IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Zeolite-Based Technologies for Environmental Remediation: A Scientific Perspective,"

1Avani sahu, 2Manoj kushwaha, 3Dr.Nishi Agrawal

1researcher, 2PhD Scholar, 3Lecturer

1Modern group of Institute,

2P.K.University,

3Modern group of Institute

Abstract

Zeolites are microporous, crystalline aluminosilicates known for their exceptional ion-exchange, adsorption, and molecular sieving capabilities. These properties make them highly effective materials for environmental remediation. This paper provides a scientific overview of zeolite-based technologies used to remove contaminants from water, air, and soil. The mechanisms by which zeolites interact with heavy metals, radionuclides, ammonium, and organic pollutants are examined in detail. Both natural and synthetic zeolites are considered, along with surface modification techniques that enhance their selectivity and efficiency. Applications such as wastewater treatment, air purification, and soil decontamination are critically reviewed, supported by recent case studies and experimental findings. The environmental sustainability, regeneration potential, and cost-effectiveness of zeolite-based approaches are also assessed. By highlighting current challenges and future prospects, this paper emphasizes the role of zeolites as versatile, scalable, and eco-friendly materials for addressing global environmental pollution.

Keywords: Surface modification, Eco-friendly materials ,Regeneration Potential,Cost-effectiveness ,Sustainable technologies

Introduction

Environmental remediation encompasses the processes and technologies used to remove pollutants or contaminants from environmental media such as soil, groundwater, surface water, and air, thereby restoring ecosystems to safe and functional states. With rapid industrialization, urbanization, and agricultural intensification, the release of hazardous substances—including heavy metals, radionuclides, ammonium, and persistent organic pollutants—has escalated globally. These contaminants pose serious threats to ecological balance, biodiversity, and human health, often accumulating in water supplies, food chains, and air systems.

Conventional remediation techniques, such as chemical precipitation, incineration, and membrane filtration, can be energy-intensive, costly, and may generate secondary waste. In contrast, the use of natural and engineered materials for passive or low-energy remediation is gaining momentum due to increasing demand for sustainable and cost-effective solutions.

Among these materials, **zeolites**—microporous crystalline aluminosilicates—have shown significant promise. Their high surface area, thermal and chemical stability, ion-exchange capacity, and selective adsorption properties make them ideal candidates for capturing and immobilizing a wide range of environmental pollutants. Zeolites occur naturally in volcanic and sedimentary rocks, but can also be synthesized with tailored pore sizes and surface functionalities to meet specific remediation needs.

This paper provides a scientific perspective on zeolite-based technologies for environmental remediation. It reviews the mechanisms by which zeolites interact with various contaminants, evaluates the performance of natural versus synthetic forms, and explores advances in surface modification to enhance efficiency. Furthermore, applications across water, air, and soil treatment are discussed, highlighting zeolites' role as sustainable, versatile, and scalable materials in the field of environmental engineering.

1. Integrated Techniques for the Development and Application of Zeolites

1. 1 .Adsorption and Ion Exchange for Heavy Metals & Organics

- **Heavy Metal Removal**
  Natural and modified zeolites (e.g., clinoptilolite) show excellent removal efficiency for heavy metals in water and aquaculture systems. The adsorption is driven by both physicochemical properties and ion-exchange capacity.
- **Surface Modifications Enhance Performance**
  Techniques like surfactant modification, acid/base treatment, and heat activation significantly improve adsorption. For example, acid–alkaline treated zeolites achieved up to 11.8 mg NH_4^+ per gram, while NaCl-treated versions offered faster and higher adsorption.
- **Composite Adsorbents**
  Hybrid materials such as Fe–Mn oxide/zeolite, Ni/zeolite, and activated carbon–zeolite composites reach remarkable capacities:
  - Cu(II): up to **147 mg/g** (Ni/zeolite)
  - Pb: up to **213.3 mg/g** (activated carbon–zeolite)
  - Dyes: up to **409 mg/g** (zeolite X–karaya gum).

