2]^{0}$, $[Cu(OH)_3]^{-}$, $Cu_2(OH)_2^{2-}$, $[Cu(OH)_4]^{2-}$, $[Cu(OH)(H_2O)_3]^{+}$, $[Cu(OH)_3(H_2O)]^{-}$.

At pH ≥ 9, more than 40% of copper is present as $[Cu(OH)_2]^{0}$ and $[CuCO_3]^{0}$.

In mining waters, copper predominantly exists as sulfate salts, so within the pH range of 1–8, the presence of Cu^{2+} and $Cu(OH)^{+}$ ions is more likely.

Hydrolysis and speciation of zinc ions significantly influence their behavior in solutions due to zinc's ability to undergo hydrolysis and form complexes. As a result, mono- and polynuclear hydroxo complexes are formed. For zinc, the following mononuclear complexes are characteristic: $[[Zn(OH)]^{+}$; $[Zn(OH)_2]^{0}$; $[Zn(OH)_8]^{6-}$; $[Zn_2(OH)_2]^{2+}$. Hydroxocomplexes such as $[Zn_2(OH)_6]^{2-}$ make up 2% of the total composition (Linnik & Nabivanets, 1986).

At pH values of 4.6-6.5, zinc is in the form of Zn2+ ions (92.4-99.8%); In the form of Zn(OH)+ (0.2-7.6%), the available ionic form of zinc at pH 2.5-4.5 corresponds to real solutions (92.4-99.5%).

The ratio between the forms of polynuclear hydroxocomplexes depends on the pH of the environment. The most prevalent form in wastewater is $[Zn(OH)]^{+}$ is the least prevalent form, followed by $[Zn(OH)_2]^{0}$. $[ZnCO_3]^{0}$ and $[Zn(HCO_3)]^{+}$ complexes are the most prevalent in aquatic systems in the absence of organic complexing agents. The formation of $[Zn(OH)]^{+}$ hydroxo complexes is also inevitable.

In an acidic medium, in the absence of organic ligands, the Zn^{2+} concentration is 85–97%. At pH 4.6–6.5, zinc occurs as Zn^{2+} ions (92.4–99.8%) and as $Zn(OH)^{+}$ (0.2–7.6%). At pH 2.5–4.5, the available ionic form of zinc accounts for 92.4–99.5% in real solutions.

The distribution balance of zinc ion forms in solution is as shown below:

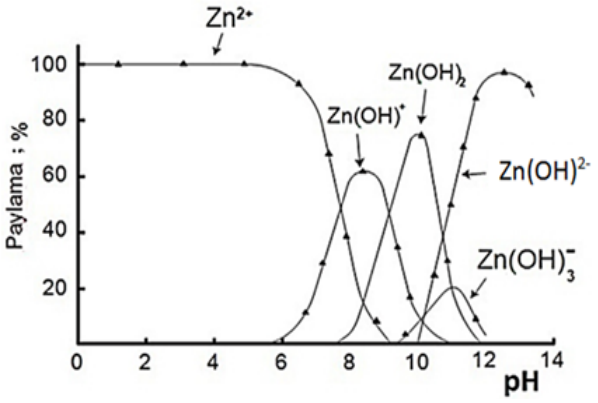
$$C(Zn^{2+}) = [Zn^{2+}] + [Zn(OH)]^{+} + [Zn(OH)_2]^{0} + + [Zn(OH)_3]^{-} + [Zn(OH)_4]^{2-}$$

The distribution of hydrolysis forms calculated according to the hydrolysis constant is as shown in Figure 2 (Hasanova et al., 2025).

Recently, sorbents have been widely used in the world for the purification of industrial wastewater used for technical purposes from waste of various chemical and biological nature,wellas for the purification of chemical and metallurgical wastewater from ions of non-ferrous, heavy and noble metals. Numerous scientific studies have also been conducted to create a technology for purifying organic compounds from wastewater by obtaining sorbents based on tree trunks and waste, using methods of their activation.

