Minireview Article

Advances in surface adsorption chemistry of Zeolites and their industrial applications

Abstract

Zeolites are crystalline minerals with a characteristic three-dimensional porous structure. They continue to receive much attention in both scientific and industrial fields. This article delves into the fascinating world of zeolites, diving into its amazing features and numerous uses in a variety of industries. Zeolites have a crystalline structure made up of linked silicon, aluminum, and oxygen atoms that forms an intricate lattice with well-defined channels and cavities. By virtue of their unique structure, zeolites may selectively adsorb molecules based on size and characteristics, making them useful for water purification, air filtration, and gas separation. Because of their exact pore structure and acidity, zeolites also function as very efficient catalysts, allowing them to promote chemical reactions, enhance reaction rates, and permit selective transformations in processes such as petroleum refining and petrochemical manufacture. Their ion exchange characteristics are useful in water softening because they remove undesirable ions, lowering hardness as well as preventing scale accumulation. Zeolites have also emerged as environmental remediation champions, capable of collecting and immobilizing toxins and pollutants in industrial effluent and soil. Zeolites improve soil structure, retain water, and offer regulated nutrient release in agriculture, supporting sustainable agricultural techniques and enhanced crop yields. Their molecular sieving capabilities are used in gas separation operations, including oxygen enrichment for medicinal uses and gas separation in a variety of industries.

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Furthermore, the tailorability of synthetic zeolites with specified features provides personalized solutions for a wide range of applications. With their adaptability and sustainability, zeolites play an important role in tackling current difficulties in technology, healthcare, agriculture, and environmental protection. Continuous research uncovers new uses and refines zeolite materials, solidifying their role as important minerals with an ever-expanding horizon of possibilities.

Key words: Zeolites; Surface Chemistry; Adsorption

1.0 Introduction

Zeolites are an enthralling family of naturally occurring or man-made minerals with a distinct crystalline structure and extraordinary characteristics[1] (**Figure** 1). These adaptable materials have found use in a variety of sectors, including catalysis, adsorption, ion exchange, and others[2]. Their particular properties have led to their application in a variety of industries ranging from petrochemicals and environmental remediation to healthcare and agriculture. The versatile properties and diverse applications of zeolites necessitate a thorough investigation of their structural characteristics, mechanisms of action, and potential for further innovation in industries such as catalysis, environmental remediation, agriculture, and gas separation.

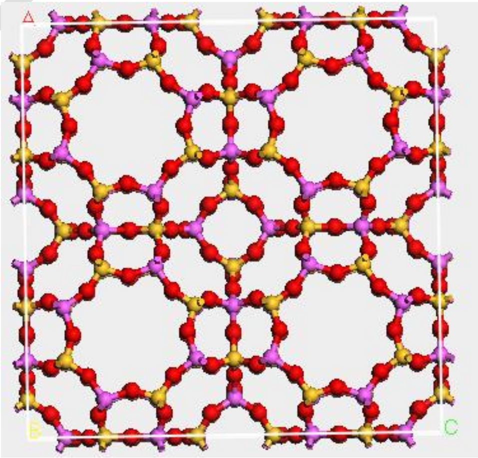

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Figure 1. An example of zeolite structure, Linte Type A zeolite (LTA).

Zeolites are categorized into many classes based on distinct characteristics. The contrast between natural and synthetic zeolites is a basic categorization[3]. Natural zeolites are minerals found in nature, such as clinoptilolite[4] and mordenite[5], whereas synthetic zeolites are generated intentionally in labs or industrial settings, and are typically customized for specific uses, such as Zeolite A[6,7] or Zeolite X[7].

Composition is another important factor of zeolite categorization. The cation content and quantity of linked water molecules are used to name zeolites. "Na-X" denotes a sodium-exchanged zeolite with a specified structure, for example[8]. Furthermore, zeolites are divided into structural families based on their crystal framework topology, such as ABC-6[9], AFI[10], LTA[11], MFI[12], and FAU[13]. The Si:Al ratio in the framework structure is also taken into account, since it influences acidity, ion-exchange capacity, and catalytic characteristics.

Cations found in zeolite structures have a role in their categorization, with sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) being frequent cations. To modify zeolite qualities for specific applications, the kind and exchange of these cations can be changed. Because of its propensity to catalyze reactions based on molecule size and form, ZSM-5 is regarded as a "shape-selective" zeolite[14,15].

Furthermore, the International Organization for Standardization (ISO) gives zeolite categorization codes to help in the identification of zeolite kinds, applications, and particular features[16]. Ultimately, zeolite categorization is an important tool for researchers, scientists, and engineers, assisting them in selecting the best zeolite for a variety of applications ranging from catalysis and ion exchange to adsorption and water treatment.

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Zeolite synthesis and modification cover a wide range of processes that allow for the manufacture and customisation of zeolite materials for a variety of industrial and scientific purposes. One of the most common ways is hydrothermal synthesis[17], which involves heating precursor solutions of alkali metal hydroxides, aluminate sources, and silica sources at high temperatures and pressures to induce crystallization. Solvothermal synthesis[18], which uses organic solvents rather of water, allows for more control over crystal form and size. Preparing a silica-rich gel and mixing it with an alumina source is followed by heating to induce crystallization. Some zeolites may be produced directly from precursor materials without the need of gels or templates.These synthesis methods allow for the customization of zeolite structures to meet individual needs.

After zeolites are produced, they can be subjected to a variety of changes to fine-tune their characteristics. Ion exchange is a typical approach that involves exchanging cations inside the zeolite framework for desired cations, hence affecting characteristics such as acidity and selectivity. Dealumination includes the removal of aluminum atoms from the zeolite structure, which can improve thermal stability. Framework substitution involves replacing framework atoms with alternative elements such as boron or phosphorus, which results in distinct catalytic characteristics[19].