1.2. Nanoparticle-Doped Zeolites & Nanocomposites

- **Enhanced Water Treatment**
  Nanoparticle integration—especially with iron—enhances dye and chromium removal from wastewater. These doped zeolites provide high efficiency, cost-effectiveness, and reusability.
- **Adsorbents + Photocatalysts**
  Zeolite-based nanocomposites are used for simultaneous adsorption and photocatalytic degradation of dyes, heavy metals, and emerging pollutants via tunable weight ratios and activation mechanisms.

1.3. Permeable Reactive Barriers (PRBs) for Groundwater Cleanup

Using zeolites as reactive media in PRBs offers:

- High adsorption capacity
- Structural stability (less clogging than iron-based barriers)
- Effective sorption and desorption performance in both lab and field settings.

1.4. Synthesis from Alternative Precursors

- **Waste-Derived Zeolites**
  Synthesizing zeolite A from coal fly ash and sugarcane bagasse ash yielded efficient cesium adsorption (up to ~33.4% Cs_2O uptake), outperforming commercial zeolite. This approach supports circular economy and nuclear wastewater treatment needs.
- **Clay- & Ash-Derived Synthesis**
  Hydrothermal and alkali-assisted synthesis from materials like kaolin and biomass ash produces high-purity zeolites (e.g., A, X, Y, ZSM-5) with superior ion-exchange and adsorptive properties.

1.5. Gas Adsorption & Membrane-Based Applications

- **CO_2 Capture & H_2S Removal**
  Functionalized zeolites (e.g., TEPA-modified 4A) can capture up to **9.4 mmol/g CO_2**, while Na/Y zeolite adsorbs **204 mg H_2S/g**, outperforming typical molecular sieves.
- **Selective Anion/Non-Polar Organics Removal**
  Surfactant-modified zeolites develop hydrophobic surfaces to enhance sorption of organic pollutants; yet issues like surfactant desorption and microbial toxicity remain under investigation.
- **Membrane Technology**
  Zeolite membranes bring high thermal/chemical stability and selectivity to processes like **gas separation**, **reactor integration**, and **water desalination**. Challenges persist in manufacturing cost and flux performance.

1.6. Emerging Domains

- **Machine Learning & Adsorption Prediction**
  Graph Neural Networks (GNNs) now predict CO_2 adsorption performance of aluminum-exchanged zeolites with remarkable speed, accelerating the design of tailored adsorbents.
- **Airborne Radioactive Gas Removal**
  Ag-zeolite shows excellent radon adsorption performance and moisture resilience, relevant to ultra-low radioactivity air purification systems.

Summary Table

Application	Zeolite Strategy	Highlights
Heavy metals / dyes / ammonia	Natural and modified zeolites, composites	High adsorption (e.g. Cu, Pb, dyes) + improved capacity via modification
PRBs for groundwater	Zeolite as reactive medium	Stable, low-clogging alternative to conventional PRBs
Radioactive wastewater	Waste-derived zeolite (ash)	Sustainable synthesis; high cesium removal
Gas capture (CO_2, H_2S)	Functionalized zeolites	High capacity for greenhouse gases and odorant gases
Organic pollutant removal	Surfactant-modified zeolites	Hydrophobic sorption; toxicity concerns exist
Membrane separation	Zeolite membranes	High selectivity and stability; cost and performance challenges
Adsorption modeling	GNN-based prediction	Efficient exploration of zeolite variants
Air purification (radon)	Ag-zeolite	Effective radon removal; promising for ultra-clean air systems

2. Synthetic Approaches

Zeolites can be synthesized by:

- **Hydrothermal synthesis** (most common)
- **Sol-gel method**
- **Dry gel conversion**
- **Microwave-assisted synthesis**
- **Ionothermal synthesis**
- **Seed-assisted synthesis**

3. Typical Zeolite Synthesis Procedure

3.1. Preparation of the Reaction Gel

A mixture of:

