(Libyan Journal of Contemporary Academic Studies) المجلة الليبية للدراسات الأكاديمية المعاصرة
LJCAS, eISSN: 5970-3005
Volume 3, Issue 2 (Part II), 2025, Pages: 109-118

The Use of Zeolite Extracted from Clay Deposits in water Purification

Mohamed Khlifa Musa *
Geology Department, College of Science, Zintan University, Libya
*Corresponding author: hmide7@gmail.com

استخدام معدن الزيوليت المستخرج من الرواسب الطينية في تنقية المياه

محمد خليفة موسى *
قسم الجيولوجيا، كلية العلوم، جامعة الزنتان، ليبيا

Received: 07-09-2025; **Accepted:** 19-11-2025; **Published:** 07-12-2025

Abstract:
This study investigates the formation processes, geochemical features, and economic potential of zeolites extracted from clay deposits, with a primary focus on their role in water purification. Owing to their high cation-exchange capacity, porosity, and molecular sieving properties, zeolites demonstrate strong efficiency in removing pollutants such as heavy metals and ammonium ions from contaminated water. The paper outlines the main extraction and processing methods applied to clay-derived zeolites and evaluates their cost-effectiveness compared to alternative treatment technologies. The widespread natural abundance of zeolites and their relatively low production costs make them a sustainable option for large-scale water purification. Additionally, growing global demand for zeolites, especially in regions prioritizing sustainable water management, underscores their strategic importance. The findings suggest that zeolites represent an economically viable and environmentally beneficial material whose role in future water treatment and management strategies is expected to expand significantly.

Keywords: Zeolite, Water Purification, Cation-Exchange Capacity, Clay Deposits, Environmental Sustainability.

الملخص :
تبحث هذه الدراسة في عمليات تكوين الزيوليت وخصائصه الجيوكيميائية وإمكاناته الاقتصادية، مع التركيز بشكل خاص على دوره في تنقية المياه. وبفضل قدرته العالية على تبادل الكاتيونات، ومساميته، وخصائص الغربلة الجزيئية، يبرع الزيوليت في إزالة الملوثات مثل المعادن الثقيلة وأيونات الأمونيوم من المياه الملوثة. كما يستعرض البحث الطرق الرئيسة لاستخلاص ومعالجة الزيوليت المشتق من الرواسب الطينية، ويقيّم جدواه الاقتصادية مقارنةً بتقنيات المعالجة البديلة. إن الوفرة الطبيعية الواسعة للزيوليت وانخفاض تكاليف إنتاجه نسبيًا تجعله خيارًا مستدامًا لمعالجة المياه على نطاق واسع. إضافة إلى ذلك، فإن الطلب العالمي المتزايد على الزيوليت، وخاصةً في المناطق التي تعطي الأولوية لإدارة المياه المستدامة، يبرز أهميته الاستراتيجية. وتشير النتائج إلى أن الزيوليت يمثل مادة ذات جدوى اقتصادية وفوائد بيئية، وأن دوره في استراتيجيات معالجة وإدارة المياه مستقبلاً مرشح للتوسع بشكل ملحوظ.

الكلمات المفتاحية: الزيوليت، تنقية المياه، قدرة تبادل الكاتيونات، الرواسب الطينية، الاستدامة البيئية.

Introduction

Zeolites are crystalline, microporous aluminosilicates that have gained considerable importance in diverse industrial sectors because of their exceptional physicochemical characteristics, including large surface area, strong ion-exchange capacity, and notable thermal stability. These properties render them highly effective for applications such as catalysis, wastewater purification, gas separation, and agricultural enhancement. Their versatility arises from a unique three-dimensional arrangement of interconnected SiO_4 and AlO_4 tetrahedra, linked through oxygen atoms. This framework generates channels and cavities capable of hosting various cations and molecules, enabling a broad range of chemical processes. Over recent decades, global demand for zeolites has increased significantly, driven both by their efficiency in addressing environmental issues like air and water pollution and by their capacity to improve industrial process performance [1], [2].

Zeolites can occur naturally or be produced synthetically. Natural occurrences are typically associated with volcanic rocks, sedimentary deposits, and especially clays, which are considered highly valuable due to their abundance and the relative simplicity of extraction. The process of obtaining zeolites from clay deposits holds both geological and industrial significance, as it requires understanding their natural formation pathways alongside the development of efficient extraction techniques. Beyond their immediate industrial roles, zeolites contribute meaningfully to sustainability objectives. Their proven ability to purify water and air, combined with their potential

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

to reduce energy demand in several industrial applications, positions them as essential materials for advancing global environmental sustainability goals [3].

The present study aims to examine the geochemical attributes of zeolites derived from clay deposits and evaluate their economic relevance, particularly with respect to water purification. This domain has been identified as a critical area of application, given zeolites' effectiveness in removing contaminants such as ammonia, heavy metals, and other toxic compounds from natural water sources. The analysis considers both geological formation processes and extraction technologies, while also assessing specific case studies of zeolite application in water treatment. Furthermore, this paper evaluates the broader economic and environmental implications, analyzing market dynamics such as production costs, supply-demand balance, and the potential macroeconomic impacts on both local and global scales [4].