Acidity, porosity, and crystal size can all be altered by post-synthesis treatments such as steaming or calcination. To achieve multifunctionality, pore size may be modified, surfaces can be functionalized, and zeolites can be combined into composite materials or encapsulated with other substances. The synthesis process and modification methodology used are determined by the individual application and desired zeolite features, demonstrating the adaptability of zeolite materials in a variety of domains such as catalysis, adsorption, and ion exchange[20].

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2.0 zeolites feature and applications

2.1. Catalysis:

Numerous researches have been conducted to investigate the use of zeolites as catalysts in various chemical processes[21,22]. Researchers have studied their efficacy in processes such as petroleum refining, petrochemical manufacture, and biomass conversion to biofuels[23]. The structure and acidity of zeolites are important factors in catalytic performance. Zeolites are well known for their excellent catalytic characteristics, which have found widespread application in a variety of industrial processes. Their distinct crystalline structure, which includes well-defined pores and a network of silicon, aluminum, and oxygen atoms, confers exceptional catalytic capabilities[24]. Zeolites' catalytic properties have been used in a variety of applications. The porous structure of zeolites functions as a molecular sieve, enabling only molecules of specified sizes and shapes to pass through their channels[25]. Because of this characteristic, zeolites may selectively catalyze reactions involving molecules that fit within their pores. Zeolites also have Bronsted and Lewis acid sites on their surfaces and within their pores[26]. These acid sites operate as active sites in a variety of processes including as isomerization, cracking, alkylation, and dehydration. Zeolites are vital in the petroleum refining industry, where they accelerate the splitting of massive hydrocarbons into useful products such as gasoline and diesel. Zeolite catalysts are also used in hydrocracking operations, which create greener fuels. They also accelerate the isomerization of straight-chain hydrocarbons into branched isomers[27], hence increasing gasoline octane rating. Furthermore, zeolites are employed in alkylation procedures to mix tiny hydrocarbons like propylene and isobutene to create high-octane gasoline components in petrochemical manufacture. They also facilitate the elimination of water from diverse compounds, such as alcohols and ethers, via dehydration processes[28].

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Zeolites are used in catalytic converters to minimize hazardous pollutants emitted by internal combustion engines in environmental applications. Due to this reason zeolite can also be used to adsorb persistent organic pollutants, POPs as seen in **Figure** 2.

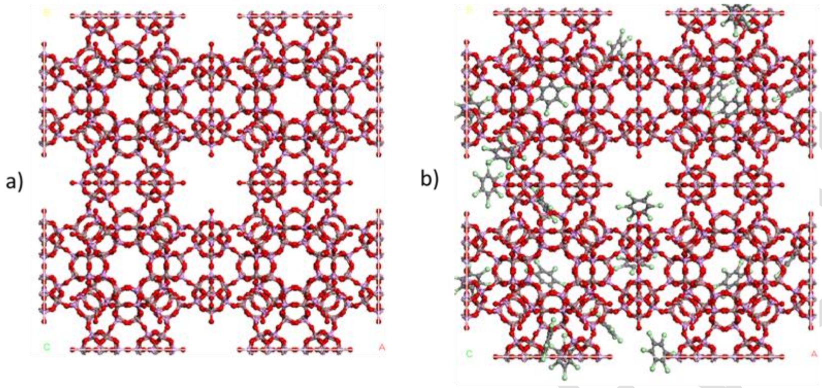

Figure 2. CLO zeolite structures before and after hexachlorobenzene (HCB) uptake, respectively.

They also aid in the transformation of nitrogen oxides (NOx) and volatile organic compounds (VOCs) into less hazardous molecules[29]. Zeolites are utilized in petrochemical and chemical synthesis processes to accelerate reactions such as the creation of petrochemical intermediates and speciality chemicals. In chiral catalysis, zeolites with customized pore diameters and shapes are utilized, allowing the manufacture of enantiomerically pure molecules, which is crucial in pharmaceutical manufacturing. Zeolite catalysts play a role in transesterification processes in biodiesel manufacturing, turning triglycerides (e.g., vegetable oils) into biodiesel fuel. Zeolite catalysts may be recycled and reused in sustainable procedures, contributing to more sustainable and cost-effective processes. While zeolites have exceptional catalytic properties, their design and selection require careful consideration of characteristics such as pore size, acidity, and stability to guarantee optimal performance. Ongoing research expands the uses of zeolites as

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catalysts and improves their efficiency in a variety of industrial processes, emphasizing their importance in the field of catalysis[30].

2.2. Adsorption and Environmental Remediation

Zeolites' adsorption properties have been widely researched, notably in the removal of pollutants and toxins from water, air, and soil[31332] . They have been studied for application in wastewater treatment, heavy metal removal, trapping volatile organic compounds (VOCs), and reducing air pollution. Adsorption on zeolites is a method that is very effective and frequently used in a variety of sectors, including the petrochemical, environmental, and healthcare industries. Zeolites are effective adsorbents for a variety of compounds and ions due to their special properties. Adsorbate molecules interact physically and chemically with the surface of zeolite crystals to form an adsorption film. Depending on the unique adsorbate and zeolite properties, these interactions involve van der Waals forces, electrostatic interactions, and even chemical reactions. For instance adsorption of organic pollutants on zeolites involve electrostatic interactions, **Figure 3**. Zeolites are highly valued for applications like gas separation, water purification, and catalysis because of their exceptional capacity to selectively adsorb molecules based on size, shape, and polarity. The controlled and reversible nature of adsorption on zeolites, along with their high surface area and thermal stability, further enhance their appeal in diverse industrial processes.

