ASEAN
Journal of Scientific and Technological Reports
Online ISSN:2773-8752

Research article

Recent Studies on the Applications of Zeolite

Ho Soonmin[1*], Riandy Putra[2], and Muhammad Akram[3]

[1] Faculty of Health and Life Sciences, INTI International University, Putra Nilai, Malaysia
[2] Faculty of Mathematics and Natural Sciences, Universitas Palangka Raya, Indonesia
[3] Department of Eastern Medicine, Government College University Faisalabad-Pakistan
* Correspondence: e-mail: soonmin.ho@newinti.edu.my

Citation:
Soonmin, H.; Putra, R.; Akram, M. Recent studies on the applications of zeolited. *ASEAN J. Sci. Tech. Report.* **2026**, *29*(12), e263670. https://doi.org/10.55164/ajstr.v29i12.263670

Article history:
Received: February 11, 2026
Revised: April 17, 2026
Accepted: June 1, 2026
Available online: November 8, 2026

Publisher's Note:
This article is published and distributed under the terms of the Thaksin University.

Abstract: Natural zeolites develop their three-dimensional microporous structures because their crystalline aluminosilicate composition contains tetrahedral silica and alumina units, which connect through oxygen atom bonds. The structural configuration creates a porous system containing numerous interconnected voids and passageways that typically hold water molecules, together with exchangeable cations. Natural zeolite has become useful for numerous applications since its discovery, including its use as a pozzolan in cement and concrete production and as an adsorbent. The market for synthetic zeolite has gained popularity because natural zeolite cannot meet current market demand. In keeping with the current trend in the building sector toward sustainable materials with superior performance, natural zeolites offer a cost-effective, environmentally friendly alternative with a variety of applications in modern cement-based systems. The research study investigating zeolites for biomedical purposes will demonstrate their value as vital components in creating affordable medical treatments that perform multiple functions. Natural zeolites can purify radioactive waste because they contain clinoptilolite, chabazite, and mordenite, which enable ion exchange, select materials, provide radiation protection, and are low-cost.

Keywords: Zeolite; wastewater treatment; water pollution; gas processing; aquaculture

1. Introduction

Natural zeolites develop their three-dimensional microporous structures because their crystalline aluminosilicate composition contains tetrahedral silica (SiO_4) and alumina (AlO_4) units that connect through oxygen atoms. The structural configuration creates a porous system containing numerous interconnected voids and passageways that typically hold water molecules, together with exchangeable cations [1]. Cations serve as essential components because they help balance the negative charges in the aluminosilicate structure, leading to improved ion-exchange performance and greater adsorption capacity that enable zeolites to fulfill industrial applications. The Swedish mineralogist Axel Fredrik Cronstedt discovered stilbite as the first zeolite mineral during his research. He observed that stilbite mineral emitted steam from its structure at high temperatures. From this observation, he designated the substance as "zeolite". Zeolite means to boil, and lithos means stone, because the mineral displays a visible boiling effect when heated [2].

Natural zeolite has become useful for numerous applications since its discovery which includes its use as pozzolans in cement and concrete production and its function as an adsorbent [3]. The market for synthetic zeolite has gained

popularity because natural zeolite produces insufficient volume to satisfy current market requirements. The discovery of extensive natural zeolite mineral deposits which contained 95 percent natural zeolite material stopped this project from continuing its work during the late 1950s. Natural processes which took place in both oceanic and freshwater systems led to the transformation of volcanic glass material into sediments. The United States marked the location of its first zeolite deposits. The zeolite layers were extracted and processed to create different products.

Material development reached its current advanced state after Cronstedt discovered natural zeolite. The initial studies focused on naturally occurring minerals, including stilbite and clinoptilolite. Researchers used these minerals for agricultural and industrial purposes. The 20th century saw rapid growth in synthetic zeolite development because natural zeolites were in insufficient supply [4]. Researchers create synthetic zeolites through controlled hydrothermal processes, enabling them to tailor pore dimensions, atomic arrangements, and physical characteristics that different industries need. More than 200 zeolite framework designs exist, but only about 40 occur in nature, while scientists create the remaining designs in laboratory settings. The study analyzes natural zeolites, including clinoptilolite and chabazite, and synthetic zeolites, including zeolite A, X, and Y (figure 1), which scientists frequently use for research purposes. The historical development from natural discovery to synthetic innovation demonstrates how zeolite research drives scientific and technological progress through its multiple applications.

In this work, the preparation and characterization of zeolites were reported. The properties of these zeolites were determined using various types of equipment. Applications of these samples were reported based on literature reviews. Several publication databases will be used to highlight the most influential articles in conjunction with the applications of zeolites.

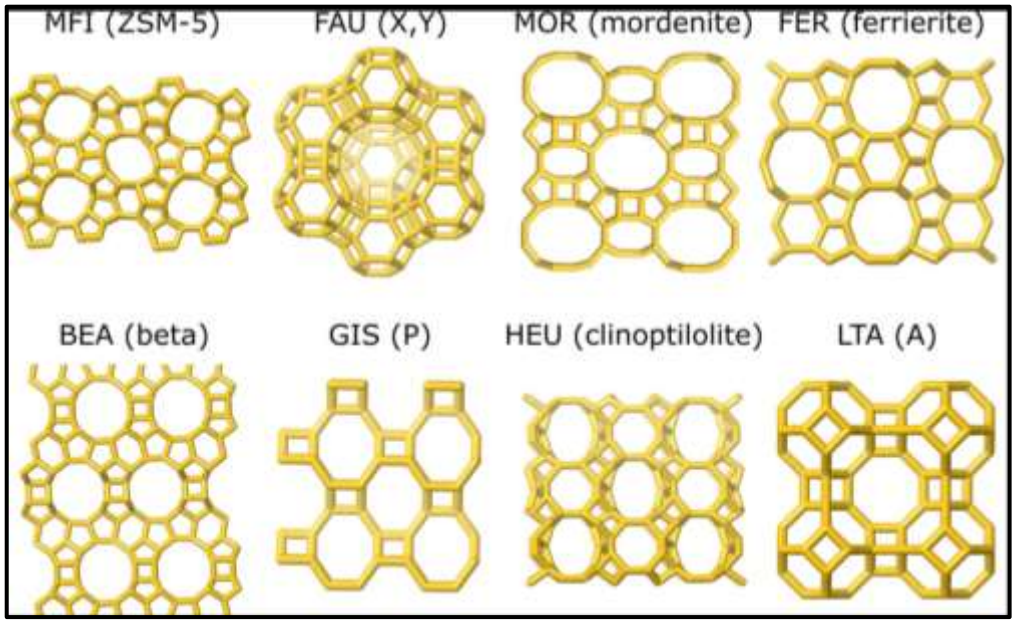


Figure 1. Structure of zeolite

2. Materials and Methods

A bibliometric database of zeolites was compiled from several publication databases, including Scopus, Web of Science, Google Scholar, and IEEE Xplore. Some important keywords, including zeolite, wastewater treatment, water pollution, contaminants, agriculture, gas processing, adsorption processes, aquaculture, medicine, construction, and radioactive waste remediation, were used to search for English-language papers published between 2000 and 2025.

3. Results and Discussion

3.1 Occurrence

Scientists first identified natural zeolites after finding zeolite minerals in volcanic sedimentary rocks, and later discovered additional zeolite minerals across multiple global locations [5]. People have shown increasing interest in natural zeolites during the past decade because they serve multiple purposes in various industries. Researchers investigate the material because its unique physicochemical characteristics are attracting growing interest. Estimates from 1988 indicated that global natural zeolite consumption reached 3.98 million tonnes, while forecasted growth would bring it to 5.5 million tonnes by 2010. The U.S. Geological Survey reported in 2025 that natural zeolite production worldwide reaches about 1,000,000 tonnes each year. The main producers in 2025 included Slovakia (220,000 tonnes), China (150,000 tonnes), South Korea (130,000 tonnes), Indonesia (120,000 tonnes), New Zealand (100,000 tonnes), and the United States (81,000 tonnes).

Natural zeolites occur in various rock types that span all geological time periods and multiple geological environments [6]. Geologists believe that zeolites form through interactions between water and rocks across different geological environments. Secondary minerals in basic igneous rocks and basalt vugs and cavities include zeolites, but various layered pyroclastic deposits use them as their primary mineral component. Natural zeolites are the primary authigenic silicate minerals that occur throughout volcanic sedimentary rock formations [7]. Natural zeolite production most commonly occurs during diagenesis, which transforms sedimentary rocks into their final state. The eight main natural zeolites exist in sedimentary environments. Natural zeolites exhibit distinct mineralogical characteristics that result from the geological formations that define their physical and chemical properties.

The classification system for natural zeolites from sedimentary rocks identifies seven distinct categories, which result from their hydrological and geological formation methods. Volcanic and non-volcanic sediments occur within alkaline soil environments and within closed hydrological systems that develop in alkaline and saline lake environments [8]. Zeolites are crystalline aluminosilicates that form microporous structures from their SiO4 and AlO4 tetrahedral frameworks, which combine silicon and aluminum atoms that each connect to four oxygen atoms. The basic components of tetrahedral structures link together through their shared oxygen atoms to create the three-dimensional zeolite. The system consists of connected channels and cages that operate as micropores to retain water molecules and additional framework cations, including Na+, K+, Ca2+, and Mg^{2+}. The substitution of Si4+ by Al3+ creates a negative charge, which is balanced by cation movements that enable zeolites to act as cation exchangers [9]. Secondary building units (SBUs) exist in multiple geometric forms, including rings and polyhedra, because they can contain up to 16 tetrahedral atoms, which can be either Si or Al, leading to different pore patterns. The scientific community has currently identified 23 distinct SBU types.