Figure 2

Percentage distribution of zinc in ionic forms in solution as a function of pH



In addition, coal-based sorbents are important for the purification of industrial wastewater and the extraction of non-ferrous metal ions (Pan et al., 2009). There have also been many scientific studies on the development of technology for cleaning organic compounds from wastewater by obtaining sorbents based on tree trunks and waste, using methods of their activation. Studies show that the extraction of heavy metal ions from wastewater by simple and inexpensive sorption is more practical and cost-effective (Jia & Lu, 2014). A number of adsorbents, such as activated carbon (Dąbrowski, 2001), clays (El Mouzdahir et al., 2007), polymers (Ovejero et al., 2010) and zeolites (Ekmekyapar et al., 2006) have been proposed and studied for the purification of various wastewaters (Gulieva et al., 2018).

Heap leaching solutions are considered an additional source of valuable metals, and their recovery is important both economically and for the protection of ecosystems. However, many methods such as precipitation, ion exchange, adsorption, and reverse osmosis are expensive and technologically challenging to implement, and some of these methods may also affect the activity of microorganisms in soil and water environments. Zeolites act as selective sorbents for non-ferrous metals (Cd^{2+}, Cu^{2+}, Zn^{2+}) and their application can help reduce heavy metal toxicity in both soil and aquatic ecosystems. The adsorption capacity of zeolites is typically enhanced through modification with acids or alkalis, which allows for the effective capture of metals without harming microbiological activity. (Dąbrowski, 2001).

The monoethanolamine (MEA) molecule contains donor-active nitrogen and oxygen atoms, a feature that allows MEA to act as both a mono- and

polydentate ligand. As a result, it enables the effective adsorption of metal ions such as Cu^{2+} and Zn^{2+} from soil and water environments, while also contributing to the protection of microorganisms and plant life from toxic metals.

Materials and methods

For the study, natural zeolites obtained from the Aydag deposit were used. The zeolites were ground into powder with an average particle size of 75 μm, and their composition was determined using X-ray fluorescence spectroscopy (Phillips Magix Pro) and X-ray diffraction (Phillips X'Pert D993). To enhance the sorbent's capacity for capturing copper (Cu^{2+}) and zinc (Zn^{2+}) ions, it was modified with monoethanolamine (MEA), triethanolamine, methylamine hydroxide, and hydroxylamine hydroxide. This modification was carried out to reduce the toxic effects of metals on soil and aquatic ecosystems and to preserve the activity of microorganisms (*Azotobacter, Pseudomonas, Bacillus*).

Prepared Solutions: In the experiments, 1000 mg/L solutions were prepared using technogenic wastewaters and salts of $CuSO_4 \cdot 5H_2O$ and $ZnSO_4 \cdot 7H_2O$. The pH of the solutions was adjusted to a range of 3–4. These solutions are not only a valuable source of metals from an economic perspective but also hold ecological and biological significance due to their potential toxic effects on soil and aquatic biogeography.

Experimental Methods: Adsorption studies were conducted using the batch equilibrium method. An appropriate amount of modified zeolite was added to the solution, and the adsorption process was carried out under continuous stirring. All experiments were performed in triplicate, and the average results were used for calculations.

Adsorption Parameters: The equilibrium adsorption capacity (Q_e, mg/g) and adsorption efficiency (R, %) were calculated using the following equations:

$$Q_e = \frac{(C_0 - C_e) \times V}{m}$$

$$R(\%) = \frac{C_0 - C_e}{C_0} \times 100$$

Here, C_0 and C_e (mg/L) represent the initial and equilibrium concentrations of metal ions, respectively; V (mL) is the solution volume, and m (g) is the sorbent mass.

Investigation of pH Effect: The pH of the solutions was varied within the range of 1.5–6.5, and the prevailing forms of Cu^{2+} and Zn^{2+} ions (Cu^{2+}, $Cu(OH)^+$, Zn^{2+}, $Zn(OH)^+$) and their adsorption efficiency were monitored. These studies are of biological and ecological significance for the protection of soil microflora and aquatic ecosystems from toxic metals.

Adsorption Isotherms and Kinetic Modeling: The adsorption results were modeled using the Langmuir and Freundlich isotherms. The Langmuir model describes monolayer adsorption, while the Freundlich model accounts for empirical adsorption behavior. This approach allows for the evaluation of the sorbent's capacity to capture metal ions and for determining its adsorption efficiency from an ecological and biological perspective.