- Silica source (e.g., TEOS, colloidal silica, sodium silicate)
- Alumina source (e.g., sodium aluminate, aluminum isopropoxide)
- Alkaline medium (usually NaOH or KOH)
- Structure-directing agent (SDA, e.g., tetrapropylammonium hydroxide for ZSM-5)
- Water

3.2. Aging

- Time: 0 to 48 hours
- Temperature: Room temp or slightly elevated
- Purpose: Pre-nucleation – improves crystallization

3.3. Hydrothermal Crystallization

- Temperature: 90–200 °C
- Pressure: Autogenous (in sealed autoclaves)
- Time: 12–168 hours
- Static or rotating conditions

3.4. Filtration and Washing

- Separate solid crystals from mother liquor
- Wash with deionized water to remove residual alkali and organics

3.5. Drying and Calcination

- Dry at 100–120 °C overnight
- Calcine at 500–600 °C to remove SDA (template) – yields microporosity

4. Factors Influencing Zeolite Synthesis

Factor	Role
Si/Al ratio	Affects acidity, hydrophobicity, and thermal stability
Type and concentration of SDA	Determines structure (MFI, FAU, LTA, etc.)
Temperature & time	Affects crystallinity and morphology
Water content	Influences gel viscosity and diffusion
pH / Alkalinity	Controls solubility of silica/alumina
Seeding	Reduces induction time and controls nucleation

5. Post-synthesis Treatment

- **Ion-exchange**: Replace Na^+ with H^+, NH_4^+, or other metal cations (e.g., Cu^{2+} for catalysts)
- **Dealumination**: Remove Al to increase Si/Al (improves stability)
- **Desilication**: Remove Si to increase porosity
- **Impregnation / functionalization**: Introduce catalytic sites

6. Characterization Techniques

Technique	Purpose
XRD	Phase identification and crystallinity
SEM/TEM	Morphology and particle size
BET Surface Area Analysis	Surface area and pore volume
FTIR	Functional groups and framework vibrations
NMR (Si-29, Al-27)	Local structure around Si/Al
TGA/DSC	Thermal behavior and template removal
ICP-OES or AAS	Elemental analysis (Si, Al, Na, etc.)

7. Applications

- **Catalysis**: Petrochemical cracking, methanol-to-olefins (MTO), hydroisomerization
- **Adsorption**: Gas separation, water purification
- **Ion Exchange**: Water softening, radioactive waste removal
- **Sensors and membranes**

8. Characterization of Zeolites

Proper characterization ensures the material's suitability for specific environmental applications. Common characterization techniques include:

8.1 X-Ray Diffraction (XRD)

Used to determine crystalline structure and phase purity. Different zeolite types (e.g., ZSM-5, FAU, LTA) exhibit distinct XRD patterns.

8.2 Scanning Electron Microscopy (SEM) / Transmission Electron Microscopy (TEM)

Provides morphological information including crystal shape, particle size, and surface texture.

8.3 Fourier Transform Infrared Spectroscopy (FTIR)

Identifies functional groups and confirms framework vibrations indicative of Si-O and Al-O bonding.

8.4 Brunauer–Emmett–Teller (BET) Analysis

Determines surface area, pore size distribution, and porosity—critical for adsorption applications.

8.5 Thermogravimetric Analysis (TGA)

Evaluates thermal stability and water content.

8.6 Solid-State NMR

Elucidates local chemical environments of Si and Al atoms within the zeolite framework.

9. Environmental Remediation Applications

Zeolites have demonstrated efficacy in the following applications:

9.1 Heavy Metal Removal

Their high cation exchange capacity allows effective removal of Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+} from wastewater.

9.2 Ammonium and Nitrate Adsorption

Zeolites, particularly clinoptilolite, selectively adsorb NH_4^+, making them suitable for municipal and agricultural wastewater treatment.