3.2 Applications of zeolites

Zeolites have various industrial uses because of their physical and chemical properties, which define their characteristics [10]. The material's negatively charged aluminosilicate framework provides high ion-exchange capacity, enabling multiple environmental applications, including wastewater treatment, agricultural use, aquaculture, and radioactive waste cleanup, through specific metal-ion, ammonium, and radionuclide extraction methods. The microporous structure of zeolites allows only specific shapes to traverse their bodies, enabling their operation as molecular sieves that assist in gas dehydration, air separation and purification, and the elimination of pollutants from water bodies. The catalytic efficiency of zeolites depends on two main factors: their ability to manage acidity and their capacity to change via ionic exchange and alterations in the Si/Al ratio [11]. The material provides exceptional thermal and chemical stability, enabling it to withstand severe conditions and making it appropriate for use in construction materials. biocompatibility makes it suitable for medical applications, including detoxification and wound healing. The complete property–application connection specifications demonstrate the scientific foundation that establishes zeolite applications [12]. The framework demonstrates that actual performance across different use cases, including environmental, industrial, medical, and advanced technological applications, depends on stability, porosity, acidity, and ion-exchange capacity as fundamental performance factors. Scientists and researchers have studied zeolites for many years because these materials demonstrate multiple uses due to their diverse

properties. Natural zeolites function as effective molecular sieves. The special properties of zeolites make them appropriate for a wide range of uses, including pollution control, water treatment, radioactive material management, agricultural practices, building construction, natural gas processing, and various other industries.

3.2.1 wastewater treatment

Zeolite with low-cost options has been prepared to remove heavy metal ions, dye compounds, pesticides, herbicides, and other pollutants from industrial and municipal streams (Table 1). The first application of natural zeolites as adsorbents occurred when Scheele and Fontana used them for their first adsorbent experiments. The material proves beneficial for various environmental solutions because its adsorption properties enable developers to use it for different environmental remediation methods. Natural zeolites function as effective adsorbents that can capture multiple substances, including NH3, H2O, SO2, H2S, CO2, NO, and NO2, among others [31]. People now require better drinking water because industrial, natural, municipal, and agricultural sources all require water treatment. The scientific community now studies natural zeolites because researchers have demonstrated their effectiveness at removing contaminants from wastewater treatment systems. Industrial processes that involve both extraction and production activities generate wastewater streams with multiple physical and chemical characteristics [32]. The waste streams from mineral processing and metal finishing operations contain multiple metal ions, including Pb, Sb, Cu, Co, Zn, Ni, and Cr. The wastewater contains dangerous levels of these metals, which can harm people even at low concentrations. Metal ions present in wastewater pose major environmental hazards and put human health at risk. Scientists completed several research projects to identify waste-treatment processes that produce safe drinking water. Natural zeolites demonstrated their ability to eliminate heavy metals from industrial wastewater by successfully extracting Pb(II), Cd(II), and Cu(II) from industrial effluent. The research used natural zeolite (clinoptilolite) to demonstrate its ability to treat water, showing its effectiveness in removing pesticides from surface and groundwater sources. The study used natural zeolite to extract heavy metals from a copper mine.

The water supply system requires ammonium (NH^{4+}) removal through its treatment facilities, which must process drinking water before delivering it to the public. Zeolite is the primary material used to extract ammonia ions from substances. The research tested three materials: chitosan zeolite, activated carbon, and bleached fiber to evaluate their capability for ammonium ion removal. The researchers analyzed clinoptilolite's capacity to extract ammonia from wastewater and found it to be a promising wastewater treatment option that met both technical and economic standards. Natural zeolites have strong potential as wastewater treatment materials because they can adsorb various pollutants, including heavy metals, pesticides, and ammonium ions. The natural availability of these materials, together with their low cost and environmental benefits, makes them appropriate for treating wastewater from industrial, agricultural, and municipal sources. The research studies demonstrate their ability to remove dangerous substances, including Pb2+, Cd2+, Cu2+, and NH4+, thus helping to create safer water resources and better public health. Natural zeolites provide a sustainable solution to current wastewater treatment problems, as they serve as an effective means of addressing the worldwide water quality crisis [33].

Table 1. Removal of various types of pollutants using zeolite or zeolite based compounds.

Adsorbent	Description	References
SUZ-4 zeolite	Zeolites showed a needle-shaped microstructure, 0.2 m in diameter and 2 μm in length. Specific surface area=247.4 m^2/g Maximum phenol adsorption capacity=90.75 mg/g when pH 4 with zeolite of 0.05 g.	[13]
Fe/SUZ-4 zeolite	The adsorbent exhibited a microstructure with a length of 5 μm. The degradation rate increased with increasing phenol concentration.	[14]

Table 1. Removal of various types of pollutants using zeolite or zeolite based compounds. (continue)

Adsorbent	Description	References
Sulfur-doped zeolite templated carbon	Sulfur-doped zeolite synthesized from BEA zeolite (89.15%-97.39%) exhibited better mercury removal efficiency than the corresponding zeolite prepared from FAU (58.9%-19.3%). SEM image: BEA-based zeolite indicated irregular morphology with a porous structure. FAU-based zeolite showed an octahedral with slit porosity.	[15]
β-zeolite, zeolite Y, mordenite	The highest removal rate of Hg(II) could be observed using zeolite Y compared to other zeolites. Freundlich isotherm supported adsorption process using β-zeolite and zeolite Y. Temkin model fits the data well using mordenite.	[16]
Y zeolite	A higher copper removal efficiency (64%) was observed than for nickel.	[17]
Natural zeolite was modified using bio-inspired polydopamine (PDA)	The Langmuir isotherm and pseudo-second-order reaction model supported the adsorption data. The maximum adsorption capacities of copper ions were found to be 14.93 mg/g and 28.58 mg/g for pristine natural zeolite and PDA treated zeolite, respectively.	[18]
zeolite P	The highest monolayer adsorption capacity was 233 mg/g using a ratio of 1.5:2:0.5 (zeolite P: activated carbon: bentonite). The pseudo-second-order model showed a slightly better fit in most cases for the adsorption of cationic blue 41 dye across various concentrations.	[19]
zeolite 13X	The Langmuir isotherm and the pseudo-second-order model supported the adsorption data. The highest removal capacity was 91.92 mg/g. Removal of Malachite Green dye was spontaneous and exothermic.	[20]
Zeolite	Removal efficiency was 96.92% (pH=9, dosage=0.75 g/L, contact time=45 min, initial methylene blue dye concentration=50 mg/L) The adsorption process obeyed the Freundlich isotherm and the pseudo-second-order kinetic model.	[21]
Natural zeolite with glycerol	Adsorption data were best fit to the pseudo-second-order kinetic model and the Langmuir isotherm. The adsorption process was endothermic and non-spontaneous. 3D-Ze/Gy50 showed the highest adsorption capacity of 1.35 mg/g at a methylene blue concentration of 15 mg/L.	[22]
Zeolite 4A	The highest removal percentage was 95.2% (pH=7.6, acid blue 90 dye concentration=20 mg/L, time=15 minutes). A magnetic zeolite-based material was observed to exhibit excellent stability over a wide pH range.	[23]
Prepare zeolite from agricultural wastes.	The percentage of removal of chlorpyrifos was 93.4% and 72.5% using bagassae zeolite and wheat husk zeolite, respectively.	[24]
NaP	Higher removal efficiencies were observed for Cr(VI), Cd(II), and Pb(II) ions under acidic, neutral, and alkaline conditions, respectively. The adsorption process follows the pseudo-second-order and the Freundlich models, respectively.	[25]

Table 1. Removal of various types of pollutants using zeolite or zeolite based compounds. (continue)

Adsorbent	Description	References
Zeolitic Imidazolate Framework-11	Optimal adsorption conditions (pH=2, stirring speed=400 rpm, contact time=70 min, dosage=20 mg, chromium concentration=50 mL). Chemisorption was confirmed using the pseudo-second-order model. The highest adsorption capacity was 10.61 mg/g.	[26]
Fe_3O_4@ZnO@Zeolite composite	The highest removal percentage was 90% (dosage=0.6 g, Congo Red dye concentration=100 mg/L). The highest adsorption capacity was 10.99 mg/g, as determined by the Langmuir model.	[27]
Zeolite/UiO-66 hybrid composite	The percentage of yellow L4G dye removal was 99.89%. Adsorption followed the Langmuir isotherm (adsorption capacity = 53.76 mg/g) and the pseudo-second-order model.	[28]
Fe_3O_4@NaY magnetic zeolite	The percentage of crystal violet dye removal reached 95.69% (25 ℃, neutral pH). Adsorption data supported by pseudo-second-order kinetics and Langmuir isotherm models (adsorption capacity was 50.1 mg/g). Surface area, pore volume, and average pore size were 583.2 m^2/g, 0.305 m^3/g, and 2.09 nm, respectively.	[29]
Faujasite-type zeolite Y	Formation of highly crystalline with a specific surface area (204 m^2/g) was reported. Adsorption data obey the pseudo-first-order model and the Langmuir isotherm (adsorption capacity of 126.5 mg/g).	[30]