The scope of the study is organized into key thematic areas. It begins with an overview of the geological formation of zeolites within clay deposits, followed by an assessment of their mineralogical and physicochemical properties, and the methods commonly used for their characterization. The discussion then moves to extraction and processing practices, emphasizing both challenges and recent technological advances. Subsequent sections focus on water purification applications, with empirical evidence demonstrating zeolites' effectiveness. Finally, an economic appraisal highlights their value in industrial and environmental contexts, supported by a discussion of sustainability considerations, before concluding with research recommendations and policy implications.

Geological Formation of Zeolites in Clay Deposits

Geological processes leading to the formation of zeolites

The genesis of zeolites within clay deposits is governed by intricate geological and geochemical processes influenced by environmental conditions. These minerals typically form in sedimentary and volcanic settings, where specific ranges of temperature, pressure, and chemical composition favor their crystallization. A key pathway involves the alteration of volcanic ash or glass under low-grade metamorphic regimes. Such transformations are frequently associated with hydrothermal circulation, in which heated groundwater interacts with volcanic substrates, progressively converting amorphous silicates into crystalline zeolite frameworks [5].

One of the most critical stages in this evolution is the alteration of volcanic glass. This transformation commonly occurs in aqueous environments, such as lacustrine or marine basins, where volcanic ash accumulates and interacts with mineral-rich waters. Through the process of devitrification, volcanic glass loses its amorphous nature and crystallizes into zeolitic phases. The type of zeolite produced depends largely on geochemical variables, including the ash composition, water pH, and prevailing pressure–temperature conditions. For example, alkaline systems favor the crystallization of analcime and phillipsite, while neutral to mildly acidic conditions typically yield clinoptilolite and heulandite [6].

Cation availability is another decisive factor in zeolite formation. During crystallization, ions such as Na^+, K^+, Ca^{2+}, and Mg^{2+} are integrated into the zeolite framework, directly influencing both structural stability and mineral type. These cations, together with silica and alumina sources, are supplied through surrounding geological processes, including feldspar weathering and the dissolution of volcanic ash in hydrothermal environments [7].

Types and Distribution of Clay Deposits Rich in Zeolites

Clay deposits enriched with zeolites are typically associated with areas shaped by volcanic activity or sedimentary basins where volcanic ash has been deposited and transformed over long geological timescales. These deposits occur in diverse geological contexts, including lacustrine sediments, marine basins, and alluvial plains. The specific type of zeolite found in such environments is determined by local geological history and environmental conditions during formation. For instance, freshwater lake basins where volcanic ash accumulates often yield clinoptilolite and mordenite. These minerals are particularly valuable due to their high cation-exchange capacity and structural stability [8].

From a global perspective, zeolite-rich clay deposits are widely distributed across continents. In the United States, particularly in western states such as Arizona, Nevada, and California, vast reserves of natural zeolites have been identified. These deposits, predominantly clinoptilolite and mordenite, originate from the alteration of volcanic tuffs. Japan also hosts significant deposits, especially in Shikoku and Kyushu, where hydrothermal alteration of volcanic glass has resulted in the development of minerals such as mordenite and analcime. In Italy, zeolitic clays are concentrated around the Roman and Neapolitan volcanic regions, reflecting the enduring influence of volcanic activity in shaping mineral formation [9].

Turkey contains some of the world's most extensive clinoptilolite resources, particularly in the Gördes and Bigadiç regions. These deposits, derived from the alteration of rhyolitic tuffs, are of substantial industrial importance. They supply raw material for a broad range of applications, including water purification systems, agricultural soil amendments, and construction materials [10]. The global presence of zeolite-bearing clay deposits underscores the universality of the geological processes that create these minerals, making them a vital resource for industries worldwide.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Geochemical Properties of Zeolites

Mineralogical composition and structure

The distinctive mineralogical composition and crystalline architecture of zeolites underpin their extensive range of industrial applications. Fundamentally, zeolites are aluminosilicates composed of a three-dimensional network of SiO_4 and AlO_4 tetrahedra. Each silicon or aluminum atom is coordinated with four oxygen atoms, forming tetrahedral units. The substitution of silicon by aluminum introduces a negative charge into the framework, which is neutralized by the presence of exchangeable cations such as Na^+, K^+, Ca^{2+}, or Mg^{2+}, located within structural cavities. This arrangement results in a porous framework characterized by interconnected cages and channels, enabling zeolites to function effectively as molecular sieves and catalysts [11].