The application of modified zeolites enables the effective adsorption of copper and zinc ions without disrupting the activity of soil microorganisms, while also preserving the life cycles of aquatic plants and microorganisms. This approach not only facilitates the economic recovery of metal ions but also maintains ecosystem functional stability and minimizes the biological and chemical impacts of contamination in soil and water environments.

Results and discussion

Copper (Cu^{2+}) and zinc (Zn^{2+}) ions were selected to study the adsorption properties of the prepared samples under static conditions. These ions are of interest not only from a technological perspective but also from a biological and ecological standpoint due to their potential toxic effects on soil and aquatic ecosystems. Experiments were conducted to investigate the influence of solution pH, initial concentrations of Cu^{2+} and Zn^{2+} ions, adsorption time, and sorbent reusability on the adsorption capacity of zeolites. This allowed for the determination of optimal adsorption conditions aimed at minimizing the impact of heavy metals on soil microflora, aquatic plants, and microorganisms, while ensuring ecological safety.

Adsorption studies were carried out using the batch equilibrium method. For this purpose, 1000 mg/L solutions of $CuSO_4 \cdot 5H_2O$ and $ZnSO_4 \cdot 7H_2O$ (pH = 3–4) were prepared in deionized water, and appropriate amounts of zeolite samples were added to specific volumes of the stock solutions. All experiments were performed in triplicate, and the average values were used for calculations. Under standard conditions, the efficiency of the adsorption process

was determined using both FEK spectrophotometric and titrimetric methods. The equilibrium adsorption capacity (Q_e, mg/g) and adsorption efficiency (R, %) were calculated using the following equations:

$$Q_e = \frac{(C_0 - C_e) \times V}{m}$$

$$R(\%) = \frac{C_0 - C_e}{C_0} \times 100$$

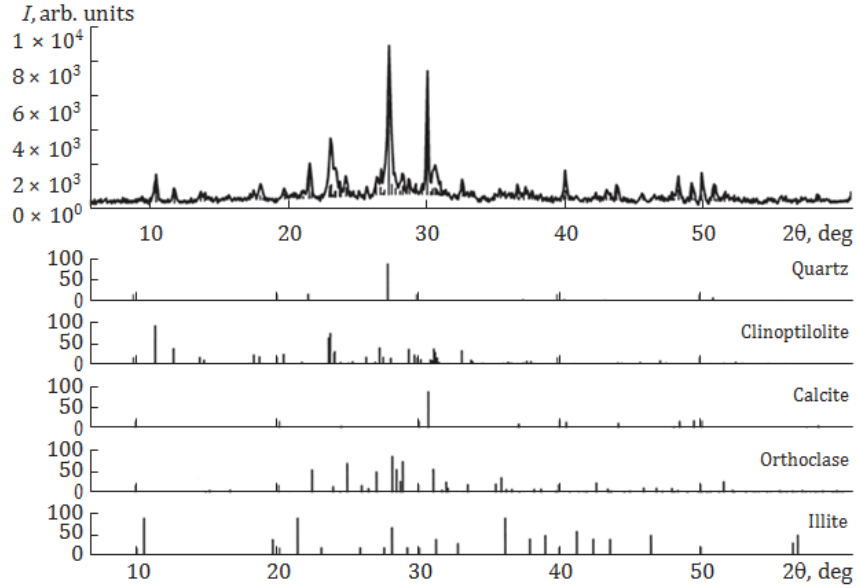
As the sorbent, high-silica zeolites containing an average of 80–85% clinoptilolite were used. The chemical composition (%) of the zeolites employed was as follows:

66.9 SiO_2, 14.2 Al_2O_3, 5.05 CaO, 3.55 Na_2O, 2.18 K_2O, 2.01 Fe_2O_3, 0.57 MgO və 5.54 H_2O.

The sorbent was ground into powder with an average particle size of approximately 75 μm, and its composition was analyzed using a Phillips X'Pert Model D993 diffractometer. The elemental composition was determined by X-ray fluorescence spectroscopy using a Phillips Magix Pro instrument (Gulieva et al., 2018).