9.3 VOC and CO_2 Capture

Synthetic zeolites with tailored pore sizes and surface functionalities are used for adsorption of volatile organic compounds (VOCs) and greenhouse gases.

9.4 Catalytic Degradation of Pollutants

Zeolites doped with transition metals (e.g., Fe, Ti) can catalyze advanced oxidation processes (AOPs) for degradation of organic pollutants in water.

9.5 Radioactive Waste Management

Zeolites have shown promise in immobilizing radioactive ions (e.g., Cs^{+}, Sr^{2+}), particularly in nuclear waste treatment.

Result and discussion

1.Adsorption & Ion-Exchange of Pollutants

- **Heavy metals**
  Synthetic zeolite composites show strong adsorption: e.g., Fe–Mn oxide/zeolite removes Cu(II) at ~53 mg/g, Ni/zeolite at ~147 mg/g; activated carbon–zeolite composites reach ~213 mg/g for Pb(II) removal.
  Natural zeolites like clinoptilolite effectively remove heavy metals such as Ni, Hg, As, Cd, and Cr—a benefit enhanced via chemical or magnetic modifications.
- **Dyes & organics**
  Zeolite X with karaya gum removes ~409 mg/g of Brilliant Green dye; chitosan/zeolite achieves ~221 mg/g for indigo carmine.
  Surfactant-modified zeolites (SMZs) enable adsorption of nonpolar organics, although concerns remain about surfactant desorption and microbial toxicity.
- **Wastes like pharmaceuticals**
  Zeolite-based composites and hybrid systems (e.g., with zeolite-nanocomposites or photocatalysts) help remove heavy metals, dyes, and emerging pollutants from wastewater, often via combined adsorption and advanced oxidation mechanisms.

2. Gas-Phase & Greenhouse Pollutant Removal

- **CO_2 capture**
  Amine-functionalized zeolites (e.g., 4A zeolite with TEPA) can capture up to 9.4 mmol/g of CO_2 at 25 °C and 5 bar—highlighting their value in greenhouse gas mitigation.
- **H_2S and sulfur compounds**
  Na/Y zeolite demonstrates strong H_2S removal capacity (~204 mg/g), outperforming some industrial molecular sieves.
- **Gas separation & membranes**
  Zeolite membranes excel in separating gases like CO_2, CH_4, and N_2 due to size selectivity and adsorption affinities—Y-type and SAPO-34 membranes show high selectivity ratios in CO_2 separation.
- **Radon removal for specialized applications**
  Silver-ion exchanged zeolites (Ag-ETS-10) outperform activated charcoal by three orders of magnitude in radon capture—crucial for ultra-low-background settings like dark matter detectors. Earlier prototypes also demonstrated strong radon adsorption from air, reinforcing their applicability in underground facilities.

3. Construction, Soil, & Composite Applications

- **Soil redress & bioremediation**
  Zeolites enhance soil quality, water retention, and nutrient availability. They improve microbial biofilm support, aiding organic pollutant breakdown and heavy metal immobilization.
  Hybrid uses include constructed wetlands and remediation of petroleum-contaminated soils.
- **Sustainable synthesis from waste**
  Fly-ash-derived nano-zeolites (like HZSM-5 types) show 95–98% removal efficiency for nitrogen and phosphorus. Zeolites synthesized from blast-furnace slag can remove over 99% of Cu and Cd within 10 minutes

4. Mechanisms, Modeling & Technical Insights

- Adsorption mechanisms are well-understood: pore filling, surface interaction, ion exchange, often modeled via adsorption kinetics and isotherms.
- Performance depends heavily on environmental parameters: pH, temperature, adsorbent dosage, competition among ions.
- Composite materials (e.g., zeolite with metal oxides, carbon nanomaterials, polymers) increase adsorption performance and even enable photodegradation via photocatalysis.