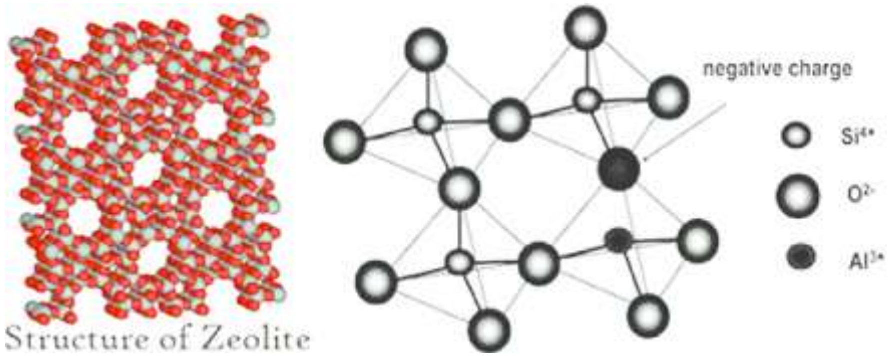

Figure 1: Structure of zeolite

The mineralogical characteristics of zeolites differ depending on their type and geological origin. Among the most common natural zeolites are clinoptilolite, mordenite, and chabazite, each with unique structural attributes. Clinoptilolite, known for its elevated Si/Al ratio, exhibits superior thermal stability and acid resistance, making it particularly suitable for wastewater remediation and environmental cleanup. Mordenite, with its larger pore structure, can adsorb bigger molecules, thus being widely applied in petrochemical industries. The variability in composition and structure across zeolite species is a decisive factor shaping their specific industrial roles [12], [11].

Physicochemical Properties of Zeolites

The functional performance of zeolites is closely tied to their physicochemical properties, including porosity, ion-exchange capacity, and thermal stability. Zeolites are characterized by high porosity, with pore sizes typically between 0.3 and 1.2 nanometers. This selective porosity allows adsorption of molecules according to their size and geometry, a feature central to applications in catalysis, gas separation, and water treatment. The extensive surface area further enhances molecule–zeolite interactions, boosting the efficiency of adsorption and catalytic reactions [13].

Table 1: Physical Properties of Pure Natural Zeolite

Specifications	Property
White/gray/green	Color
24.9- 40	Surface Area - m^2/gm
800-1041	Bulk Density - kg/m^3
1.6-2.0	Cation Exchange Capacity (CEC) - MEq/gm
0.4-0.7	pore diameter, nm
11-Mar	Stability, pH
0.65	Particle size - mm
1.89	specific gravity
5-Apr	Hardness, mohs
1.6	Uniformity coefficient - (d_{60}/d_{10})
Less than 10	Moisture - %

Ion-exchange capacity is another defining attribute. It is primarily governed by the aluminum content of the zeolite framework, as each Al atom introduces a charge balanced by exchangeable cations. Zeolites with higher aluminum concentrations generally demonstrate greater ion-exchange capacity, making them effective for heavy-metal remediation, water softening, and soil enhancement. Clinoptilolite is extensively employed in water treatment for the removal of ammonium ions and toxic metals owing to this property [3], [13].

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Thermal stability is equally critical for industrial operations at elevated temperatures, such as catalytic cracking. The structural resistance of zeolites to heat is linked to their Si/Al ratio, with higher ratios conferring stronger thermal durability. This stability ensures that zeolites retain integrity under harsh thermal and chemical environments, extending their utility in high-temperature petrochemical processes [14].

Methods of Characterizing Zeolites Extracted from Clay

Characterization of zeolites from clay deposits is essential for assessing their structural and chemical suitability for industrial use. A range of analytical tools is employed to evaluate mineralogical, structural, and physicochemical properties. **X-ray diffraction (XRD)** is widely used to identify crystalline phases and determine the atomic arrangement within the zeolite framework. This method is particularly effective in distinguishing between zeolite types and verifying material purity [6], [7].

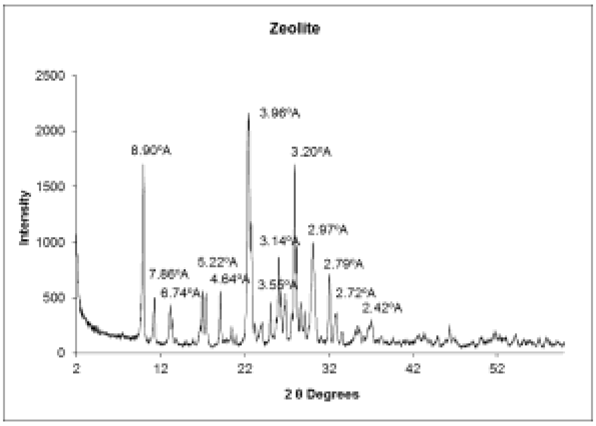

Figure 2: X-ray diffraction of natural zeolite samples

Scanning electron microscopy (SEM) offers high-resolution images of zeolite morphology, providing insights into pore distribution and surface structures. When coupled with **energy-dispersive X-ray spectroscopy (EDS)**, SEM also facilitates elemental composition analysis, particularly of framework cations [15].

Fourier-transform infrared spectroscopy (FTIR) and **nuclear magnetic resonance (NMR)** further enrich zeolite characterization. FTIR identifies functional groups and adsorbed species within the pores, while NMR provides atom-specific information on silicon and aluminum environments, offering insights into framework composition and bonding. Collectively, these methods form a comprehensive toolkit for understanding zeolite behavior and tailoring them for targeted industrial applications [16], [6].