The diffraction pattern of the initial natural zeolite from the Aydag deposit is shown in Figure 3.

Figure 3
X-ray diffraction pattern and bar X-ray diffraction pattern of the starting zeolite from the Aidagsk deposit



To determine the optimal pH range, experiments were conducted under static conditions with continuous stirring. Depending on the pH, the ligand groups of the modified zeolites adopt favorable configurations, resulting in maximum adsorption. Since technogenic solutions obtained via heap leaching have varying compositions and acidities, it is important to study the effect of pH on metal ion adsorption. The adsorption behavior varies with solution acidity because it is directly related to the prevailing forms of the ions.

To enhance the adsorption capacity of zeolites, they were modified with various amines (MEA, triethanolamine, methylamine hydroxide, hydroxylamine hydroxide). The adsorption performance of the tested sorbents was compared with that of the highly acidic ion-exchange resin KU-2-8. The results demonstrated that MEA-modified zeolite exhibits higher selectivity for non-ferrous metals compared to other modifications and does not adsorb alkaline soil metals from sulfuric acid solutions. According to the findings, the recovery of copper and zinc increases with the pH of the solution. In highly acidic environments (1 N H_2SO_4), metal adsorption does not occur, indicating that desorption of metal ions is possible when using ion-exchange resins in acidic solutions.

For the MEA-modified zeolite, copper and zinc sorption increased sharply at pH 4.4–5, reaching 99.95% and 100%, respectively. These results

indicate that the MEA-modified zeolite has a high sorption capacity for both metals. The kinetic data for Cu^{2+} and Zn^{2+} sorption by unmodified and MEA-modified zeolites from the Aidag deposit are presented in Figures 4 and 5. At pH 5, the amount adsorbed increased with contact time, reaching maximum values of 95.6 for Cu^{2+} and 94 for Zn^{2+}. Sorption occurred rapidly during the first 15 minutes, and equilibrium was established within 1 hour for all metal ions (Gulieva et al., 2018).

Effect of contact time on Zn^{2+} sorption by modified (a) and natural (b) zeolites (C_{Me²⁺} = 100 mg/L, pH = 6, T = 20 °C, *m* = 1 g, *V* = 0.2).

Figure 4
Dependence of the degree of sorption of Cu2+

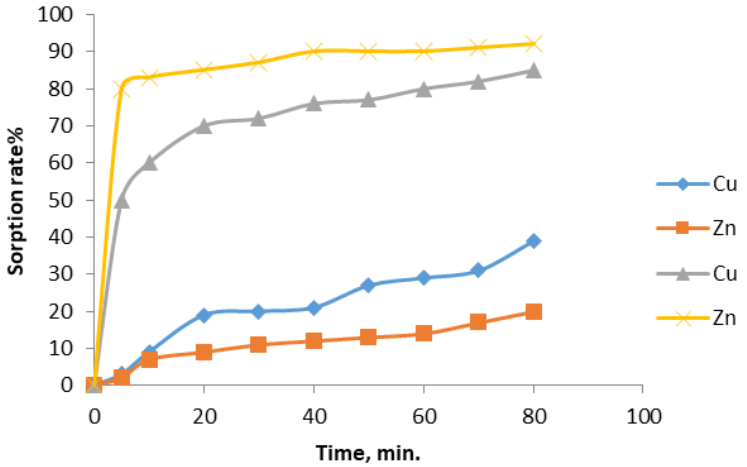
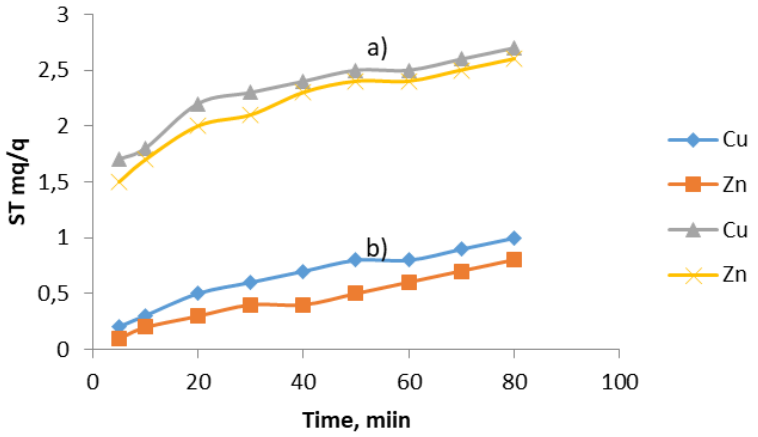