3.2.2 Agriculture

Natural zeolites enhance soil characteristics by providing cation exchange capacity and moisture retention, resulting in increased crop production, reduced environmental impact from agricultural practices, and improved soil moisture distribution [34]. The research demonstrates that natural zeolites function as both soil amendments and permanent fertilizer solutions, according to the results of the study [35]. The clinoptilolite-rich tuff was used as a soil conditioner, resulting in significant improvements in crop yields. The application of zeolite at 4 to 8 tons per acre resulted in production increases of 19 to 55 percent for eggplants, 13 to 38 percent for apples, 13 to 15 percent for wheat, and 63 percent for carrots. The application of 15 tons of clinoptilolite on sandy loam soils in Ukraine resulted in increased yields of wheat, barley, potato, and clover [36]. The research conducted by Cataldo and his team shows that zeolite addition to soil improves its capacity to retain nutrients and water, resulting in greater agricultural productivity and reduced fertilizer runoff [37]. The research shows that zeolites will effectively clean up environmental contamination because they absorb heavy metals and ammonium ions, preventing plants from taking them up and preventing groundwater contamination. The study investigates the effects of natural zeolite on poultry and cattle, as well as on pig feed efficiency, growth, and weight gain. Initial research in Japan tested 10% mordenite and clinoptilolite as feed additives for poultry and swine. The test animals grew faster than the control group because they spent less on feed and consumed less. Pigs fed a diet containing 5% clinoptilolite gained 16% more weight than those fed standard diets. Natural zeolites reduced animal waste odor by absorbing NH^{4+} ions, resulting in fewer severe, less frequent intestinal disease outbreaks.

The research assessed how zeolite dietary supplements for dairy cows affected milk production, showing that the supplements helped dairy cows produce more milk. Natural zeolites are particularly effective at protecting animals from mycotoxins, making them effective mycotoxin protection agents. Natural zeolite material demonstrates its ability to absorb aflatoxins from animal feed, resulting in improved health outcomes for sheep, chickens, and pigs. The research team, led by Abdelrahman, conducted a feeding trial

using natural zeolite to determine broiler chicken responses to various feeding methods [38]. The researchers experimented with 560 one-day-old female Ross-308 broilers assigned to five dietary groups receiving zeolite at 0-20 g/kg feed throughout the 35-day testing period. The study results showed that 10 grams of zeolite per kilogram of feed improved carcass characteristics, meat quality factors, and intestinal measurements. The study results established that the major changes induced by zeolite applications affected litter pH, breast meat color intensity, cooking loss, chewiness, total weight, and small intestine length. The research demonstrated that zeolite is a successful feed additive for broiler diets because it improves meat quality and intestinal health through its larger particle size, which does not affect weight gain. The studies we examined demonstrate that natural zeolites provide multiple benefits for agricultural systems, which lead to improved plant growth and enhanced animal production. Adding materials such as zeolites to soil helps maintain steady nutrient levels and protects water from contamination [39]. Researchers can apply zeolites directly to the soil or spray them onto plant leaves. Either way, surface chemistry, particle size, porosity of zeolites (Table 2), and how much you use end up being important—they shape how zeolites behave and whether they're safe for plants. Researchers deliver zeolites through the roots or by spraying them on leaves. When you look at particle size, you'll see a pattern: bigger particles usually have bigger pores. That's not surprising, but it actually matters a lot if you're designing zeolites for a specific job. Crystal sizes can swing anywhere from 10 to 1000 nanometers. If you want zeolites with bigger mesopores or macropores (which are useful in agriculture), you have to "grow" them using special ingredients like surfactants, organic cations, and templates. These control both particle size and pore size. When you have large pores, you get more surface area, which means zeolites can absorb more—fertilizer, for example, sticks better to them. Surface area and pore size matter because they dictate how much fertilizer these nano-zeolites can carry and how they hold onto it. But if the pores are on the smaller side, solvents rush through too quickly, making slow-release delivery tough. On the other hand, shrinking zeolite particles and creating meso- or macropores (with chemical tricks) ramps up their surface-to-mass ratio. This helps roots absorb more nutrients from the soil, making zeolites more effective at boosting plant health. Zeolites enhance soil fertility by retaining water and releasing nutrients to plants, leading to increased crop yields and reduced environmental pollution. The use of zeolites in livestock management offers significant opportunities, as they improve feed efficiency while protecting animal well-being and supporting their development. The sustainable agricultural benefits of natural zeolites make them essential, environmentally friendly materials that improve farming, gardening, and animal management through their multiple advantages.

Table 2. Porosities of zeolites and their findings.

Zeolite type	Synthesis technique	Research findings
FAU	Organic template-free room temperature synthesis [40]	Crystallization time up to 38 days Pore diameter=0.74 nm Particle size=40-50 nm
Zeolite Beta	organic structure directing agent-free synthesis [41]	Microporous volume=0.16-0.23 cm^3/g Particle size> 100 nm
EMT	Organic template-free homogenous suspension [42]	Pore size=0.2-0.45 nm Pore volume=0.28-0.85 cm^3/g
FAU (Y)-type	Autoclaved synthesis [43]	Pore diameter=0.74 nm Particle size=20-30 nm
Zeolite beta, ZSM-5	Sustainable synthesis [44]	Particle size=50-100 nm Pore volume=0.2 cm^3/g
ZSM-5, ZSM-8	Hydrothermal synthesis [45]	Particle size> 50 nm Pore diameter=0.6 nm
Mesoporous zeolites BEA, MOR, CHA, ZSM-5, ZSM-34, ECR-1	Green synthesis [46]	Particle size=50-100 nm Pore size=7-50 nm

Table 2. Porosities of zeolites and their findings. (continue)

Zeolite type	Synthesis technique	Research findings
Beta-H, ZSM-5-H	Autoclave crystallization [47]	Pore size=5-40 nm Particle size (Beta-H)= 200-400 nm Particle size (ZSM-5-H)=0.3-1 μm
Meso-Z5	self-assisted seed induction method [48]	Particle size=400 nm Pore size=10-40 nm
MFI type	Steam-assisted crystallization-aggregation method [49]	Particle size=0.5-3 μm Pore size=11-15 nm
Zeolite Y (Sodalite type)	Hydrothermal synthesis [50]	Particle size=1-3 μm Pore size=5-15 nm
Na-A zeolite	Sol gel method [51]	Particle size=75 nm Pore size=2.8 nm
Zeolite beta	Dense gel steam-assisted conversion [52]	Particle size=20-40 nm Pore diameter=13 nm
Macroporous zeolites SAPO-34 (CHA-type)	Hydrothermal synthesis [53]	Particle size=5-10 μm Pore size=100 nm
ZSM-5	Alkaline-media erosion method [54]	Particle size=150-200 nm Pore size=2-100 nm
ZSM-5, MFI Type	Organic template Hydrothermal synthesis [55]	Particle size=290-680nm Pore diameter = 137-300 nm
TS-1 zeolite (MFI type)	Steam-assisted crystallization [56]	Particle size=1.5-2 μm Pore size=100 nm

3.2.3 Aquaculture

Global aquaculture production reached its peak in 2022, when the industry produced 130.9 million tonnes of fish, including 94.4 million tonnes of fishery products. The earliest records show that aquaculture reached higher production levels than capture fisheries, which produced 51 percent of all aquatic animal life. The aquaculture industry considers zeolite a highly effective solution that has emerged in recent years to achieve environmental sustainability goals. Natural zeolites provide three essential benefits for aquaculture because they (i) remove ammonium ions from aquarium and hatchery and transit waters, (ii) produce oxygen-saturated air for transport and aquarium aeration systems, and (iii) enhance fish meals through their supplementary benefits. Natural zeolites possess special features that make them essential for aquaculture operations [57]. The ammonium ion removal efficiency from saltwater systems operates below its freshwater system performance because zeolite functions as the most affordable treatment option when compared to activated carbon and all other treatment materials. Treating fish ponds with zeolite improves water quality by reducing dissolved solids and suspended organic matter, which benefits fish health and growth performance. The Egyptian field study demonstrated that earthen ponds that received zeolite treatment achieved reductions in TDS, ammonium, and pH from 635 to 400 mg/L, 0.51 to 0.01 ppm, and 8.65 to 8.4, respectively, compared with untreated ponds. The application of zeolite to fish feed decreased water turbidity [58]. The researchers studied how zeolite treatment improved water quality, which affected the tilapia living in the study area, while measuring heavy metal pollution levels at the research site. The research team applied zeolite to treat pond water, using 200 grams during the initial pond setup and 100 grams every 15 days throughout the entire breeding season. The researchers discovered that zeolite treatment produced major effects, achieving statistically significant results across three growth evaluation periods: 0 to 42 days, 43 to 84 days, and 85 to 126 days, in treatment ponds compared to control ponds. The groups that received zeolite treatment showed statistically significant improvements in weight gain compared to the control group. The research found that feed conversion ratio decreased while water quality improved, as ammonia and heavy metal concentrations decreased. Aquaculture operators who apply zeolite to their ponds experience enhanced fish growth because it creates cleaner water, leading to better aquaculture operations [59]. The study's findings demonstrate that

sustainable farming methods must be implemented across the entire aquaculture industry to increase worldwide fish production. Natural zeolites demonstrate their ability to improve water quality by eliminating environmental pollutants, thereby supporting fish growth and well-being [60]. The research supports the use of these materials because their low cost and multiple functions are effective for modern aquaculture systems.