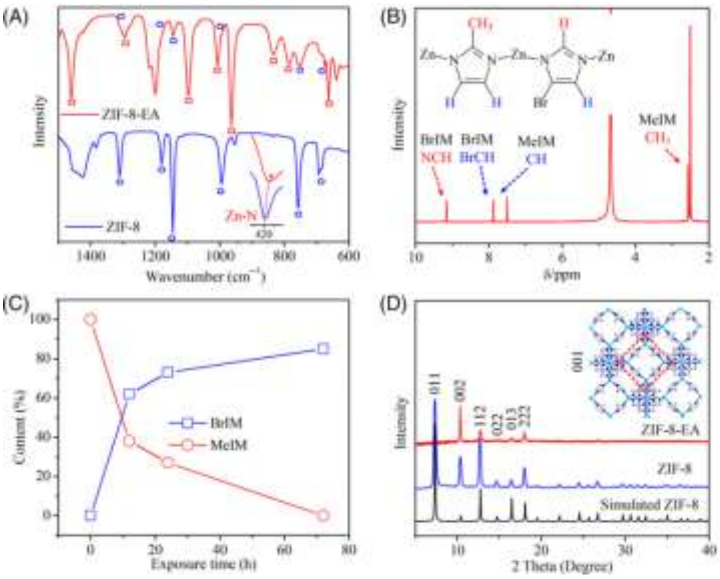

Figure 3: Fourier transform infrared (FTIR) spectra of the zeolitic

Extraction and Processing Techniques

The transformation of zeolites from raw clay deposits into industrial-grade materials involves a series of extraction and processing stages. These stages require close attention to the geological setting, the mineralogical composition of the zeolite present, and the level of purity and performance expected for the end application. The chosen methods significantly affect the quality and usability of zeolites across diverse sectors, including catalysis, wastewater treatment, and environmental remediation.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Methods of Extracting Zeolites from Clay Deposits

The first stage involves geological surveys to identify zeolite-rich clay deposits. Upon locating a suitable site, mining operations such as open-pit or strip mining are typically employed. Open-pit mining removes substantial overburden to access deeper zeolite-bearing clays, whereas strip mining progressively removes horizontal layers of material. While effective for large-scale extraction, both techniques can cause environmental issues such as habitat loss, soil erosion, and landscape disruption [17].

Once extracted, the clay undergoes preliminary processing to enrich its zeolite content. Mechanical screening is frequently applied to separate zeolitic particles from coarser impurities like gravel or rock fragments. Crushing and grinding are often performed to reduce particle size and increase surface area, thereby improving downstream processing. In addition, washing with water can eliminate soluble impurities and reduce unwanted mineral concentrations [18], [17].

Processing and Purification Techniques

Refined processing steps are then implemented to purify and optimize the properties of the zeolites. **Hydrothermal treatment** is a widely used method that replicates the natural conditions of zeolite formation. Here, clay is treated with alkaline aqueous solutions at elevated pressures and temperatures, which facilitates the dissolution of silica and alumina and promotes recrystallization into zeolitic structures. This approach enhances crystallinity and overall material purity, preparing zeolites for high-value applications [19].

Ion exchange is another critical technique. By replacing the framework cations with alternative ions, the physical and chemical properties of zeolites can be tuned for specific functions. For instance, ion exchange may be employed to increase catalytic activity or to boost ion-exchange efficiency in water treatment. Following exchange, washing and drying steps are typically required to stabilize the modified zeolite [2].

Additional purification measures may also be necessary. **Calcination**, involving controlled heating at high temperatures, is commonly used to eliminate organic matter and volatile impurities. It also enhances the thermal resistance and mechanical strength of the material, expanding its suitability for high-temperature applications such as catalytic cracking. **Magnetic separation** can further purify zeolite concentrates by removing ferromagnetic contaminants [20], [19].

In advanced cases, **chemical leaching** is applied to achieve superior levels of purity. Acidic or alkaline leaching agents selectively dissolve undesirable mineral phases, including iron oxides and other metallic impurities that can compromise performance. The specific leaching conditions depend on both the composition of the clay and the required characteristics of the final zeolite [21], [20].

Overall, the efficiency, cost, and environmental consequences of extraction and processing methods must be carefully balanced. With the increasing global demand for zeolites, continuous innovations in extraction and processing technology will be essential to improve yields, reduce ecological impacts, and meet industrial standards.

Applications in Water Purification

Zeolites have become highly relevant in water purification due to their distinct structural and chemical features. Their high surface area, cation-exchange capacity, and molecular sieve functionality enable them to capture diverse pollutants, ranging from heavy metals and ammonia to organic contaminants. These properties make them indispensable materials in both municipal and industrial water treatment systems.