Figure 5
Dependence of the sorption capacity of Cu2+, Zn2+ ions on the contact time of modified (a) and natural zeolites (b). (CMe2+=100 mg/l, pH=6, t=20°S, m=1g, V solution= 200 ml)



The sorption characteristics for each of the studied ions were calculated by the Langmuir (Eq. 3) and Freundlich (Eq. 4) equations. Two isothermal models are the simplest and most frequently used isotherms for the representation of the adsorption of components from the liquid phase by the solid adsorbent surface (Barakat, 2008; Hui et al., 2005). The Langmuir model assumes monolayer adsorption and the Freundlich model assumes empirical adsorption (Boddu et al., 2003). The Langmuir equation was used to describe an adsorption isotherm (Guliyeva et al., 2023).

$$SE = (ST⟧_max\ K_L\ C)/(1+K_L\ C)\ , \qquad (3)$$

STmax is the ultimate limit of adsorption capacity, (mg/g), k is the adsorption equilibrium constant. The Freundlich equation is used in the analysis of experimental results corresponding to the middle part of the adsorption isotherm (Guliyeva et al., 2023).

$$ST = K'Ce1/n \qquad (4)$$

ST is the amount of solute in equilibrium (mg/g), K′ and n are empirical constants, and K′ is the adsorption value when the adsorbent concentration is 1 mg/l.

The obtained equilibrium data on adsorption were reduced to linearly transformed. (Langmuir and Freundlich equations, respectively) (Figs. 6, 7). As follows from the presented plots, the results obtained from the Langmuir and Freundlich models for all studied metal ions correspond to the experimental data.

The Freundlich equation is only valid for the ranges of the initial and medium concentrations. The constants of the Freundlich equation (K ‘, n) were determined graphically (see Fig.6).

The sorption characteristics of metal ion adsorption on the MEA-modified zeolite calculated by the Langmuir and Freundlich equations are presented in Table

Figure 6

Langmuir isotherm for the adsorption of Cu2+, Zn2+ ions

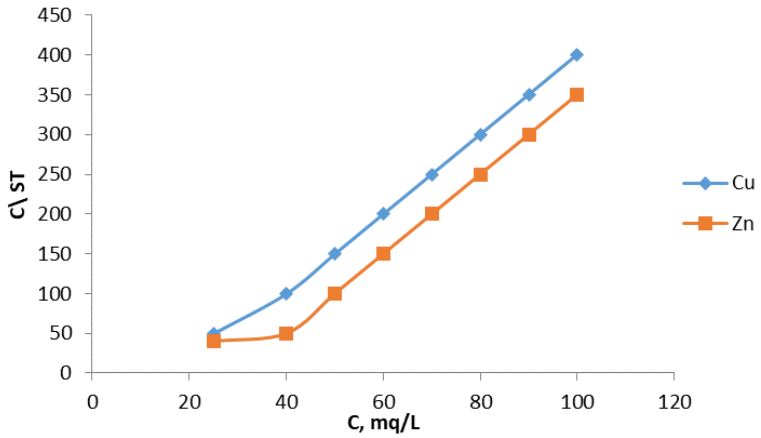
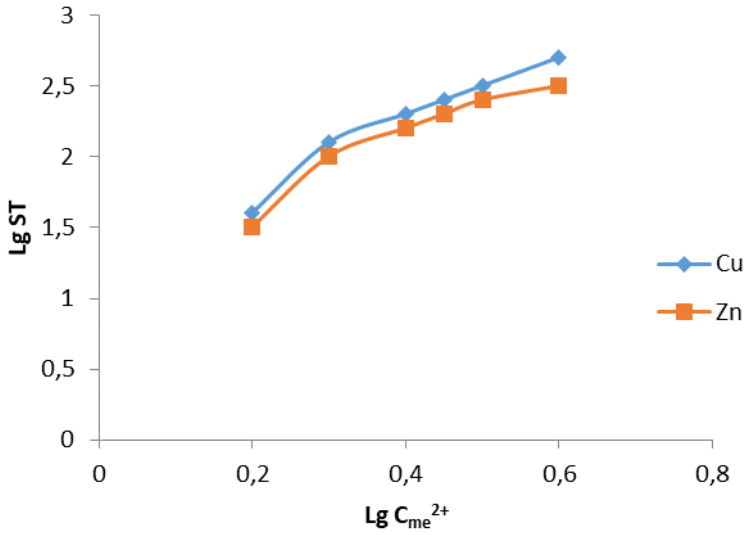