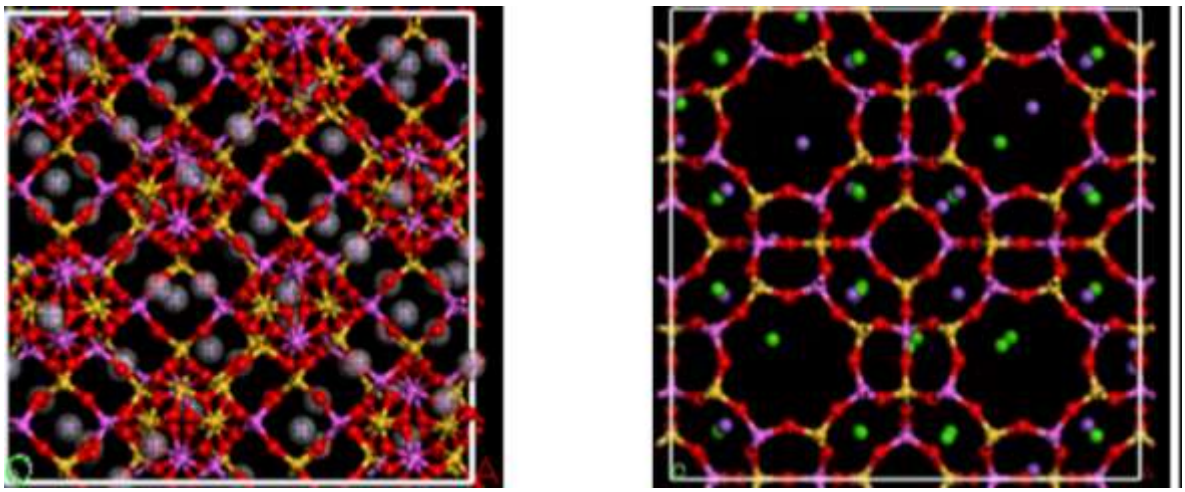
3.2.4 Gas processing

The primary industrial application of zeolites depends on their essential physical properties, which enable gas processing operations. The material exhibits microporous structures that enable it to selectively adsorb substances used in gas dehydration, gas separation, and gas purification processes [61]. Natural gas dehydration processes use zeolites as effective adsorbents because they adsorb water molecules, helping protect pipelines and processing systems from corrosion and hydrate formation. The natural gas industry uses zeolite-based adsorbents as its standard material for this specific purpose [62]. The technology needs air separation processes to operate, which produce nitrogen and oxygen gases at high purity levels. The PSA systems use zeolites 5A and 13X to capture nitrogen while continuously enriching oxygen. The structure of these zeolites was represented in Figure 2. Zeolites act as gas purification agents, removing pollutants such as carbon dioxide, nitrogen, argon, xenon, methane, carbon monoxide, and hydrogen sulfide. These harmful materials caused global warming, acid rain formation, climate change, and various types of diseases (Table 3). Removal of harmful gases can be carried out through adsorption to protect human health and other living organisms.

Table 3. Harmful effects of various gases

Gases	Impact
Carbon dioxide	Global warming
argon	dizziness
Nitrogen	Respiratory issues
xenon	Nauses
Carbon monoxide	Reduced oxygen level
methane	suffocation

The presented examples demonstrate that zeolites operate successfully in gas processing systems while highlighting their critical role in energy efficiency, industrial safety, and the unending delivery of clean gas to all industrial sectors, including energy generation, metallurgy, and healthcare. Acetone is used as a solvent, which can lead to skin irritation. It has a highly volatile, fruity odor and is pungent. It was noted that acetone could be removed using zeolite (Figure 3). In general, acetone will adhere to the surface of the adsorbent during the process [63] through physisorption. It was observed that larger surface areas and well-developed micropore volumes will improve adsorption capacity.



(a) **(b)**

Figure 2. Structure of zeolites 13X (a) and 5A (b)

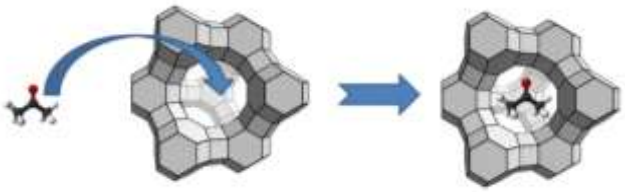


Figure 3. Adsorption of acetone into a zeolite [63]

3.2.5 Construction

The construction industry relies on concrete as its main building material because it shows outstanding physical properties and mechanical strength. The construction industry uses natural zeolites in concrete production because these materials offer improved performance, longer-lasting strength, and enhanced structural and mechanical properties [64]. Experts believe that natural zeolite is the primary material used in construction and building activities worldwide. The volcanic rock phonolite contains 45% zeolite, which is used as a concrete material in Germany and France. The cement industry in China is the largest user of zeolite in the country. Natural zeolites function as building materials in the construction industry because they enable builders to mix concrete quickly, provide protection against non-alkali frost, have antibacterial properties, support moisture management, and serve as fluidizing agents to enhance concrete workability. Natural zeolite has been used in construction since the Greeks and Romans used it for building purposes. The hydration process that occurs during cement production generates calcium hydroxide (Ca(OH)2), which makes concrete highly susceptible to destruction. The solution to the problem requires adding natural zeolite to the cement mixture. The production process of cement results in hardened concrete and cement with a dense microstructure, as the Al2O3 and SiO2 components of natural zeolite form aluminate hydrate gels. The use of natural zeolite in concrete production leads to lower chloride-ion absorption, which occurs when water penetrates the concrete [65]. The introduction of natural zeolite into concrete reduces weight while enhancing its thermal protection. Research findings in construction demonstrated that concrete or cement containing an appropriate quantity of natural zeolite exhibits excellent performance capabilities [66].

The latest research demonstrates that natural zeolites operate as additives for concrete mixtures [67]. The recent study investigated how different zeolite powder concentrations affected concrete made from sea sand and seawater. The testing results showed that OPC-based concrete achieved higher compressive strength results than PPC-based concrete. The highest compressive strength at 56 days was achieved with 7.5% zeolite added to the ordinary Portland cement (OPC) mix. The 10% zeolite addition to Portland Pozzolan Cement (PPC) concrete improved durability, particularly enhancing the material's ability to withstand sulfate attack during 90 days of exposure to a 5% Na_2SO_4 solution. The findings show that natural zeolites improve concrete performance by enhancing mechanical properties and durability while supporting environmental protection. Natural zeolite materials serve as effective partial cement replacements in concrete production, according to research studies [68]. The material demonstrates pozzolanic properties because its physicochemical characteristics enable it to strengthen structural integrity, protect against sulfate and chloride chemical attacks, and provide thermal defense. The latest study results demonstrate their vital role in promoting sustainable building methods, as they enable partial cement replacement, reducing carbon dioxide emissions and environmental impacts. Strength test results and long-term durability performance are enhanced by the addition of zeolite to cement compositions containing Portland pozzolan and ordinary Portland cement. In keeping with the current trend in the building sector toward sustainable materials with superior performance, natural zeolites offer a cost-effective, environmentally friendly alternative with a variety of applications in modern cement-based systems.

3.2.6 Medicine

Many researchers use different types of zeolites as medical research tools (Table 4) and as biotechnological study materials because these minerals possess ion-exchange capabilities and adsorption properties. The materials humans and animals use for detoxification also function as tools for separating cells and biomolecules, detecting disease biomarkers, creating biosensors, boosting animal immunity, delivering drugs and genes, and performing

oxygen scavenging. Scientists demonstrate that zeolites function as scaffold materials that engineers use to build bioactive and anticorrosive coatings for bone implants and to construct bone, skin, and vascular tissue. The system allows for dialysis solution reuse across portable and home dialysis systems. Medical professionals use zeolites to treat diarrhea in patients who need medical care. The application of zeolite powder enables surgical cuts and skin injuries to heal faster, making it an effective treatment for athlete's foot. Workers at three USA mining sites reported that zeolite dust from the mining area helped them heal from scrapes and cuts more quickly. Cuban veterinarians use clinoptilolite powder to treat wounds on cows and horses because it speeds healing.