Mechanisms of Water Purification Using Zeolites

The dominant mechanism underlying zeolite-based purification is **ion exchange**. Their crystalline framework contains negatively charged sites that attract cations, enabling the substitution of structural cations such as Na^+ or Ca^{2+} with toxic ions present in water, including Pb^{2+}, Cd^{2+}, and NH_4^+. This not only eliminates hazardous contaminants but also stabilizes them within the zeolite lattice, thereby preventing secondary contamination. Effectiveness depends on the zeolite species; for instance, clinoptilolite demonstrates a strong affinity for ammonium ions, making it highly effective in treating wastewater with elevated ammonia levels [18].

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

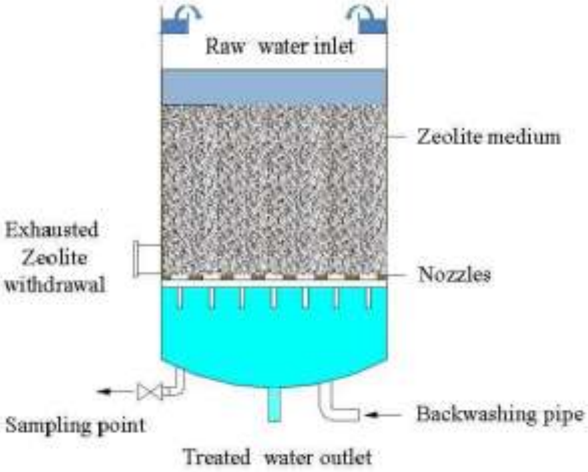

Figure 4: The Zeolite filtration unit

Beyond ion exchange, zeolites also purify water through **adsorption**. Their interconnected pore systems offer a large surface area for capturing organic compounds and volatile organic contaminants. Acting as molecular sieves, they selectively adsorb molecules according to size and shape, enabling targeted pollutant removal while preserving essential water components. Surface modifications further enhance this capacity, allowing zeolites to be engineered for specific contaminants and expanding their potential applications in purification [2], [22].

Case Studies of Zeolite Application in Water Treatment

Real-world applications illustrate the adaptability of zeolites in diverse water treatment contexts.

- **Rural Drinking Water:** In developing regions where safe drinking water is scarce, natural zeolites have been employed as low-cost filtration materials. A study in Bangladesh demonstrated the efficiency of clinoptilolite in reducing arsenic levels in contaminated groundwater to within WHO guidelines, providing a practical and affordable solution for marginalized communities [23].
- **Industrial Wastewater:** Zeolites have also been integrated into industrial effluent treatment, particularly in sectors producing metal-rich wastewater. For example, in India's textile industry, chemically modified zeolites successfully removed chromium and other heavy metals, achieving up to 90% reduction and allowing water reuse within industrial operations [24].
- **Municipal Wastewater:** Ammonia pollution from sewage and agricultural runoff presents a major challenge for urban water systems. In Japan, municipal treatment facilities have adopted zeolite filters to reduce ammonia concentrations in wastewater. The results show significant improvement in effluent quality and a clear reduction in eutrophication risk in receiving water bodies [22].

These examples highlight the versatility of zeolites, which are effective in contexts ranging from community-scale drinking water systems to industrial effluent treatment and municipal sewage management. Their ability to remove a wide spectrum of contaminants confirms their role as an indispensable tool in securing clean water resources.

Environmental and Sustainability Implications of Using Zeolites

Environmental Advantages of Natural Zeolites in Water Treatment

Natural zeolites have a lot of environmental benefits which make them the most sustainable water purification material, especially in areas that are under pressure to reduce the dependency on chemicals and to adopt low-impact treatment technologies. Their crystalline structure, high cation-exchange capacity, and molecular sieving properties are what mainly allow zeolites to be pollutant-free as afterward, no chemicals are added, hence secondary contaminants are minimized. This is a great advantage over chemical precipitation and coagulation methods, which often require further treatment and disposal of the substantial sludge volumes that they produce. Ion exchange and adsorption are the main processes in zeolite-based purification systems, and both occurring processes limit waste through the stabilization of contaminants within the mineral matrix, thus reducing the environmental burdens related to sludge management, and hazardous waste transport [23]. Moreover, natural zeolites are non-toxic, biocompatible, and commonly found throughout the world, thus being very good for water treatment in decentralized and rural areas where there are no chemical supply chains and specialized equipment.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

At the same time, Industrial countries cause the Earth's inhabitants to suffer a lot. Even though the children are being educated in the school with the best science and the best teachers, the actual nature of the world they live in is fast disappearing. As it happens, they won't really have enough time in the Earth to see all the changes- the kind of changes made by adults- that they will have to live with every day! Long before their dreams come true, they will have to start changing the way of life depending on their environment and the Earth.

Scientists say that the environmental problem has arisen because on one hand the governments of many countries act in acknowledgment of global warming as the major cause of environmental pollution, and the cities are not large enough to encompass the effects of the soot and gases, and last but not least, the technologies the industries use are still very much based on fossil fuels.