Figure 7

Freundlich isotherm of Cu2+, Zn2+ ions with MEA-modified zeolites at 20°C



Table

Cation	Langmuir equation		Freundlich equation	
	SEmax, mg/g	KL, L/mg	K ‘	N
Cu^{2}+	1.733	0.030	1.52	3.125
Zn^{2}+	2.356	0.013	0.90	2.000

Sorption characteristics calculated using the Lang muir and Freundlich equations (Eqs. (3) and (4), respec- tively) for the adsorption of te metal ions by the modified zeolite.

Conclusion

The study demonstrated the feasibility of purifying copper and zinc from technogenic solutions generated from the old wastes of the Dashkasan Ore Processing and Enrichment Plant using MEA-modified zeolite via adsorption. This approach not only enables the economic recovery of metal ions but also maintains the ecological stability of soil and aquatic ecosystems, supports the activity of soil microorganisms (*Azotobacter, Pseudomonas, Bacillus*) and earthworms, preserves the life cycles of aquatic plants and microorganisms, and thereby minimizes the biological impacts of heavy metal toxicity. At the same time, this method contributes to the restoration of the biological and chemical balance of ecosystems, the reduction of contamination in soil and water environments, and the enhancement of biomonitoring capabilities. This approach is important for ensuring ecological safety and sustainable ecosystem management, as MEA-modified zeolite effectively adsorbs toxic metals, thereby protecting both living organisms and the environment.

The application of modified zeolite allows for the high-level recovery of all valuable metals. This approach is significant not only from an economic perspective but also for the protection of soil and aquatic ecosystems, as the adsorption behavior of Cu^{2+} and Zn^{2+} ions from both model and technogenic solutions under static and dynamic conditions has been studied. This has enabled the minimization of the toxic effects of heavy metals on soil microorganisms (*Azotobacter, Pseudomonas, Bacillus*), earthworms, aquatic plants, and microorganisms. The modification of natural zeolites with MEA enhances their selectivity for non-ferrous metal ions (Cu^{2+}, Zn^{2+}), thereby preventing metal accumulation in ecosystems and protecting the life activities of organisms. The adsorption mechanism of non-ferrous metals by natural zeolites modified with complexing agents has been established: in MEA-modified zeolites, adsorption occurs through the formation of surface complexes between the modifier and the metal ions, followed by desorption, in which the metal ions are released back into the solution upon complex decomposition. This process reduces the bioavailability of toxic metals and contributes to the restoration of ecological balance in soil and water environments.

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ҚОРШАҒАН ОРТА ЛАСТАУШЫЛАРЫНЫҢ БИОТАҒА ЖӘНЕ ТҰРҒЫНДАР ДЕНСАУЛЫҒЫНА ӘСЕРІН БАҒАЛАУ

Section 2

ASSESSMENT OF ENVIRONMENTAL POLLUTION ON BIOTA AND HEALTH

Раздел 2

ОЦЕНКА ДЕЙСТВИЯ ЗАГРЯЗНИТЕЛЕЙ ОКРУЖАЮЩЕЙ СРЕДЫ НА БИОТУ И ЗДОРОВЬЕ НАСЕЛЕНИЯ