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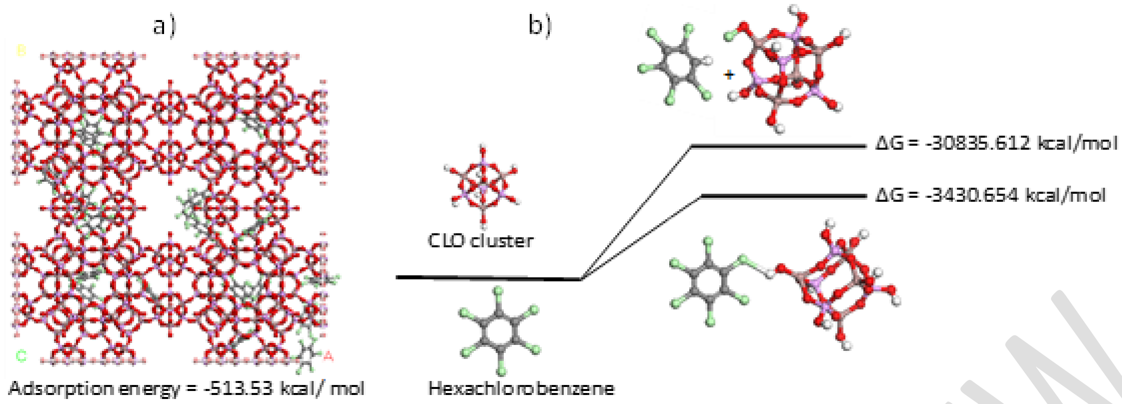

Figure 3. Adsorption mechanism for hexachlorobenzene on zeolites is much favored by electrostatic interactions compared to bond formation.

Adsorption isotherms also depict the relationship between the concentration of adsorbate molecules in the gas or liquid phase and the amount adsorbed onto the zeolite surface under specific temperature and pressure conditions. Three common isotherm models help describe this behavior. The Langmuir isotherm assumes a monolayer adsorption process on specific sites, while the Freundlich isotherm accommodates heterogeneous surfaces and multilayer adsorption, allowing for more flexibility in modeling. The BET isotherm, on the other hand, extends the Langmuir model to multilayer adsorption and is particularly suited for porous materials like zeolites. These isotherms aid in determining critical parameters such as adsorption capacity, surface area, and adsorption energy, which are vital for optimizing and designing processes that rely on zeolite-based adsorption. The choice of which isotherm to apply depends on the zeolite's characteristics and the nature of the adsorbate, often necessitating experimental data fitting for accurate parameter determination. **Figure 4** shows adsorption isotherms for various organic pollutants on various zeolites.

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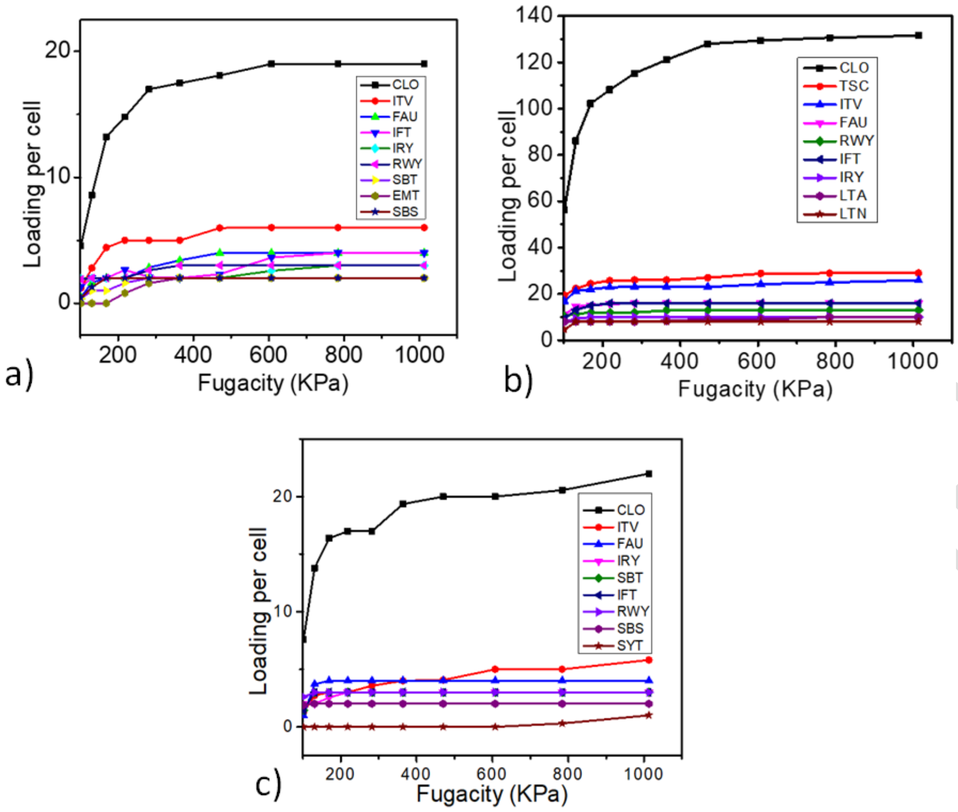

(Give the meaning of the acronyms)

Figure 4. adsorption isotherm for hexachlorobenzene a), octachlorotetradecane b) and hexachlorodecane.

2.3. Gas Separation:

Several studies have been conducted to study the use of zeolites in gas separation procedures, where their exact pore sizes allow for the selective adsorption of certain gas molecules[33] . These uses span from medical oxygen enrichment to gas separation in industrial operations. Zeolites are particularly effective gas separation agents due to their distinctive crystalline structure with well-defined pores and a framework of silicon, aluminum, and oxygen atoms[34]. Because of their molecular sieving characteristics and customized pore widths, they are indispensable in a variety

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of gas separation procedures. One of the most important aspects to consider when using zeolites for gas separation is molecular sieving. Zeolites function as molecular sieves, selectively adsorbing some gas molecules while rejecting others based on size and form. This property enables precise separation of gas mixtures. Aside from molecular sieving, another use for zeolites to explore is gas separation. Zeolites are used in a variety of gas separation processes[35], including oxygen enrichment, in which zeolites are used to separate oxygen from air, producing oxygen-enriched streams for medical and industrial applications; hydrogen purification, in which zeolite membranes can separate hydrogen from gas mixtures, which is critical in hydrogen production and fuel cell technologies[36]; and natural gas purification, in which zeolites remove impurities such as water and carbon dioxide from natural gas. In carbon capture and storage (CCS) systems, zeolites are being investigated as sorbents for absorbing carbon dioxide emissions from flue gases[37]. Another aspect to consider when using zeolites as gas separation agents is customization. Zeolites may be produced or changed to have certain pore diameters and surface chemistries, allowing zeolite materials to be tailored to varied gas separation requirements. Finally, difficulties in application should not be overlooked as a problem in zeolite gas separation. While zeolites excel in gas separation, scaling up operations, maintaining stability under high-temperature or corrosive environments, and ensuring long-term endurance can be difficult. In general, the role of zeolites as gas separation agents is critical in a wide range of sectors, from medicine to energy generation and environmental protection. Their molecular sieving characteristics and adaptability drive gas separation technology innovation, providing answers to urgent difficulties in gas purification and environmental sustainability.