Natural zeolites are another reason for discussion about the circular economy because they come in handy for regenerating and reusing. Zeolites that are already spent can be brought back to life and their adsorption capacity reestablished just with rather simple methods like washing them with water containing salt or treating them with a not too aggressive heat. The waste generated during the process is close to none and there is no need for any hazardous chemicals to be used. in some cases, metal-loaded zeolites can be even further used purposefully, not only for being raw materials of other products. Rather, they could be used to remediate contaminated soils or as catalysts, hence, they would contribute to reducing waste and increasing resource efficiency. Apart from that, as compared to mining for metals or for raw materials from fossils, the impact of zeolite extraction is lighter on the environment. Natural zeolite deposits are usually found close to the surface from where they can be extracted through low-energy open-pit mining, which would, in turn, reduce the environmental impact of deep mining.

In broad terms, the eco-advantages of natural zeolites are about the minimal energy consumption to produce them, less chemical input, rare release of secondary pollution, and the possibility of the methods used being compatible with resources that could be managed sustainably. Moreover, their use in water purification systems is completely in line with the world's eco-sustainability objectives, especially those which are pinpointing the employment of environment-friendly and less harmful technologies as well as the provision of quality water. These facts alone would make natural zeolites a crucial player in ecological water treatment systems and a very attractive material for upcoming sustainability schemes [26].

Life-Cycle Assessment (LCA) of Zeolite-Based Purification Systems

The comparative environmental benefits of zeolite-based water purification systems have been established through the life-cycle assessment (LCA) of all the product life cycle stages – extraction, processing, operation, and end-of-life. Life-cycle Assessments (LCAs) across natural zeolites have always yielded results sustaining that they have a smaller environmental load than rivaling techniques such as activated carbon, ion-exchange resins, and membrane systems. The surface mining involved at the extraction stage of natural zeolites is quite energy-intensive and generates a large amount of CO2 emissions. The production of synthetic sorbents, which are the main competitors to the natural zeolites as the raw materials for the water purification process, is a very energy-intensive process [24]. Water purification market competitors are frequently made from energy-intensive processes that use amine precursors from fossil sources, photolysis and chlorination as key technologies to lower carbon emissions by only about 500 GJ/t. Life cycle analyses of natural zeolite processing show a relatively small carbon footprint on the environment as it involves only a crushing, sieving, and washing step to purify the material from impurities. During the operating phase, the water treatment systems based on zeolite prove more ecologically-friendly. Due to this mechanism of utilizing zeolites, which is passive ion exchange and adsorption, the systems do not consume much energy, have a low pressure requirement, or perform oxidations. Such is not the case with the membrane technology, for instance, reverse osmosis; it demands a lot of energy during operation, and what is more, the brine wastes have to be kept in check by careful disposal. In comparison, zeolites do not only have the tiniest operational carbon footprint but are also the least eco-destructive. Life-cycle analyses of zeolite filtration versus the membrane methods have indicated that, in the climate change, eutrophication, and energy aspects, for example, zeolites are much better than membrane systems and thus stand out as a desirable choice for environmentally-friendly water treatments. The mentioned benefits are not the only ones; their long life in the plant and relatively constant performance through several cycles of regeneration are the other positive factors that can be taken as a benefit to cost ratio in medium and large treatment plants.

The environmental profile of natural zeolites has also a first winning point in terms of end-of-life management. The absorption property of zeolites had been rejuvenated with some of the nutrients like ammonium which makes it possible for them to act as a slow-release fertilizer. On the agricultural field, this process opens a very productive way to reuse zeolites which can thereby reduce the need to dispose of the contaminated filters. At the same time, risk of leaching heavy metals from zeolites is cut down by immobilizing them in the mineral structure and disposal thus becomes safer and more environmentally friendly as compared to the chemicals produced by the generated sludge. The treating and main issue of heavy metals adsorption is also addressed in a zeolite purification system through the absorptive capacity of minerals. The reason for this is that currently a so-called closed-loop model is even more than supported but enabled through the incorporation of beneficial reuse routes with zeolite-based purification systems and, thereafter, this smooth working leads to good products just like the circular economy. [29]. Their inert and non-toxic properties are proved by several LCA studies to aid in avoiding contamination through disposal thus not contributing to soil or groundwater.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Generally, the evidence from the life-cycle analysis is strong that natural zeolites are one of the most environmentally friendly materials for water purification. The total environmental consequences that come with them from extraction to disposal are consistently lower than those from alternatives that require lots of chemicals and energy. The use of life-cycle assessment in system design further supports the importance of zeolites as a key part of the water treatment that is both environmentally and economically sustainable, particularly in countries aiming at the use of low-resource, and environmentally friendly technologies [30].