Table 4. Pharmaceutical applications of zeolites

Zeolite	Research findings
Clinoptilolite	As an anti-diarrheal drug [69] 75.6% was recovered from diarrhea within 24 hours and 24.4% in 36 hours.
Clinoptilolite	Excess of hydrochloric acid was neutralized using Antacid (Neutacid) [70].
Clinoptilolite	as a gastroprotective agent Significant reductions could be observed in pain (56%), heartburn (44%), and discomfort (54%) based on the ENGORD study [71].
Clinoptilolite	As Antiviral [72]. Micronized zeolite inhibited HSV-1, echovirus 7, and coxsackievirus B5.
Clinoptilolite	Anti-cancer therapy [73] It inhibited protein kinase B (c-Akt), induced expression of tumor suppressor proteins, and successfully blocked cell growth in several cancer cell lines.
Clinoptilolite	Treatment of Osteoporosis [74] Panaceo Micro Activation-zeolite-clinoptilolite indicated reduction in pain, and increased bone formation.
MFI borosilicate	Anti-cancer drug [75] A higher drug release rate was observed at lower pH with Doxorubicin-loaded borosilicate samples.
MFI	Antimicrobial prophylaxis for implantable devices [76] The maximum amounts of lysozyme were adsorbed at shorter times and with specific intermediate volumes (400 and 600 μL).
NaX, NaY and HY	Leprosy treatment [77] Formation of H-type aggregates was observed due to the smaller spaces in the zeolite pores, which favor stronger CLZ–CLZ interactions.
Zeolite Beta, MFI, and NaX	Antilipidemic [78] The highest and lowest aluminum content was observed in NaX (which reduced the rate of probucol) and BEA, respectively.
Zeolite X	Antimicrobial activity [79] Silver-loaded zeolite X retained its antimicrobial activity against Escherichia coli, Pseudomonas aeruginosa , and *Staphylococcus aureus.*
Faujasite	fibrocystic breast disease [80] Results confirmed that zeolite served as a carrier for the oral delivery of poorly water-soluble danazol.
Zeolite 5A	Anti-cancer drug curcumin [81] SEM images highlighted microporous crystalline structures in curcumin-loaded zeolite 5A, demonstrating its excellent pharmaceutical carrier properties.
Zeolite Beta	pulmonary disease [82] Molecular dynamics indicated that salbutamol diffuses more freely than theophylline.
Clinoptilolite/ Mordenite	Antimicrobial activity [83] Zeolite doped with copper salt ions showed good antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus.*

The research findings demonstrate that zeolite-based materials function as effective biomedical solutions for treating wounds. The hydrogel achieved its healing function through two mechanisms: its ability to remove reactive oxygen species (ROS) and its capacity to block inflammatory cytokines. At the same time, it promoted blood vessel growth at the wound site [84], showing that clinicians could use purified clinoptilolite-tuff to absorb unpleasant-smelling amines from chronic wound exudates, demonstrating its potential as an effective odor-control agent in wound dressings. Natural zeolite, which meets clinical standards, allows medical professionals to use these materials as essential tools for advanced wound care because they provide therapeutic effects while maintaining safe, sterile conditions for patient treatment. The high potential of zeolites for medical and biotechnological applications arises from their ability to exchange ions and adsorb materials while maintaining biocompatibility. The company develops detoxifying products and treatments for digestive disorders, as well as advanced wound care techniques and tissue regeneration processes [85]. The medical solutions that combine zeolite-infused hydrogels with odor-controlling dressings tackle complex healthcare challenges. The research study investigating zeolites for biomedical purposes will demonstrate their value as vital components in creating affordable medical treatments that perform multiple functions.

3.2.7 Radioactive waste remediation

Natural zeolites attracted significant attention in the 1950s for their potential use in the disposal of radioactive waste. Originally, these techniques were used to monitor low-level radioactive waste. Thanks to their innovative uses, they can currently manage intermediate and high-level radioactive waste. A significant ion-exchange capacity, superior ion selectivity, and enhanced radiological stability against beta, alpha, and gamma radiation are only a few of the benefits of natural zeolites. They also offer readily available, reasonably priced solutions [86]. Natural zeolites demonstrate superior radionuclide retention, according to research, with clinoptilolite performing better than most natural zeolites. The treatment solution for all three radioactive wastewater categories, which contain low-level, intermediate-level, and high-level wastewater, uses clinoptilolite natural zeolite because it efficiently removes cesium-137. The Chornobyl nuclear power plants have used natural clinoptilolite and mordenite to treat their radioactive wastewater, which they discharged into the environment. The researchers assessed Iranian natural zeolite for its ability to adsorb strontium and cesium from environmental sources. The system achieved 67.8 percent efficiency for cesium removal, while its efficiency for strontium removal reached approximately 93.5 percent according to the results [87]. Natural zeolites and their synthetic and modified counterparts have proven effective for removing radioactive isotopes, including cesium, strontium, and others. The research results demonstrate that natural clinoptilolite functions as an effective adsorbent that can successfully extract cobalt ions from water via adsorption [88]. According to a study evaluating the efficiency of bentonite and natural Greek zeolite in extracting uranium from liquid solutions, the latter was superior to the former [89]. According to a study evaluating the efficiency of bentonite and natural Greek zeolite in extracting uranium from liquid solutions, the latter was superior to the former. The study suggests that uranium and thorium can effectively remove radionuclides from acidic solutions by adsorbing onto Jordanian zeolitic tuff, which is primarily composed of phillipsite and chabazite. Phosphate-modified clinoptilolite has been demonstrated to be an effective adsorbent for the removal of radioactive actinides due to its ability to remove thorium (IV) from aqueous solutions [90]. Natural zeolites can purify radioactive waste because they contain clinoptilolite, chabazite, and mordenite, which enable ion exchange, select materials, provide radiation protection, and are low-cost. The substance demonstrates its value in three nuclear operations that handle substantial amounts of radioactive waste. Scientists developed phosphate functionalization techniques to create effective methods that enhance actinide capture, with thorium as a specific application.

4. Current challenges and prospects

The current applications of zeolite for water treatment, animal husbandry, and agricultural practices, as well as its use in construction, chemical, aquaculture, medical, and biotechnology, and other fields, show that zeolite research will lead to new technological innovations. through unknown uses of antimicrobial and pharmaceutical properties, 66, which will create new global markets for zeolite. Researchers will develop new zeolite methods to extract carbon dioxide from primary sources of climate change. Recent studies show that

zeolites serve as vital components that scientists need to develop solutions to climate change challenges. The study showed that scientists achieved 25% higher CO2 absorption capacity with clinoptilolite treated with Na+ and Ca2+ than with commercial zeolite 13X during testing at 338 K. The study conducted by Grifasi and his team in 2024 confirms these findings by demonstrating that clinoptilolite's composition helps enhance CO_2 adsorption capacity at elevated temperatures. The results show that clinoptilolite operates as a cost-effective and efficient carbon capture adsorbent that performs well in real flue gas processing. Future studies should focus their research efforts on three primary areas: zeolite selectivity improvement, regeneration process enhancement, and industrial production method development. The development of zeolite membranes has now reached its most advanced stage, enabling future technological developments. The combination of zeolite membranes and their molecular sieving capabilities with membrane systems creates a material that uses energy-efficient selective separation methods to separate different substances. The research on these materials extends to gas separation applications, including CO2/CH4 and N2/O2 separation, and pervaporation for alcohol and organic dehydration. The energy-saving separation methods that zeolite membranes require for their operational needs provide essential solutions to international energy demands and environmental challenges, as they exceed conventional separation techniques. The research programs that aim to develop improved production methods and enhance zeolite membrane durability will make zeolite membranes essential components for future advancements in zeolite technology.

5. Conclusions

Natural zeolite, consisting of tetrahedral silica and alumina units, displayed microporous structures. Replacing silicon with aluminum makes the structure negatively charged. This negative charge requires the presence of cations within the framework's pores to achieve electrical neutrality. Prepared zeolites could be used in many applications, such as medicine, wastewater treatment, gas processing, agriculture, aquaculture, and radioactive waste remediation. Researchers have concluded that zeolite is cheaper than other adsorbents. Research findings showed that many different types of pollutants can be removed effectively using zeolite. In keeping with the current trend in the building sector toward sustainable materials with superior performance, natural zeolites offer a cost-effective, environmentally friendly alternative with a variety of applications in modern cement-based systems. The research study, which investigates zeolites for biomedical purposes, proved their value as vital elements needed to create affordable medical treatments that provide multiple functions

6. Acknowledgements

This research work (HO SM) was financially supported by INTI International University.

Author Contributions: Conceptualization, Ho. and Riandy; methodology, Ho; formal analysis, Akram and Riandy; writing—original draft preparation, Ho and Riandy; writing—review and editing, Ho and Akram. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by INTI International University in terms of financial support.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Mumpton, A.; La, M. Uses of Natural Zeolites in Agriculture and Industry. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96*, 3463–3470. https://doi.org/10.1073/pnas.96.7.3463

[2] Ismail, S.; Cemil, Y.; Bilgin, K.; Derek, B. Adsorption Properties of a Natural Zeolite-Water Pair for Use in Adsorption Cooling Cycles. *Appl. Energy* **2010**, *87*, 2062–2067. https://doi.org/10.1016/j.apenergy.2009.11.027

[3] Król, M. Natural vs. Synthetic Zeolites. *Crystals* **2020**, *10*, 622. https://doi.org/10.3390/cryst10070622

[4] Low, W.; Chai, Y.; Lee, H.; Abdul, R. Pollutants Removal Using Zeolite and Saltwater Clamshell (*Paratapes textilis*) in Fabricated Model. *Environ. Eng. Manage. J.* **2024**, *23*, 377–386. https://doi.org/10.30638/eemj.2024.030

[5] Rahmani, A.; Mahvi, A.; Mesdaghinia, R.; Nasseri, S. Investigation of Ammonia Removal from Polluted Waters by Clinoptilolite Zeolite. *Int. J. Environ. Sci. Technol.* **2004**, *1*, 125–133. https://doi.org/10.1007/BF03325825