2.4. Ion Exchange and Water Treatment:

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Zeolites' ion exchange characteristics have been studied for water softening and purification. These investigations seek to comprehend the kinetics and processes of ion exchange, as well as the effects of variables such as pH, temperature, and competing ions. Zeolites serve an important part in ion exchange and water treatment processes, helping to purify and condition water in a variety of applications. Zeolites have been used in ion exchange to remove hardness ions from water, especially calcium (Ca^{2+}) and magnesium (Mg^{2+}). When hard water travels through a zeolite bed, the zeolite structure's sodium (Na^{+}) ions exchange for the hardness ions, thus softening the water. This procedure avoids scale accumulation in pipes and appliances[38]. Second, zeolites are utilized to remove heavy metals. Zeolites may also exchange heavy metal ions such as lead (Pb^{2+}), cadmium (Cd^{2+}), and copper (Cu^{2+}). This makes them useful in the treatment of industrial wastewater and polluted groundwater, where hazardous heavy metal removal is critical. Zeolites are beneficial in water treatment because they have a high surface area and selective adsorption characteristics, allowing them to collect a wide range of pollutants. Organic substances, ammonia, nitrate, phosphate, and other contaminants are included.

Zeolites can be employed as adsorbents in municipal and industrial wastewater treatment facilities to lower the amounts of contaminants such as organic compounds, heavy metals, and nutrients before the treated water is discharged into the environment. Zeolites have also been studied for their capacity to trap and collect radioactive ions, making them a possible nuclear waste containment and storage material[39]. Furthermore, zeolites are used in point-of-use water filtration systems and cartridges to offer safe and clean drinking water by eliminating pollutants including bacteria, viruses, and hazardous chemicals. Zeolite membranes are used in several desalination procedures to selectively remove ions and contaminants from saltwater or brackish water, rendering it acceptable for drinking or industrial use. Because of their capacity to

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regenerate and reuse, zeolites are ideal for ion exchange and water treatment. Zeolites are frequently regenerated by flushing them with a solution having a high concentration of sodium ions, which releases the trapped ions and restores their ion exchange capability. In long-term water treatment applications, this regeneration process makes zeolites cost-effective and ecologically beneficial. Because of their ion-exchange capabilities, specific adsorption qualities, and adaptability, zeolites are important materials in ion exchange and water treatment. They help to remove hardness ions, heavy metals, organic compounds, and other impurities from water, making it safer and more suited for a variety of applications ranging from home water softening to industrial wastewater treatment and environmental cleanup.

2.5. Agriculture and Soil Improvement:

The benefits of employing zeolites as soil additives in agriculture have been studied[40]. Water retention, nutrient availability, soil structure, and plant development have all been studied. The capacity of zeolites to gradually release nutrients has piqued the interest of sustainable agricultural techniques. Because of their unique qualities, zeolites offer a wide range of uses in agriculture and soil development. Zeolites, with their porous nature, may absorb and store water, functioning as a natural water reservoir in the soil. This feature aids in the retention of water in sandy soils and dry or drought-prone areas, ensuring a more regular water supply for plant roots. Soils modified with zeolites can reduce irrigation frequency and preserve water resources. Furthermore, zeolites have a high cation exchange capacity (CEC), which allows them to collect and retain important nutrients including ammonium, potassium, and calcium. These nutrients are steadily delivered over time when plants require them. This regulated fertilizer delivery can improve plant growth and prevent nutrient leakage into groundwater, reducing environmental pollution. Zeolites can improve soil structure, especially in clay soils, by avoiding compaction

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and promoting aeration and drainage. This promotes root growth and nutrient absorption in plants. By buffering against abrupt variations in pH, zeolites can also help regulate soil pH levels. They can aid to lower soil acidity in acidic soils or counterbalance alkalinity in alkaline soils[41], hence improving plant development conditions. Zeolites can assist reduce soil salinity in saltwater areas by exchanging sodium ions for calcium and magnesium ions, making the soil less toxic to plants. Zeolites can be used as a feed component in animal feed. They can aid in the improvement of digestion, the reduction of ammonia emissions in animal facilities, and the enhancement of nutrient use in cattle and poultry. Zeolites can be used to improve fertilizer performance. Fertilizers and micronutrients can be carried by zeolites. They aid in the prevention of nutrient runoff, the enhancement of nutrient availability to plants, and the reduction of the danger of over-fertilization. Zeolites can be used in livestock bedding and manure management to decrease ammonia emissions and minimize smells, improving animal living conditions and lowering environmental pollution. Zeolites have been utilized in phytoremediation initiatives, which include using plants to remove heavy metals and other toxins from polluted soils[42]. By improving soil conditions, zeolites can aid in plant development in such initiatives. By delivering a regulated release of nutrients and keeping enough soil moisture, zeolite-based seed coverings can boost seed germination rates and early seedling growth. In general, zeolites are used in agriculture and soil development to improve soil quality, boost crop yields, and encourage sustainable farming techniques by lowering water consumption, nutrient runoff, and environmental effect.