Sustainability Challenges and Future Green Innovations

Even though natural zeolites have a lot of benefits, their use in water treatment implies also lots of sustainability challenges to be faced for them to be fully recognized as the Earth-friendly cleaning agents. One of these is the mining issue. Despite the fact that the zeolite industry has a relatively low environmental impact when compared with others, bad mine management can still result in problems like land use change, natural habitats disruption, dust emissions and soil run-off. The safe mining activities (progressive rehabilitation, erosion control, and reclamation of land after extraction) are crucial for the environmental health of the geologically important locations. Hence, the research found that extraction methods which are environmentally friendly and the better management of the extraction site can lower the ecological disturbance to a significant extent, and it is the reason for making sustainable mining aged zeolite producing regions as the focus for development worldwide [31]. Another sustainability issue emerges from how different the natural zeolites are in terms of their composition, this variance being a big driver of the technology's overall performance. Differentiation calls for the proper techniques to characterize the ore and may sometimes involve a pretreatment step, which in turn, may lead to an increase in power consumption unless managed economically.

Regeneration and long-term reuse are 2 other significant challenges. Zeolites are indeed regenerable, but the regenerating process could need saline solutions or low heating, which may create additional waste streams if not managed well. Therefore, regenerating methods that are friendly to the environment are definitely a must for the next step in our work of innovation. Besides, it is important to still be extra cautious when in possession of the used zeolites containing toxic heavy metals. Even though the metals are firmly locked into the zeolite lattice, they still cannot be left as they are, disposal or stabilization must be done. The few first studies, however, suggest that if we embed the spent zeolites into ceramic materials or geopolymers, we would be creating also a safe and sustainable waste management strategy, while leaching would be completely prevented and the materials used will be of higher quality [32.]

There are various improvements which can be environmentally-friendly and sustainable that one might expect in the near future, and some of these are indeed promising even for the zeolite-based systems. To the eyes of researchers, one such exciting path is the eco-friendly functionalization method development which alters the materials` properites through non-polluting agents only. Surfactants which are bio-based, polymers derived from plants, as well as microorganisms` applications, have the potential to control the adsorption process via the "green" means and with an increase in efficiency. The other focus is on the utilization of natural zeolites within the hybrid treatment systems as they form the perfect match with biofilters, wetlands that are human-made, or membrane energy systems that are low. In other words, these types of configurations will treat more contaminants, consume less energy, and be more eco-friendly. Moreover, the new applications of zeolites, which are tailor-made for the problem and at the same time made of industrial waste such as red ash, glass waste, and rice husk ash, are much in the limelight of scientific discussions. The combined factors of mineral resource saving, on the one hand, and waste material re-application in the sorbent production cycle, on the other, speak for a circular economy model in the environmental science area [33].

In the end, technological progress indicates the adoption of nano-enhanced zeolites that are exceptionally efficient in the field of adsorption due to the use of nanoparticles or nanostructured films that greatly enhance the selectivity, and regeneration performance. The above-mentioned technologies provide great benefits and it is of desperate need to be cautious in the analysis to provide that nano-scale materials do not bring forth new environmental hazards. To sum up, the current environmental problems will be successfully mitigated alongside green innovations, and it will be guaranteed that natural zeolites are still the major material for eco-friendly water purification systems and sustainable development tactics all around the globe [34].

Conclusion

The investigation of zeolites, particularly those sourced from clay deposits, emphasizes their broad industrial significance, with water purification standing out as a key domain of application. This study has examined their geological origins, geochemical features, extraction and processing methods, and economic potential, collectively underscoring the multifaceted importance of zeolites in both environmental management and industrial practices.

Zeolites originate through complex geological transformations, often involving the hydrothermal alteration of volcanic ash or glass. These processes yield highly porous crystalline frameworks that combine structural stability with functional versatility. Their mineralogical composition and physicochemical traits—most notably ion-exchange capacity, adsorption ability, and thermal resilience—make them highly effective in removing

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

contaminants such as heavy metals and ammonium, affirming their utility across industrial and environmental applications.

Extraction and refinement techniques, including mechanical separation, hydrothermal synthesis, and ion-exchange modification, have been optimized to enhance both purity and performance. These approaches ensure that natural zeolites can be supplied in forms that meet modern industrial and environmental standards while maintaining cost-effectiveness and relatively low ecological impact.

From an economic perspective, zeolites offer distinct advantages. They are abundant, inexpensive to process, and capable of delivering cost-efficient alternatives to conventional water treatment technologies. Their growing global demand is reinforced by the need for sustainable water management solutions, while extensive natural deposits guarantee market stability. On a local scale, mining and processing activities stimulate economic growth and employment, whereas globally, zeolite trade contributes to industrial development and supports sustainability goals.

Environmentally, zeolites provide significant benefits by improving water quality and reducing ecological degradation. Their role in removing toxic pollutants contributes directly to public health improvements while advancing broader environmental objectives, including reduced contamination and increased water reuse in agriculture and industry.

Looking ahead, continued advances in research and technology are likely to expand both the efficiency and scope of zeolite applications. Innovations in processing and functional modification will further enhance their performance, while exploration of additional natural deposits will sustain global supply. Together, these developments position zeolites as a vital resource not only for water purification but also for emerging areas of environmental protection and industrial innovation.

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that they have no conflict of interest.