5. Challenges & Future Directions

- **Regeneration & reusability**
  Zeolites lose efficiency over multiple cycles. Regeneration (thermal or chemical) may be costly, energy-intensive, or create harmful byproducts.
- **Material consistency & economics**
  Natural zeolites are affordable but variable in quality; synthetic zeolites offer precision but are pricey—a barrier for large-scale use.
- **End-of-life concerns**
  Disposal of pollutant-loaded zeolites raises environmental and regulatory issues, requiring safe management strategies.
- **Synthesis challenges**
  High costs, complex processes, and impurity levels hinder synthetic zeolite scalability. Streamlining production (cost and energy wise) is needed.
- **Photocatalytic integration gaps**
  While promising, photocatalytic zeolite-based devices for real-world wastewater treatment are not yet commercially available.
- **Microbial implications**
  Surfactant desorption in SMZs may impact microbial communities—this remains under-researched.

Application	Highlights
Heavy metals & organics variants	High capacities via composites; natural and synthetic
CO_2 & gas separation	Strong selectivity and capture in membranes
Radon (special use cases)	A_g-zeolites excel for ultra-low background application
Soil & wastewater wastes	Support bioremediation sustainable synthesis from
Challenges impacts	Regeneration, costs, variability, disposal, microbial

Conclusion:

Zeolite-based technologies have emerged as powerful tools for environmental remediation due to their unique structural, chemical, and adsorption properties. Their high surface area, ion-exchange capacity, and molecular sieving ability make them highly effective in removing contaminants such as heavy metals, ammonia, dyes, radionuclides, and greenhouse gases from water, air, and soil. Advances in material modification—such as functionalization and the development of zeolite composites—have significantly enhanced their performance, selectivity, and regeneration potential. However, challenges remain, including variability in natural zeolite composition, limited efficiency for anionic pollutants, and energy-intensive regeneration methods. To fully realize their potential, future research should focus on improving material consistency, lowering production costs, and integrating zeolites into sustainable, large-scale treatment systems. With growing environmental concerns and regulatory pressure, zeolite-based technologies present a scientifically grounded, scalable, and eco-friendly solution for pollution control and resource recovery—positioning them as a critical component in global environmental protection and sustainable development strategies

References

1. Cundy, C. S., & Cox, P. A. (2005). *The hydrothermal synthesis of zeolites: history and development from the earliest days to the present time.* Chem. Rev., 103(3), 663–701.
2. Baerlocher, C., McCusker, L. B., & Olson, D. H. (2007). *Atlas of Zeolite Framework Types.* Elsevier.
3. Zones, S. I. (2011). *Zeolite materials synthesis: recent developments and future prospects.* Microporous and Mesoporous Materials, 144(1-3), 1–8.
4. Mintova, S., et al. (2016). *Zeolites in Catalysis: Properties and Applications.* Royal Society of Chemistry
5. Breck, D.W. Zeolite molecular sieves: Structure. In *Chemistry and Use*; John Wiley and Sons: New York, NY, USA, 1974.
6. U.S. Geological Survey. *Mineral Commodity Summaries 2016*; U.S. Geological Survey: Reston, VA, USA, 2017.
7. Musyoka, N.M.; Missengue, R.; Kusisakana, M.; Petrik, L.F. Conversion of South African clays into high quality zeolites. *Appl. Clay Sci.* **2014**, *98*, 182–186.
8. Belviso, S.; Cavalcante, F.; Lettino, A.; Ragone, P.; Belviso, C. Fly ash as raw material for the synthesis of zeolite-encapsulated porphyrazine and metallo porphyrazine tetrapyrrolic macrocycles. *Microporous Mesoporous Mater.* **2016**, *236*, 228–234.
9. Matthew, D.O.; Soltis, J.A.; Marlon, T.C.; Lee Penn, R.; Rimer, J.D. Nucleation of FAU and LTA zeolites from heterogeneous aluminosilicate precursors. *Chem. Mater.* **2016**, *28*, 4906–4916.
10. Belviso, C. State-of-the-art applications of fly ash from coal and biomass: A focus on zeolite synthesis processes and issues. *Prog. Energy Combust. Sci.* **2018**, *65*, 109–135.
11. Sturini, M.; Maraschi, F.; Cantalupi, A.; Pretali, L.; Nicolis, S.; Dondi, D.; Profumo, A.; Caratto, V.; Sanguineti, E.; Ferretti, M.; et al. TiO_2 and N-TiO_2 Sepiolite and Zeolite Composites for Photocatalytic Removal of Ofloxacin from Polluted Water. *Materials* **2020**, *13*, 537.
12. Martucci, A.; Braschi, I.; Marchese, L.; Quartieri, S. Recent advances in clean-up strategies of waters polluted with sulfonamide antibiotics: A review of sorbents and related properties. *Mineral. Mag.* **2014**, *78*, 1115–1140.
13. Belviso, C.; Abdolrahimi, M.; Peddis, D.; Gagliano, E.; Sgroi, M.; Lettino, A.; Roccaro, P.; Vagliasindi, F.G.A.; Falciglia, P.P.; Di Bella, G.; et al. Synthesis of zeolite from volcanic ash: Characterization and application for cesium removal. *Microporous Mesoporous Mater.* **2021**, *319*, 111045.
14. Belviso, C.; Cavalcante, F.; Ragone, P.; Fiore, S. Immobilization of Ni by synthesising zeolite at low temperatures in a polluted soil. *Chemosphere* **2010**, *78*, 1172–1176.