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2.6. Medical and Pharmaceutical Applications:

Previous research has looked at the usage of zeolites in drug delivery systems and medicinal applications[43]. The porous structure of zeolites can be used as a carrier for controlled medication release, and its potential antibacterial characteristics have also been investigated. Because of their unique structure and surface chemistry, zeolites have antibacterial capabilities. These characteristics are mostly due to processes such as; Bacterial Adsorption: The porous nature of zeolites allows them to adsorb and trap bacteria on their surfaces. Zeolites' negatively charged surfaces can attract and bind positively charged bacteria, inhibiting their multiplication. Dehydration: Zeolites have the ability to remove water molecules from bacterial cells, resulting in desiccation and death of the microorganisms. This dehydration effect is especially effective against germs that are sensitive to variations in osmotic pressure. Metal Ion Release: Some zeolites include metal ions (such as silver and copper) in their structure or on their surfaces. These metal ions can be discharged into the environment, damaging bacterial cell membranes and interfering with biological activities, eventually leading to bacterial cell death. Their pH Regulation: Zeolites have the ability to change the pH of their environment. Zeolites can generate adverse circumstances for bacterial growth and survival by adjusting the pH. Zeolites have been investigated for a variety of purposes, including water filtration, due to their antibacterial qualities. In water treatment systems, zeolite-coated or embedded materials are utilized to limit bacterial development and assure the safety of drinking water. One of the medicinal applications of zeolites has also been investigated[44]: wound dressings. By limiting bacterial populations, zeolite-containing wound dressings have been produced to prevent infections and enhance wound healing. Food packaging is another important application for zeolites. By limiting bacterial contamination, zeolites can be used into food packaging materials to improve the shelf life of perishable items. Medical equipment with zeolite coatings, such as catheters, are used to lower the risk of bacterial infections caused by these devices. Zeolites are also utilized in air filtration systems to remove microorganisms from the air and keep indoor air

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quality high. The antibacterial capabilities of zeolites make them important materials in a variety of industries where bacterial contamination must be controlled for human health and safety. Their capacity to limit bacterial growth via adsorption, dehydration, metal ion release, and pH modulation adds to their use in various applications.

2.7. Zeolites in Nuclear Waste Management:

The capacity of zeolites to trap radioactive ions has been investigated in the context of nuclear waste management[45]. Researchers are looking at how zeolites can immobilize and trap radioactive isotopes, which might help with the safe storage and disposal of nuclear waste. Zeolites are important in nuclear waste management because they may immobilize and confine radioactive waste elements. Their distinct qualities make them useful for a variety of facets of this complicated and crucial process. Because of their high cation exchange capacity (CEC), zeolites can collect and immobilize radioactive ions including cesium (Cs^+), strontium (Sr^{2+}), and others. Radioactive ions can be adsorbed onto the surfaces of zeolite crystals or within their pores. Zeolites can exchange radioactive ions for non-radioactive ions like sodium (Na^+). Because of this selectivity, radioactive pollutants are successfully eliminated from the surrounding environment. Zeolites are extremely stable at high temperatures and in chemically demanding conditions. This feature is crucial for nuclear waste forms' long-term stability. Radioactive ions adsorbed on zeolites can be absorbed into waste forms such as cement or glass matrices. The zeolite-containing waste form is intended to immobilize and isolate radioactive elements from the environment. Zeolite-containing waste forms operate as leaching barriers, preventing radioactive ions from seeping into groundwater or the surrounding environment. This confinement is critical to the safety of nuclear waste storage. The use of zeolites in waste reduction can result in the concentration of radioactive ions in a smaller container, lowering the

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overall amount of nuclear waste that must be controlled and stored. Zeolites can be used for in-situ remediation of polluted groundwater at nuclear facilities in the remediation of contaminated groundwater. They can selectively absorb and remove radioactive ions from groundwater, helping to clean up the environment. Adsorbed radioactive ions in zeolites can possibly be regenerated and reused, decreasing waste and enhancing the efficiency of nuclear waste treatment procedures. While zeolites provide considerable benefits in nuclear waste management, they are often utilized in conjunction with other materials and technical controls to develop strong waste containment systems. The choice of zeolite types and waste forms is determined by the radioactive waste stream and the disposal plan (e.g., geological deposit, interim storage, or remediation). Zeolites, in general, serve an important role in the immobilization, containment, and cleaning of radioactive waste in nuclear power plants. Their distinguishing characteristics, such as selective ion exchange and high stability, make them useful components in the creation of safe and dependable nuclear waste management solutions.

2.8. Zeolites in Building Materials

Because of their moisture-regulating capabilities, zeolites have been investigated as building material additives[46,47]. In construction materials, research has shown that they have the ability to improve insulation, reduce humidity, and increase energy efficiency. With their varied qualities, zeolites are increasingly being used into a variety of architectural materials to increase sustainability, performance, and address environmental problems. Zeolites may be used in construction materials for a variety of purposes, including moisture control and thermal insulation. To improve moisture regulation, zeolites can be applied to building materials such as concrete, plaster, and cement. They have the capacity to absorb and release moisture, which aids in the prevention of difficulties such as efflorescence and increases the durability of buildings.

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Furthermore, zeolite-enhanced materials can have better thermal insulation qualities, resulting in more energy-efficient structures. Builders can lower the carbon footprint of building by using zeolites as a partial replacement for regular cement or as a component in concrete mixtures to lessen environmental effect. Materials containing zeolites need less energy to manufacture, resulting in fewer greenhouse gas emissions. This is consistent with sustainable building methods and green building requirements. Zeolites have the potential to absorb volatile organic compounds (VOCs) and odorous emissions, which can help to enhance air quality. Zeolites, when used in interior finishes such as paints and varnishes, can assist improve indoor air quality by collecting and neutralizing hazardous contaminants, resulting in better living conditions. Zeolites can improve the fire resistance of building materials, which is beneficial for fire safety. Zeolites can operate as a fire retardant when applied to gypsum boards, for example, delaying the spread of flames and enhancing the overall fire safety of structures. Zeolites can also be utilized to improve material durability and strength. Zeolites have the ability to improve the mechanical qualities of construction materials. They can increase compressive strength and prevent cracking in concrete. As a result, buildings are more robust and have a longer service life, decreasing the need for repairs and replacements. Zeolites can help cut maintenance costs by creating self-healing properties in concrete. Zeolites are being used in research to create self-healing concrete[48,49]. When fractures form in concrete, zeolites can release healing agents like calcium or silicate compounds, which react with the environment to close the fissures and restore the material's integrity. Zeolites can also be used to manage waste. Zeolites can be utilized to absorb and immobilize harmful elements in building waste aggregates. This method reduces the possibility of pollutant leaching from building trash. Zeolites can also be used to create sustainable roofing materials. To increase thermal insulation, minimize heat absorption, and cut