[6] Metes, A.; Papic, S.; Kovacevic, D. The Role of Zeolites in Wastewater Treatment of Printing Inks. *Water Res.* **2004**, *38*, 3373–3381. https://doi.org/10.1016/j.watres.2004.04.012

[7] Krstić, V. Role of Zeolite Adsorbent in Water Treatment. In *Handbook of Nanomaterials for Wastewater Treatment*; Elsevier: Amsterdam, The Netherlands, 2021; pp 417–481. https://doi.org/10.1016/B978-0-12-821496-1.00024-6

[8] Cheng, T.; Chai, W.; Chang, Y.; Show, P. Removal of Protein Wastes by Cylinder-Shaped NaY Zeolite Adsorbents Decorated with Heavy Metal Wastes. *Int. J. Biol. Macromol.* **2021**, *185*, 761–772. https://doi.org/10.1016/j.ijbiomac.2021.06.177

[9] Wang, S.; Zhu, Z. Characterisation and Environmental Application of an Australian Natural Zeolite for Basic Dye Removal from Aqueous Solution. *J. Hazard. Mater.* **2006**, *136*, 946–952. https://doi.org/10.1016/j.jhazmat.2006.01.038

[10] Murat, A.; Abdulkerim, K. Promoted Dye Adsorption Performance over Desilicated Natural Zeolite. *Microporous Mesoporous Mater.* **2011**, *145*, 157–164. https://doi.org/10.1016/j.micromeso.2011.05.012

[11] Markovic, R.; Gardic, V.; Obradovic, L.; Djordjievski, S. The Application of a Natural Zeolite for Acid Mine Drainage Purification. *Mater. Trans.* **2015**, *56*, 2053–2057. https://doi.org/10.2320/matertrans.M2015292

[12] Elboughdiri, N. The Use of Natural Zeolite to Remove Heavy Metals Cu(II), Pb(II), and Cd(II) from Industrial Wastewater. *Cogent Eng.* **2020**, *7*, 1782623. https://doi.org/10.1080/23311916.2020.1782623

[13] Palakorn, B.; Kriangkrai, B. Adsorption Isotherm of Phenol by Synthesis SUZ-4 Zeolite from Rice Husk Ash. *ASEAN J. Sci. Technol. Rep.* **2015**, *18*, 64–71.

[14] Boonsai, P.; Paisan, K. Kinetics Oxidation Reaction of Wastewater Containing Phenolic Compounds by H_2O_2 and Fe/SUZ-4 Zeolite. *ASEAN J. Sci. Technol. Rep.* **2014**, *17*, 69–77.

[15] Liu, Y.; Wang, J.; Wang, T.; Pan, W. Removing Mercury from Flue Gas by Sulfur-Doped Zeolite-Templated Carbon: Synthesis and Adsorption Mechanism. *Sep. Purif. Technol.* **2022**, *294*, 121228. https://doi.org/10.1016/j.seppur.2022.121228

[16] Murthy, P.; Parikh, P.; Patel, B. Application of β-Zeolite, Zeolite Y, and Mordenite as Adsorbents to Remove Mercury from Aqueous Solution. *J. Dispersion Sci. Technol.* **2013**, *34*, 747–755. https://doi.org/10.1080/01932691.2012.685839

[17] Mark, A. The Removal of Copper and Nickel from Aqueous Solution Using Y Zeolite Ion Exchangers. *Colloids Surf., A* **1998**, *138*, 11–20. https://doi.org/10.1016/S0927-7757(97)00078-2

[18] Yang, Y.; Ellis, V.; Joseph, G.; Rachel, P.; John, W. Copper Removal Using Bio-Inspired Polydopamine Coated Natural Zeolites. *J. Hazard. Mater.* **2014**, *273*, 174–182. https://doi.org/10.1016/j.jhazmat.2014.03.048

[19] Jitlada, C.; Jutamas, S.; Thidarat, H.; Javadi, B.; Ohama, P. Synthesis of Zeolite P-Metal Organic Composite Beads for Superior Cationic Dye Removal. *Inorg. Chem. Commun.* **2025**, *177*, 114344. https://doi.org/10.1016/j.inoche.2025.114344

[20] Arroussi, A.; Laksaci, H.; Djaafri, M. Prepared 13X Zeolite from Local Natural Clay as a Promising Adsorbent for the Removal of Malachite Green Dye from Aqueous Medium. *Fibers Polym.* **2025**, *26*, 2031–2041. https://doi.org/10.1007/s12221-025-00930-3

[21] Parastar, S.; Asl, F. B.; Poureshgh, [initials or remaining author information needed]. Assessment of the Efficiency of Methylene Blue Removal from Aqueous Solutions Using Iron Magnetic Nanoparticles Immobilized on Clinoptilolite Zeolite. *Int. J. Environ. Res.* **2025**, *19*. https://doi.org/10.1007/s41742-024-00702-6

[22] Fauzi, I.; Khairurrijal, K.; Arif, M.; Abdul, M.; Kuwat, T. Glycerol-Assisted Modification of 3D-Printed Zeolite (3D-Ze/Gy) for Enhanced Methylene Blue Dye Removal in Aqueous Solutions. *Adv. Eng. Mater.* **2025**, *27*. https://doi.org/10.1002/adem.202402555

[23] Feze, F.; Kenda, T.; Raoul, T.; Fotsop, C. Design and Characterisation of Activated Magnetic Zeolite 4A from Naturally Occurring Kaolin Clay of Cameroonian Origin for Optimised Dye Removal by Fenton-like Degradation. *Int. J. Environ. Anal. Chem.* **2025**, *105*, 5211–5239. https://doi.org/10.1080/03067319.2024.2389417

[24] Singh, S.; Kumar, N. Removal of Chlorpyrifos from Waste Water by Using Lignocellulosic Zeolites. *J. Exp. Zool. India* **2026**, *29*, 911–915. https://doi.org/10.51470/jez.2026.29.1.911

[25] Luong, H.; Le, P.; Phan, H.; Duong, Q.; Tran, T. Single and Competitive Adsorption of Lead, Cadmium, and Chromium Ions Using NaP Zeolite: Kinetics, Isotherms, and Adsorption Properties. *CLEAN – Soil, Air, Water* **2026**, *54*. https://doi.org/10.1002/clen.70151

[26] Lamari, R.; Benamar, B.; Hamza, M.; Brahmi, A.; Souad, D. Experimental and Modelling Study of Adsorption and Diffusion of Hexavalent Chromium in Zeolitic Imidazolate Framework-11. *Int. J. Environ. Anal. Chem.* **2026**, *106*, 183–204. https://doi.org/10.1080/03067319.2025.2511989

[27] Ramutshatsha, D.; Mnisi, M.; Akawa, N. Adsorptive Removal of Congo Red from Wastewater Using Magnetite@ZnO@Zeolite Composite. *Discover Water* **2026**, *6*. https://doi.org/10.1007/s43832-026-00359-6

[28] Jing, L.; Xin, Y. Highly Efficient Removal of SYSPERSE Yellow L4G Textile Dye Using a Zeolite/UiO-66 Composite: Optimization, Mechanism, and Reusability. *J. Indian Chem. Soc.* **2026**, *103*, 102502. https://doi.org/10.1016/j.jics.2026.102502

[29] Yu, D.; Li, F.; Wang, Q.; Liu, Q.; Che, Y. An Oil Shale Ash-Based Fe_3O_4@NaY Magnetic Zeolite with Rapid and High Removal Efficiency for Crystal Violet. *J. Environ. Chem. Eng.* **2026**, *14*, 122444. https://doi.org/10.1016/j.jece.2026.122444

[30] Arroussi, A.; Laksaci, H.; Hiri, A. Faujasite Zeolite Y Synthesized from Natural White Clay for the Adsorptive Removal of Amoxicillin from Wastewater. *React. Kinet. Mech. Catal.* **2026**, *139*, 1395–1417. https://doi.org/10.1007/s11144-026-03045-9

[31] Pucarevic, M.; Stojic, N.; Kuzmanovski, I. Removal of Pesticides from Water Using Zeolites. *Kuwait J. Sci.* **2017**, *44*, 99–105.

[32] Nur, F.; Abdul, Q.; Azat, S.; Hafi, O. Revolutionizing Dye Removal in Wastewater: An Optimization Study of Curcumin-Functionalized Zeolite Beads for Methylene Blue Adsorption. *Surf. Interfaces* **2025**, *72*, 107434. https://doi.org/10.1016/j.surfin.2025.107434

[33] Safie, N.; Zahrim, Y.; Rajin, M.; Ismail, M.; Saalah, S. Adsorption of Ammonium Ion Using Zeolite, Chitosan, Bleached Fibre and Activated Carbon. *IOP Conf. Ser.: Mater. Sci. Eng.* **2019**, *606*, 012003. https://doi.org/10.1088/1757-899X/606/1/012003

[34] Usa, O.; Choorod, P. Removal of Lead and Copper on ZSM-5 Zeolite by Computational Chemistry Method. *ASEAN J. Sci. Technol. Rep.* **2014**, *17*, 143–151.