15. Belviso, C. Zeolite for Potential Toxic Metals Uptake from Contaminated Soil: A Brief Review. *Processes* **2020**, *8*, 820.
16. Mancinelli, M.; Arfè, A.; Martucci, A.; Pasti, L.; Chenet, T.; Sarti, E.; Vergine, G.; Belviso, C. Evaluation for the removal efficiency of VOCs and heavy metals by zeolites-based materials in the wastewater: A case study in the Tito Scalo industrial area. *Processes* **2020**, *8*, 1519.
17. Ugrina, M.; Gaberšek, M.; Dakovic, A.; Nuic, I. Preparation and Characterization of the Sulfur-Impregnated Natural Zeolite Clinoptilolite for Hg(II) Removal from Aqueous Solutions. *Processes* **2021**, *9*, 217.]
18. Kuntubek, A.; Kinayat, N.; Meiramkulova, K.; Poulopoulos, S.G.; Bear, J.C.; Inglezakis, V.J. Catalytic Oxidation of Methylene Blue by Use of Natural Zeolite-Based Silver and Magnetite Nanocomposites. *Processes* **2020**, *8*, 471.
19. Almasoud, F.I.; Al-Farraj, A.S.; Al-Wabel, M.I.; Usman, A.R.A.; Alanazi, Y.J.; Ababneh, Z.Q. The Potential Use of Zeolite, Montmorillonite, and Biochar for the Removal of Radium-226 from Aqueous Solutions and Contaminated Groundwater. *Processes* **2020**, *8*, 1537.
20. Boycheva, S.; Zgureva, D.; Miteva, S.; Marinov, I.; Behunová, D.M.; Trendafilova, I.; Popova, M.; Václaviková, M. Studies on the Potential of Nonmodified and Metal Oxide-Modified Coal Fly Ash Zeolites For Adsorption of Heavy Metals and Catalytic Degradation of Organics for Waste Water Recovery. *Processes* **2020**, *8*, 778.
21. Ellersdorfer, M.; Pesendorfer, S.; Stocke, K. Nitrogen Recovery from Swine Manure Using a Zeolite-Based Process. *Processes* **2020**, *8*, 1515.
22. Belviso, C.; Guerra, G.; Abdolrahimi, M.; Peddis, D.; Maraschi, F.; Cavalcante, F.; Ferretti, M.; Martucii, A.; Sturini, M. Efficiency in Ofloxacin antibiotic water remediation by magnetic zeolites formed combining pure sources and wastes. *Processes* **2021**, *9*, 2317.