References

1. D. W. Breck, Zeolite Molecular Sieves: Structure, Chemistry, and Use. New York, NY: John Wiley & Sons, 2013.
2. C. S. Cundy and P. A. Cox, “The hydrothermal synthesis of zeolites: Precursors, intermediates, and reaction mechanisms,” Microporous and Mesoporous Materials, vol. 82, no. 1–2, pp. 1–78, 2003.
3. F. A. Mumpton, “La roca magica: Uses of natural zeolites in agriculture and industry,” Proc. Natl. Acad. Sci. USA, vol. 96, no. 7, pp. 3463–3470, 1999.
4. E. M. Flanigen, “Introduction to zeolite science and practice,” in Studies in Surface Science and Catalysis, vol. 137, pp. 11–35, Elsevier, 2001.
5. T. Armbruster and M. E. Gunter, “Crystal structures of natural zeolites,” in Natural Zeolites: Occurrence, Properties, Applications, Reviews in Mineralogy & Geochemistry, vol. 45, pp. 1–67, 2001.
6. D. S. Coombs, A. Alberti, A. Armbruster, G. Artioli, E. Galli, J. D. Grice, et al., “Recommended nomenclature for zeolite minerals: Report of the Subcommittee on Zeolites of the International Mineralogical Association, Commission on New Minerals and Mineral Names,” European Journal of Mineralogy, vol. 10, no. 5, pp. 1037–1081, 2004.
7. D. L. Bish and D. W. Ming, “Natural zeolites: Occurrence, properties, applications,” in Natural Zeolites: Occurrence, Properties, Applications, Reviews in Mineralogy & Geochemistry, vol. 45, pp. 1–68, 2001.
8. R. L. Hay and R. A. Sheppard, “Occurrence of zeolites in sedimentary rocks: An overview,” in Natural Zeolites: Occurrence, Properties, Applications, Reviews in Mineralogy & Geochemistry, vol. 45, pp. 217–234, 2001.
9. E. Passaglia and R. A. Sheppard, “Zeolite deposits in volcanic rocks: A review,” in Natural Zeolites: Occurrence, Properties, Applications, Reviews in Mineralogy & Geochemistry, vol. 45, pp. 91–117, 2001.
10. B. Keskin and A. Akgül, “Occurrence and genesis of clinoptilolite deposits in the Gördes and Bigadiç areas, western Turkey,” Clays and Clay Minerals, vol. 62, no. 2, pp. 145–159, 2014.
11. C. Baerlocher, L. B. McCusker, and D. H. Olson, Atlas of Zeolite Framework Types, 6th ed. Amsterdam: Elsevier, 2007.
12. A. Corma, “State of the art and future challenges of zeolites as catalysts,” Journal of Catalysis, vol. 216, no. 1–2, pp. 298–312, 2003.
13. D. M. Ruthven, Principles of Adsorption and Adsorption Processes. New York: Wiley, 1984.
14. E. M. Flanigen, J. M. Bennett, R. W. Grose, J. P. Cohen, R. L. Patton, R. M. Kirchner, and J. V. Smith, “Silicalite, a new hydrophobic crystalline silica molecular sieve,” Nature, vol. 271, no. 5645, pp. 512–516, 1978.
15. G. Gottardi and E. Galli, Natural Zeolites. Berlin: Springer-Verlag, 1985.
16. J. F. Haw, “Solid-state NMR studies of zeolites,” Chemical Reviews, vol. 102, no. 8, pp. 3643–3662, 2002.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

17. B. Keskin and A. Akgül, "Occurrence and genesis of clinoptilolite deposits in the Gördes and Bigadiç areas, western Turkey," Clays and Clay Minerals, vol. 62, no. 2, pp. 145–159, 2014.
18. V. J. Inglezakis and A. A. Zorpas, Handbook of Natural Zeolites. Sharjah, UAE: Bentham Science Publishers, 2012.
19. C. Colella and A. F. Gualtieri, "Zeolites and their uses in the environment," in Environmental Mineralogy II: European Mineralogical Union Notes in Mineralogy, vol. 9, pp. 389–420, 2007.
20. R. D. Crangle, "Zeolites (natural)," U.S. Geological Survey Mineral Commodity Summaries, pp. 178–179, 2012.
21. D. D. Eberl, "User-friendly guide to natural zeolite properties," in Natural Zeolites: Occurrence, Properties, Applications, Reviews in Mineralogy & Geochemistry, vol. 45, pp. 485–509, 2003.
22. S. Wang and Y. Peng, "Natural zeolites as effective adsorbents in water and wastewater treatment," Chemical Engineering Journal, vol. 156, no. 1, pp. 11–24, 2010.
23. J. Margeta, N. Logar, M. Šiljeg, and A. Farkaš, Natural Zeolites in Water Treatment: How Effective is Their Use. Rijeka, Croatia: InTech, 2013.
24. A. Bhatnagar and M. Sillanpää, "Utilization of natural zeolites in water and wastewater treatment: A review," Chemical Engineering Journal, vol. 163, no. 3, pp. 23–35, 2010.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of **LJCAS** and/or the editor(s). **LJCAS** and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).