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cooling expenses, zeolites can be used into roofing materials. These materials can also aid in storm water runoff management by holding water during rainfall. The integration of these key substances can also result in sustainable flooring. Zeolites are utilized in environmentally friendly flooring materials such as terrazzo and concrete overlays. They have the potential to improve the aesthetic, durability, and sustainability of flooring surfaces. Another area of focus is innovative construction blocks. Improved insulating characteristics of zeolite-based building blocks or bricks are being developed, leading to energy-efficient building designs.

To summarize, when employed as building material additions, zeolites have several advantages. Their ability to manage moisture, improve air quality, increase durability, and minimize environmental effect corresponds with the rising need for environmentally friendly and sustainable building methods. Zeolites are expected to play an increasingly important role in the building sector as technology and research improve.

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2.9. Zeolites in Food and Beverages

Previously, research have looked into the usage of zeolites as food and beverage additives[50]. Certain products can benefit from the usage of zeolites to eliminate contaminants, improve flavor, and increase shelf life. Zeolites are used in the food and beverage industries, typically as food additives or as processing aids. Zeolites are used in food and beverages to absorb mycotoxin. Mycotoxins, which are harmful substances generated by mouldthat can contaminate food, are adsorbable by zeolites. Mycotoxins can be bound by zeolites, lowering their presence in food and minimizing the health concerns associated with their ingestion. Zeolites are used to enhance the shelf life of perishable items in food packaging materials. They have the ability to absorb moisture and smells, which aids in the preservation of the quality and freshness of packed goods. Furthermore, zeolites are employed in food storage containers to absorb and neutralize undesirable aromas, ensuring that stored food is free of off-flavors. Zeolites can be used as fining agents in winemaking and beverage manufacturing to clear liquids by adsorbing suspended particles and haze-forming chemicals[51]. This enhances the finished product's look and stability. Zeolites are occasionally used to improve the flavor, texture, and mouthfeel of food items. Their capacity to adjust taste compound release can be employed to make more enticing and consumable meals and beverages. In food and beverage compositions, zeolites can be used as transporters for nutrients, tastes, or colors. They may gradually release these compounds, giving regulated and longer release, which is very important in functional meals. To avoid clumping and maintain the free-flowing quality of powders such as spices, seasonings, and powdered drinks, zeolites are utilized as anti-caking agents in powdered food items. Zeolites can be used in water treatment operations to remove pollutants and impurities from water sources used in food and beverage manufacturing, guaranteeing that the water fulfills food safety quality requirements. Zeolites can operate as chelating agents, attaching to metal ions and preventing them from interacting with food components, which could result in undesired changes in flavor, color, or texture. Zeolites are occasionally incorporated in cattle and poultry feed to promote nutrient retention and utilization by animals, resulting in healthier livestock and improved food safety. It's vital to note that zeolites used in the food and beverage industries must fulfill stringent safety and regulatory criteria to guarantee that they don't endanger customers' health. Furthermore, the exact application of zeolites in food and beverage items differs based on the desired outcome and the specific needs of each product category.

3.0 Precautions when working with zeolites

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Certain care must be taken while employing zeolites in diverse applications to ensure their safe and successful deployment. To begin, workers in industrial processes involving zeolite catalysts or adsorbents should be provided with appropriate personal protective equipment (PPE) to prevent dust particle inhalation or skin contact with zeolite materials, as prolonged exposure can irritate the respiratory system and skin. Second, zeolites must be handled with caution to minimize physical damage or fracture, which might impair their efficiency. Furthermore, to avoid unintentional discharge of pollutants, wasted zeolites, particularly those that have absorbed toxins, should be disposed of in accordance with environmental rules[52]. Furthermore, because zeolites have varied ion exchange capabilities, they must be meticulously monitored and maintained when used in water softening systems to ensure proper ion exchange and prevent hardness breakthrough. Finally, for agricultural uses, it is critical to adhere to specified zeolite application rates and avoid adding excessive quantities to the soil, which might upset nutrient balance. To summarize, while zeolites have various advantages, cautious handling, disposal, and attention to safety requirements are required to optimize their benefits while minimizing potential hazards.

4.0 Limitations of zeolites application

Despite their extraordinary qualities and many uses, zeolites have several limits that should be addressed before employing them in a variety of applications. While zeolites' selective adsorption capabilities are useful in many applications, they may also be restrictive. Because zeolites can only adsorb molecules that fit within their pore size limits, they may be ineffective for eliminating some big or extremely tiny compounds. This restricts their usefulness in circumstances when a wide variety of pollutants must be eliminated. Zeolites have a finite adsorption capacity[53] and must be renewed or replaced once they become saturated with

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adsorbed molecules. The regeneration process might be energy-intensive and does not always completely restore adsorption capacity. This constraint may raise operational expenses in applications such as water treatment and air filtration. When there are competing ions in the solution, zeolites might be less effective in ion exchange applications. Ion exchange activities can be hampered by high concentrations of ions with comparable charges to the ions in the zeolite structure. Synthetic zeolites can be costly to produce, and their expense may not be justified in some applications when other materials or technologies are more cost-effective. Natural zeolite mining and processing can have negative environmental consequences, such as habitat disturbance and energy use. Furthermore, the disposal of wasted zeolites after usage in environmental remediation may necessitate caution to avoid the release of collected toxins. Some zeolite structures are vulnerable to strong chemical environments or high temperatures[54], restricting their usage in some industrial operations that need exceptional stability. While synthetic zeolites allow for flexibility, creating and synthesizing zeolites with specified features may be a time-consuming and difficult procedure. Transitioning from laboratory-scale studies to large-scale commercial applications can be difficult since zeolites' desired features and performance may require extensive engineering and process optimization. In other words, while zeolites are very adaptable and important materials, their limits, such as selectivity, saturation, and regeneration issues, should be carefully addressed when designing and implementing zeolite-based processes and applications. To overcome these restrictions, novel methods or the combination of zeolites with complementary technologies may be required.