[35] Eroglu, N.; Emekci, M.; Athanassiou, C. Applications of Natural Zeolites on Agriculture and Food Production. *J. Sci. Food Agric.* **2017**, *97*, 3487–3499. https://doi.org/10.1002/jsfa.8312

[36] Mazur, G.; Medvid, K.; Grigora, T. Use of Natural Zeolites for Increasing the Fertility of Light Textured Soils. *Pochvovedenie* **1984**, *10*, 70–77.

[37] Cataldo, E.; Salvi, L.; Paoli, F.; Fucile, M. Application of Zeolites in Agriculture and Other Potential Uses: A Review. *Agronomy* **2021**, *11*, 1547. https://doi.org/10.3390/agronomy11081547

[38] Abdelrahman, M.; Al-Baadani, H.; Qaid, M.; Al-Garadi, M. Using Natural Zeolite as a Feed Additive in Broilers' Diets for Enhancing Growth Performance, Carcass Characteristics, and Meat Quality Traits. *Life* **2023**, *13*, 1548. https://doi.org/10.3390/life13071548

[39] Khachlouf, K.; Hamed, H.; Gdoura, R.; Gargouri, A. Effects of Dietary Zeolite Supplementation on Milk Yield and Composition and Blood Minerals Status in Lactating Dairy Cows. *J. Appl. Anim. Res.* **2019**, *47*, 54–62. https://doi.org/10.1080/09712119.2018.1563548

[40] Pérez-Ramírez, J.; Christensen, C. H.; Egeblad, K.; Christensen, C. H.; Groen, J. C. Hierarchical Zeolites: Enhanced Utilisation of Microporous Crystals in Catalysis by Advances in Materials Design. *Chem. Soc. Rev.* **2008**, *37*, 2530–2542. https://doi.org/10.1039/B809030K

[41] Grose, R. W.; Flanigen, E. M. Novel Zeolite Compositions and Processes for Preparing and Using Same. U.S. Patent 4,257,885, March 24, 1981.

[42] Wu, Q.; Wang, X.; Qi, G.; Guo, Q.; Pan, S.; Meng, X.; Xu, J.; Deng, F.; Fan, F.; Feng, Z.; et al. Sustainable Synthesis of Zeolites without Addition of Both Organotemplates and Solvents. *J. Am. Chem. Soc.* **2014**, *136*, 4019–4025. https://doi.org/10.1021/ja500098j

[43] Wang, L.; Zhang, Z.; Yin, C.; Shan, Z.; Xiao, F.-S. Hierarchical Mesoporous Zeolites with Controllable Mesoporosity Templated from Cationic Polymers. *Microporous Mesoporous Mater.* **2010**, *131*, 58–67. https://doi.org/10.1016/j.micromeso.2009.12.001

[44] Möller, K.; Yilmaz, B.; Jacubinas, R. M.; Müller, U.; Bein, T. One-Step Synthesis of Hierarchical Zeolite Beta via Network Formation of Uniform Nanocrystals. *J. Am. Chem. Soc.* **2011**, *133*, 5284–5295. https://doi.org/10.1021/ja108698s

[45] Ng, E.-P.; Goupil, J.-M.; Vicente, A.; Fernandez, C.; Retoux, R.; Valtchev, V.; Mintova, S. Nucleation and Crystal Growth Features of EMT-Type Zeolite Synthesized from an Organic-Template-Free System. *Chem. Mater.* **2012**, *24*, 4758–4765. https://doi.org/10.1021/cm3035455

[46] Majeed, N. S.; Majeed, J. T. Synthesis of Nanozeolite NaA from Pure Source Material Using Sol Gel Method. *J. Eng.* **2017**, *23*, 52–62. https://doi.org/10.31026/j.eng.2017.06.04

[47] Zhang, H.; Song, K.; Wang, L.; Zhang, H.; Zhang, Y.; Tang, Y. Organic Structure Directing Agent-Free and Seed-Induced Synthesis of Enriched Intracrystal Mesoporous ZSM-5 Zeolite for Shape-Selective Reaction. *ChemCatChem* **2013**, *5*, 2874–2878. https://doi.org/10.1002/cctc.201300242

[48] Xi, D.; Sun, Q.; Xu, J.; Cho, M.; Cho, H. S.; Asahina, S.; Li, Y.; Deng, F.; Terasaki, O.; Yu, J. In Situ Growth-Etching Approach to the Preparation of Hierarchically Macroporous Zeolites with High MTO Catalytic Activity and Selectivity. *J. Mater. Chem. A* **2014**, *2*, 17994–18004. https://doi.org/10.1039/C4TA03030C

[49] Gu, F.; Wei, F.; Yang, J. Y.; Lin, N.; Lin, W.-G.; Wang, Y.; Zhu, J.-H. New Strategy to Synthesis of Hierarchical Mesoporous Zeolites. *Chem. Mater.* **2010**, *22*, 2442–2450. https://doi.org/10.1021/cm903785r

[50] Weissenberger, T.; Machoke, A. G.; Bauer, J.; Dotzel, R.; Casci, J. L.; Hartmann, M.; Schwieger, W. Hierarchical ZSM-5 Catalysts: The Effect of Different Intracrystalline Pore Dimensions on Catalyst Deactivation Behaviour in the MTO Reaction. *ChemCatChem* **2020**, *12*, 2461–2468. https://doi.org/10.1002/cctc.201902362

[51] Zampieri, A.; Colombo, P.; Mabande, G. T. P.; Selvam, T.; Schwieger, W.; Scheffler, F. Zeolite Coatings on Microcellular Ceramic Foams: A Novel Route to Microreactor and Microseparator Devices. *Adv. Mater.* **2004**, *16*, 819–823. https://doi.org/10.1002/adma.200306304

[52] Li, C.; Wang, Y.; Shi, B.; Ren, J.; Liu, X.; Wang, Y.; Guo, Y.; Guo, Y.; Lu, G. Synthesis of Hierarchical MFI Zeolite Microspheres with Stacking Nanocrystals. *Microporous Mesoporous Mater.* **2009**, *117*, 104–110. https://doi.org/10.1016/j.micromeso.2008.06.017

[53] Smeets, V.; Gaigneaux, E. M.; Debecker, D. P. Hierarchical Micro-/Macroporous TS-1 Zeolite Epoxidation Catalyst Prepared by Steam-Assisted Crystallization. *Microporous Mesoporous Mater.* **2020**, *293*, 109801. https://doi.org/10.1016/j.micromeso.2019.109801

[54] Khaleque, A.; Alam, M.; Hoque, M.; Mondal, S.; Bin Haider, J.; Xu, B.; Johir, M.; Karmakar, A. K.; Zhou, J.; Ahmed, M. B.; et al. Zeolite Synthesis from Low-Cost Materials and Environmental Applications: A Review. *Environ. Adv.* **2020**, *2*, 100019. https://doi.org/10.1016/j.envadv.2020.100019

[55] Wang, Y.; Wang, R.; Xu, D.; Sun, C.; Ni, L.; Fu, W.; Zeng, S.; Jiang, S.; Zhang, Z.; Qiu, S. Synthesis and Properties of MFI Zeolites with Microporous, Mesoporous, and Macroporous Hierarchical Structures by a Gel-Casting Technique. *New J. Chem.* **2016**, *40*, 4398–4405. https://doi.org/10.1039/C5NJ03387J

[56] Wojciechowska, K. The Influence of Desilication/Dealumination Processes on the Physicochemical Properties of Clinoptilolite. *Clay Miner.* **2019**, *54*, 111–119. https://doi.org/10.1180/clm.2019.17

[57] Aly, A.; Abdel-Rahim, M.; Lotfy, M.; Abdelaty, B. The Applicability of Activated Carbon, Natural Zeolites, and Probiotics (EM®) and Its Effects on Ammonia Removal Efficiency and Fry Performance of European Seabass (*Dicentrarchus labrax*). *J. Aquac. Res. Dev.* **2016**, *7*, 459. https://doi.org/10.4172/2155-9546.10004590

[58] Abdel-Rahim, M. Sustainable Use of Natural Zeolites in Aquaculture: A Short Review. *Oceanogr. Fish. Open Access J.* **2017**, *2*, 70–75. https://doi.org/10.19080/OFOAJ.2017.02.555593

[59] Hasan, M.; Haque, M.; Hasan, A.; Bashar, A. Assessing the Impacts of Zeolite on Water Quality, Growth Performance, Heavy Metal Content, and Health Condition of Farmed Tilapia (*Oreochromis niloticus*). *Aquac. Rep.* **2023**, *31*, 101678. https://doi.org/10.1016/j.aqrep.2023.101678

[60] Wang, S.; Peng, Y. Natural Zeolites as Effective Adsorbents in Water and Wastewater Treatment. *Chem. Eng. J.* **2010**, *156*, 11–24. https://doi.org/10.1016/j.cej.2009.10.029

[61] Mouctar, H.; Hassan, G.; Bimbo, N.; Abbas, S.; Shigidi, I. Comparative Assessment and Deployment of Zeolites, MOFs, and Activated Carbons for CO_2 Capture and Geological Sequestration Applications. *Inventions* **2025**, *10*, 78. https://doi.org/10.3390/inventions10050078

[62] Li, Y.; Li, L.; Yu, J. Applications of Zeolites in Sustainable Chemistry. *Chem* **2017**, *3*, 928–949. https://doi.org/10.1016/j.chempr.2017.10.009

[63] Zheng, Y.; Li, X.; Dutta, K. Exploitation of Unique Properties of Zeolites in the Development of Gas Sensors. *Sensors* **2012**, *12*, 5170–5194. https://doi.org/10.3390/s120405170

[64] Tran, T.; Lee, J.; Kumar, P.; Kim, K. Natural Zeolite and Its Application in Concrete Composite Production. *Compos. Part B Eng.* **2019**, *165*, 354–364. https://doi.org/10.1016/j.compositesb.2018.12.084

[65] Rashetnia, R.; Dousti, A.; Khatami, D.; Ahmadi, B. Effect of Natural Zeolite and Silica Fume as Pozzolanic Materials on the Chloride Diffusion of Concrete. In *Proceedings of the International Congress on Durability of Concrete*; Trondheim, Norway, June 18–21, 2012.