5.0 Conclusion

To summarize, zeolites are extremely adaptable minerals with distinct characteristics and numerous uses. Their precise crystalline structure, with regular pores and specific adsorption

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capabilities, makes them useful in a variety of industries. Zeolites excel in catalysis, ion exchange, adsorption, and gas separation, helping to solve problems in sectors ranging from petrochemicals to agriculture. Customizable synthetic zeolites provide customised solutions, whilst natural zeolites contribute to environmentally friendly practices. Some limits, such as selectivity constraints, saturation concerns, and regeneration challenges, should, nevertheless, be carefully examined. To fully realize their potential, zeolites must be handled with care, adhere to safety requirements, and investigate novel techniques to overcome their limits. Zeolites continue to be important in tackling current technological and environmental concerns, with continual research driving innovation and broadening their potential.

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References

1 Khan, J. A. & Jabin, S. in *Nanocomposites-Advanced Materials for Energy and Environmental Aspects* 469-494 (Elsevier, 2023).

2 Gottesfeld, S. *et al.* Anion exchange membrane fuel cells: Current status and remaining challenges. **375**, 170-184 (2018).

3 Szerement, J., Szatanik-Kloc, A., Jarosz, R., Bajda, T. & Mierzwa-Hersztek, M. J. J. o. C. P. Contemporary applications of natural and synthetic zeolites from fly ash in agriculture and environmental protection. **311**, 127461 (2021).

4 Laurino, C. & Palmieri, B. J. N. h. Zeolite:“the magic stone”; main nutritional, environmental, experimental and clinical fields of application. **32**, 573-581 (2015).

5 Narayanan, S., Tamizhdurai, P., Mangesh, V., Ragupathi, C. & Ramesh, A. J. R. a. Recent advances in the synthesis and applications of mordenite zeolite–review. **11**, 250-267 (2021).

6 Schulman, E., Wu, W. & Liu, D. J. M. Two-dimensional zeolite materials: structural and acidity properties. **13**, 1822 (2020).

7 Petrov, I. & Michalev, T. J. H. т. н. р. у. Synthesis of zeolite A: a review. **51**, 30-35 (2012).

8 Fetisov, E. O., Shah, M. S., Knight, C., Tsapatsis, M. & Siepmann, J. I. J. C. Understanding the Reactive Adsorption of H2S and CO2 in Sodium-Exchanged Zeolites. **19**, 512-518 (2018).

9 Lee, H., Choi, W., Choi, H. J. & Hong, S. B. J. A. M. L. PST-33: A Four-Layer ABC-6 Zeolite with the Stacking Sequence AABC. **2**, 981-985 (2020).

10 Shi, Q. *et al.* Zeolite CAN and AFI-type zeolitic imidazolate frameworks with large 12-membered ring pore openings synthesized using bulky amides as structure-directing agents. **138**, 16232-16235 (2016).

11 Antúnez-García, J. *et al.* The effect of chemical composition on the properties of LTA zeolite: A theoretical study. **196**, 110557 (2021).

12 Li, Y. *et al.* Preparation, mechanism and applications of oriented MFI zeolite membranes: A review. **312**, 110790 (2021).

13 Nazir, L. S. M., Yeong, Y. F. & Chew, T. L. J. J. o. A. C. S. Methods and synthesis parameters affecting the formation of FAU type zeolite membrane and its separation performance: a review. **8**, 553-571 (2020).

14 Alotibi, M. F. *et al.* ZSM-5 zeolite based additive in FCC process: A review on modifications for improving propylene production. **24**, 1-10 (2020).

15 Seifert, M. *et al.* Ethanol to Aromatics on Modified H-ZSM-5 Part I: Interdependent Dealumination Actions. **12**, 6301-6310 (2020).

16 Gonzalez-Olmos, R., Gutierrez-Ortega, A., Sempere, J. & Nomen, R. J. J. o. C. U. Zeolite versus carbon adsorbents in carbon capture: A comparison from an operational and life cycle perspective. **55**, 101791 (2022).

17 Schmidt, R., Prado-Gonjal, J. & Morán, E. J. a. p. a. Microwave assisted hydrothermal synthesis of nanoparticles. (2022).

18 Lai, J., Niu, W., Luque, R. & Xu, G. J. N. T. Solvothermal synthesis of metal nanocrystals and their applications. **10**, 240-267 (2015).

19 Peng, Y. *et al.* Applications of metal–organic framework-derived N, P, S doped materials in electrochemical energy conversion and storage. **466**, 214602 (2022).

20 Pérez-Botella, E., Valencia, S. & Rey, F. J. C. R. Zeolites in adsorption processes: State of the art and future prospects. **122**, 17647-17695 (2022).

21 Valtchev, V., Majano, G., Mintova, S. & Pérez-Ramírez, J. J. C. S. R. Tailored crystalline microporous materials by post-synthesis modification. **42**, 263-290 (2013).

22 Li, J., Corma, A. & Yu, J. J. C. S. R. Synthesis of new zeolite structures. **44**, 7112-7127 (2015).

23 Okolie, J. A. *et al.* A review on subcritical and supercritical water gasification of biogenic, polymeric and petroleum wastes to hydrogen-rich synthesis gas. **119**, 109546 (2020).

24 Chizallet, C. J. A. C. Toward the atomic scale simulation of intricate acidic aluminosilicate catalysts. **10**, 5579-5601 (2020).

25 Cundy, C. S. & Cox, P. A. J. C. r. The hydrothermal synthesis of zeolites: history and development from the earliest days to the present time. **103**, 663-702 (2003).

26 Wei, F., Guo, X., Liao, J., Bao, W. & Chang, L. J. F. P. T. Ultra-deep removal of thiophene in coke oven gas over Y zeolite: Effect of acid modification on adsorption desulfurization. **213**, 106632 (2021).

27 Chen, Y.-K., Hsieh, C.-H. & Wang, W.-C. J. R. E. The production of renewable aviation fuel from waste cooking oil. Part II: Catalytic hydro-cracking/isomerization of hydro-processed alkanes into jet fuel range products. **157**, 731-740 (2020).

28 Gupta, J. *et al.* CaO catalyst for multi-route conversion of oakwood biomass to value-added chemicals and fuel precursors in fast pyrolysis. **285**, 119858 (2021).

29 Bang, J. H., Santos, C. A., Jo, Y. M. J. P. S. & Protection, E. Energy efficient treatment of indoor volatile organic compounds using a serial dielectric barrier discharge reactor. **153**, 29-36 (2021).

30 Vu, T. T. N., Desgagnés, A. & Iliuta, M. C. J. A. C. A. G. Efficient approaches to overcome challenges in material development for conventional and intensified CO2 catalytic hydrogenation to CO, methanol, and DME. **617**, 118119 (2021).

31 Karthigadevi, G. *et al.* Chemico-nanotreatment methods for the removal of persistent organic pollutants and xenobiotics in water–A review. **324**, 124678 (2021).

32 Borji, H. *et al.* How effective are nanomaterials for the removal of heavy metals from water and wastewater? **231**, 1-35 (2020).

33 Okello, F. O. *et al.* Towards estimation and mechanism of CO2 adsorption on zeolite adsorbents using molecular simulations and machine learning. **36**, 106594 (2023).

UNDER PEER REVIEW

34 Kianfar, E., Mahler, A. J. Z. a. i. r. & applications. Vol. 1 (Chapter, 2020).

35 Alami, A. H. *et al.* Perovskite Membranes: Advancements and Challenges in Gas Separation, Production, and Capture. **13**, 661 (2023).

36 Valappil, R. S. K., Ghasem, N., Al-Marzouqi, M. J. J. o. I. & Chemistry, E. Current and future trends in polymer membrane-based gas separation technology: A comprehensive review. **98**, 103-129 (2021).

37 Nie, L., Mu, Y., Jin, J., Chen, J. & Mi, J. J. C. J. o. C. E. Recent developments and consideration issues in solid adsorbents for CO2 capture from flue gas. **26**, 2303-2317 (2018).

38 Nsabimana, A., Li, P., Wang, Y., Alam, S. K. J. E. M. & Assessment. Variation and multi-time series prediction of total hardness in groundwater of the Guanzhong Plain (China) using grey Markov model. **194**, 899 (2022).

39 Muhire, C., Reda, A. T., Zhang, D., Xu, X. & Cui, C. J. C. E. J. An overview on metal Oxide-based materials for iodine capture and storage. **431**, 133816 (2022).

40 Osman, A. I. *et al.* Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. **20**, 2385-2485 (2022).

41 Halimat, O. I. Actinobacterial and archaeal diversity in lake Magadi, Kenya. (2013).

42 Rajendran, S. *et al.* A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. **287**, 132369 (2022).

43 Jakubowski, M. *et al.* Zinc forms of faujasite zeolites as a drug delivery system for 6-mercaptopurine. **343**, 112194 (2022).

44 Zhu, B. *et al.* Multifunctional composite dressings based on Bletilla striata polysaccharide and zeolite for rapid hemostatic and accelerated wound healing. **58**, 5427-5443 (2023).

45 Kwon, S. *et al.* Relationship between zeolite structure and capture capability for radioactive cesium and strontium. **408**, 124419 (2021).

46 Castellano, J., Sanz, V., Cañas, E. & Sánchez, E. J. C. I. Compositional effect on humidity self-regulation functionality in gibbsite-based ceramic tiles. **48**, 36318-36325 (2022).

47 Zhu, J., Zhang, X., Hua, W., Ji, J. & Lv, X. J. J. o. E. S. Current status and development of research on phase change materials in agricultural greenhouses: A review. **66**, 107104 (2023).

48 Akhtar, J., Khan, R. A., Khan, R. A., Akhtar, M. N. & Nejem, J. K. J. C. E. J. Influence of natural zeolite and mineral additive on bacterial self-healing concrete: a review. **8**, 1069-1085 (2022).

49 Fernandez, C. A. *et al.* Progress and challenges in self-healing cementitious materials. **56**, 201-230 (2021).

50 Yang, T. *et al.* Food and beverage ingredients induce the formation of silver nanoparticles in products stored within nanotechnology-enabled packaging. **13**, 1398-1412 (2021).

51 Kammerer, J., Carle, R., Kammerer, D. R. J. J. o. a. & chemistry, f. Adsorption and ion exchange: basic principles and their application in food processing. **59**, 22-42 (2011).

52 González-Martínez, A., de Simón-Martín, M., López, R., Táboas-Fernández, R. & Bernardo-Sánchez, A. J. S. Remediation of potential toxic elements from wastes and soils: analysis and energy prospects. **11**, 3307 (2019).

53 Díez, E., Redondo, C., Gómez, J. M., Miranda, R. & Rodríguez, A. J. W. Zeolite adsorbents for selective removal of Co (II) and Li (I) from aqueous solutions. **15**, 270 (2023).

54 James, J. B. & Lin, Y. J. T. J. o. P. C. C. Kinetics of ZIF-8 thermal decomposition in inert, oxidizing, and reducing environments. **120**, 14015-14026 (2016).

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