[66] Wahyuni, A.; Mulyati, S.; Hayati, Y. Performance Analysis of Ordinary Portland Cement and Portland Pozzolan Cement in Improving Sea Sand and Sea Water Concrete with Zeolite Powder. *J. Ecol. Eng.* **2025**, *26*, 264–274. https://doi.org/10.12911/22998993/200278

[67] Jana, D. A New Look to an Old Pozzolan, Clinoptilolite—A Promising Pozzolan in Concrete. In *Proceedings of the 29th ICMA Conference on Cement Microscopy*; Quebec City, QC, Canada, May 20–24, 2007; Curran Associates, Inc.: New York, NY, USA, 2007; pp 168–206.

[68] Mostafaei, H.; Bahmani, H. Sustainable High-Performance Concrete Using Zeolite Powder: Mechanical and Carbon Footprint Analyses. *Buildings* **2024**, *14*, 3660. https://doi.org/10.3390/buildings14113660

[69] Rodriguez, G.; Barrios, M.; Perdomo, I.; Iraizoz, A.; Cedre, B. Enterex: Antidiarrheic Drug Based on Purified Natural Clinoptilolite. *Zeolites* **1997**, *19*, 441–448. https://doi.org/10.1016/S0144-2449(97)00087-0

[70] Gerardo, R.; Aramis, R.; Maria, A.; Antonio, I. Antacid Drug Based on Purified Natural Clinoptilolite. *Microporous Mesoporous Mater.* **2006**, *94*, 200–207. https://doi.org/10.1016/j.micromeso.2006.03.032

[71] Potgieter, W.; Samuels, S.; Snyman, R. Potentiated Clinoptilolite: Artificially Enhanced Aluminosilicate Reduces Symptoms Associated with Endoscopically Negative Gastroesophageal Reflux Disease and Nonsteroidal Anti-Inflammatory Drug-Induced Gastritis. *Clin. Exp. Gastroenterol.* **2014**, *7*, 215–220. https://doi.org/10.2147/CEG.S51222

[72] Grce, M.; Pavelić, K. Antiviral Properties of Clinoptilolite. *Microporous Mesoporous Mater.* **2005**, *79*, 165–169. https://doi.org/10.1016/j.micromeso.2004.10.039

[73] Pavelić, K.; Hadžija, M.; Bedrica, L.; Pavelić, J.; Signikić, D.; Katić, M. Natural Zeolite Clinoptilolite: New Adjuvant in Anticancer Therapy. *J. Mol. Med.* **2000**, *78*, 708–720. https://doi.org/10.1007/s001090000176

[74] Pavelić, K.; Micek, V.; Bobinac, D.; Bazdulj, E.; Gianoncelli, A.; Krpan, D. Treatment of Osteoporosis with a Modified Zeolite Shows Beneficial Effects in an Osteoporotic Rat Model and a Human Clinical Trial. *Exp. Biol. Med.* **2021**, *246*, 529–537. https://doi.org/10.1177/1535370220968752

[75] Khatamian, M.; Yavari, A.; Akbarzadeh, A.; Alizadeh, E. Synthesis and Characterization of MFI-Type Borosilicate Zeolites and Evaluation of Their Efficiency as Drug Delivery Systems. *Mater. Sci. Eng. C* **2017**, *78*, 1212–1221. https://doi.org/10.1016/j.msec.2017.03.008

[76] Avery, K. L.; Peixoto, C.; Barcellona, M.; Bernards, M. T.; Hunt, H. K. Lysozyme Sorption by Pure-Silica Zeolite MFI Films. *Mater. Today Commun.* **2019**, *19*, 352–359. https://doi.org/10.1016/j.mtcomm.2019.03.004

[77] Angiolini, L.; Cohen, B.; Douhal, A. Single Crystal FLIM Characterization of Clofazimine Loaded in Silica-Based Mesoporous Materials and Zeolites. *Int. J. Mol. Sci.* **2019**, *20*, 2859. https://doi.org/10.3390/ijms20122859

[78] Karavasili, C.; Kontogiannidou, E.; Chatzitaki, A. T.; Barmpalexis, P.; Fatouros, D. G. Experimental and Molecular Dynamics Simulation Studies of an Anti-Hyperlipidemic Drug Release from Microporous Zeolites Differing in Si/Al Content. *Microporous Mesoporous Mater.* **2020**, *305*, 110343. https://doi.org/10.1016/j.micromeso.2020.110343

[79] Kwakye, B.; Williams, C.; Kenward, M. A.; Radecka, I. Antimicrobial Action and Efficiency of Silver-Loaded Zeolite X. *J. Appl. Microbiol.* **2008**, *104*, 1516–1524. https://doi.org/10.1111/j.1365-2672.2007.03673.x

[80] Kontogiannidou, E.; Karavasili, C.; Kouskoura, G.; Filippousi, M.; Van Tendeloo, G. In Vitro and Ex Vivo Assessment of Microporous Faujasite Zeolite (NaX-FAU) as a Carrier for the Oral Delivery of Danazol. *J. Drug Deliv. Sci. Technol.* **2019**, *51*, 177–184. https://doi.org/10.1016/j.jddst.2019.02.036

[81] Ahali, Z.; Saviano, G.; Ballirano, P.; Santonicola, G. Curcumin-Loaded Zeolite as Anticancer Drug Carrier: Effect of Curcumin Adsorption on Zeolite Structure. *Pure Appl. Chem.* **2020**, *92*, 461–471. https://doi.org/10.1515/pac-2018-1213

[82] Fatouros, D.; Douroumis, D.; Nikolakis, V.; Ntais, S.; Moschovi, A.; Trivedi, V. In Vitro and in Silico Investigations of Drug Delivery via Zeolite BEA. *J. Mater. Chem.* **2011**, *21*, 7789–7794. https://doi.org/10.1039/C1JM10204D

[83] Vergara, J.; Alejandro, S.; Pesenti, H.; Cerda, F.; Fernández, A. Obtaining Nanoparticles of Chilean Natural Zeolite and Its Ion Exchange with Copper Salt (Cu^{2+}) for Antibacterial Applications. *Materials* **2019**, *12*, 2202. https://doi.org/10.3390/ma12132202

[84] El-Kasaby, A.; Nanoff, C.; Nizet, S.; Tschegg, C.; Freissmuth, M. Purified Clinoptilolite-Tuff as a Trap for Amines Associated with Chronic Wounds: Binding of Cadaverine, Putrescine, Histamines and Polyamines. *Sci. Pharm.* **2025**, *93*, 7. https://doi.org/10.3390/scipharm93010007

[85] Qi, Y.; Qian, K.; Chen, J.; Shi, Y.; Li, H. Thermoreversible Antibacterial Zeolite-Based Nanoparticles Loaded Hydrogel Promotes Diabetic Wound Healing via Detrimental Factor Neutralization and ROS Scavenging. *J. Nanobiotechnol.* **2021**, *19*, 414. https://doi.org/10.1186/s12951-021-01151-5

[86] Abdollahi, T.; Towfighi, J.; Rezaei, H. Sorption of Cesium and Strontium Ions by Natural Zeolite and Management of Produced Secondary Waste. *Environ. Technol. Innov.* **2020**, *17*, 100592. https://doi.org/10.1016/j.eti.2019.100592

[87] Borai, H.; Harjula, R.; Paajanen, A. Efficient Removal of Cesium from Low-Level Radioactive Liquid Waste Using Natural and Impregnated Zeolite Minerals. *J. Hazard. Mater.* **2009**, *172*, 416–422. https://doi.org/10.1016/j.jhazmat.2009.07.033

[88] Jakupi, S.; Lisickov, K.; Golomeova, M.; Atkovska, K. Separation of Co(II) Ions from Water Resources by Natural Zeolite (Clinoptilolite). *Zaštita Mater. i Životn. Sred.* **2016**, *5*, 57–66.

[89] Viglasova, E.; Krajnak, A.; Galambos, M.; Rosskopfova, O. *Removal of Uranium from Water Media by Bentonite and Zeolite*; Vydavatelstvo Univerzity Komenskeho: Bratislava, Slovakia, 2014.

[90] Alotaibi, M.; Ismail, F. Modification of Clinoptilolite as a Robust Adsorbent for Highly Efficient Removal of Thorium(IV) from Aqueous Solutions. *Int. J. Environ. Res. Public Health* **2022**, *19*, 13774. https://doi.org/10.3390/ijerph192113774