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Zeolite as an Efficient Nanocarrier and Its Applications: A Mini Review

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ABSTRACT

Objective: Nanoparticles possess significant potential across a wide array of applications; however, their unencapsulated deployment is impeded by various challenges, including aggregation, instability, and toxicity. Zeolites, which are crystalline aluminosilicate minerals, have surfaced as promising carriers to mitigate these issues, thereby enhancing the stability, functionality, and targeting capabilities of nanomaterials.

Methods: The relevant literatures were searched from the google scholar, web of science (WOS), Scopus and PubMed data bases transverse from the year 2013 to 2024 with search keywords switching from zeolite, nano zeolite, nanoparticles to nanocomposite applications.

Results: The unique microporous architecture, extensive surface area, and remarkable stability of zeolites render them suitable for applications within the biomedical, environmental, and industrial domains. In the field of biomedicine, zeolites facilitate targeted drug delivery by leveraging their pH-responsive characteristics to release therapeutic agents consequently improving therapeutic efficacy whilst reducing adverse effects. Furthermore, zeolites are conducive to theragnostic applications, which integrate both diagnostic and therapeutic functionalities. In the context of environmental remediation, nano-zeolites proficiently eliminate pollutants via mechanisms including ion-exchange, sorption, and photodegradation, with green synthesis methodologies further promoting their sustainability. In industrial sector, zeolites serve as catalysts, wherein the incorporation of metal nanoparticles into their frameworks enhances catalytic efficiency, selectivity, and stability. In agricultural settings, these materials enable delivery of nutrients and agrochemicals, thereby fostering sustainable practices. Moreover, their application in gas delivery systems, such as the transport of nitric oxide and carbon dioxide, underscores their versatility in biomedical environments. Nevertheless, their extensive applicability, challenges pertaining to scalable synthesis and cost-effectiveness necessitate attention.

Conclusion: This review accentuates the transformative potential of zeolites as multifunctional nanocarriers, thereby paving the way for innovations within the biomedical, environmental, and industrial sectors.

Keywords: Nanoparticles, Carriers, Zeolite, Nano zeolite, Applications

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Introduction

Nanoparticles have attracted considerable scholarly interest across diverse scientific disciplines owing to their distinctive characteristics; however, their application in the absence of carriers presents significant challenges. When these tiny entities remain unencapsulated, they are susceptible to agglomeration, which can compromise their intended functionalities and hinder their effectiveness in applications such as drug delivery and environmental remediation [1]. Additionally, unbound nanoparticles frequently demonstrate inconsistent behaviour within biological systems, raising fears regarding their stability and potential toxicity [2]. Their swift clearance from the organism further constrains their therapeutic promise, necessitating high dosages and intensifying the risk of adverse effects [3]. These impediments emphasize the imperative for carriers that can enhance the stability, targeting abilities, and overall efficacy of nanoparticles. Among the myriad carriers investigated, zeolites, a category

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of crystalline aluminosilicate minerals, have surfaced as a notably promising alternative due to their exceptional structural and functional attributes [4]. Zeolites are distinguished by their three-dimensional microporous frameworks, which facilitate their role as molecular sieves, enabling the separation of molecules based on size. Their extensive surface area, structural variability, and remarkable stability have rendered them indispensable in industrial applications, such as catalysis, adsorption, and ion-exchange processes [5]. Recent advancements in the engineering of nanosized and hierarchically structured zeolites have further broadened their applicability by prevailing the diffusional constraints of conventional zeolites, thereby enhancing their performance in catalytic and adsorptive reactions [6].

Within the biomedical domain, zeolites are progressively being acknowledged as efficacious nanocarriers for drug delivery systems. Their porous characteristics and pH-sensitive attributes facilitate the encapsulation and selective liberation of therapeutic agents into targeted environments, such as the acidic tumor microenvironment [7–9]. Empirical studies have substantiated the effectiveness of zeolite-based systems in administering drugs such as doxorubicin, 5-fluorouracil, and curcumin, illustrating significant potential to augment cancer therapies while mitigating the adverse effects associated with conventional treatments [6,10]. Furthermore, the multifunctionality of zeolite nanocrystals, which are amenable to functionalization for the transportation of bioactive molecules and fluorescent markers, emphasizes their prospective applications in theragnostic paradigms that integrate therapeutic and diagnostic functionalities [11, 12].

Beyond their applications in biomedicine, zeolites have demonstrated exceptional potential in the realm of environmental remediation. Nano-zeolites are particularly effective in the treatment of water and wastewater through mechanisms such as ion-exchange, sorption, and photodegradation, thereby providing sustainable methodologies for the capture and degradation of pollutants [13, 14]. Progress in eco-friendly synthesis techniques and their application in environmental catalysis further underscores the pivotal role of zeolites in facilitating sustainable practices within industrial contexts. In the domain of chemical catalysis, zeolites are distinguished as adaptable materials that can incorporate metal nanoparticles into their porous structures. This incorporation significantly enhances catalytic efficiency, yielding high activity and selectivity while preserving stability under extreme conditions. Such advancements have augmented the effectiveness of numerous catalytic processes, thereby consolidating the status of zeolites as a fundamental element in sophisticated catalytic systems.

The continuous investigation into zeolite synthesis and functionalization persists in revealing novel opportunities, thereby reaffirming their importance as multifunctional nanomaterial carriers. Spanning from biomedical applications to environmental sustainability and advanced catalytic processes, zeolites epitomize the transformative potential of nanotechnology in fostering innovative solutions across a variety of disciplines.

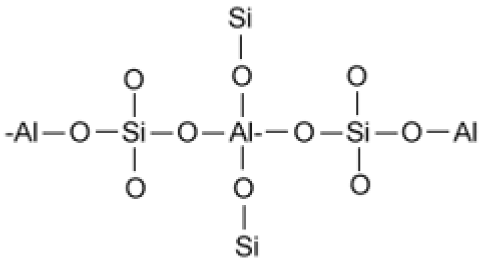

Table 1: Summarizing recent studies involving nano zeolite applications

Article Title	Methodology	Application	Novelty	Reference
Nanozeolite ZSM-5 Electrolyte Additive for Sodium-Ion Batteries	Synthesis of ZSM-5 nano zeolite and its integration as an electrolyte additive	Sodium-ion battery improvement	Enhances cycle life and interface stability compared to conventional additives	[15]
Applications of Nano-Zeolite in Wastewater Treatment: an overview	Analysis of ion-exchange, adsorption,	Wastewater treatment	Highlights nanozeolites' efficiency in removing heavy metals and organic pollutants	[14]

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	and photodegradation techniques			
Zeolite Nanosheets for Catalysis	Fabrication of nanosheets with enhanced surface exposure and minimized thickness	Catalysis in fine chemicals	Reduced diffusion constraints, enabling faster reactions and improved selectivity	[16]
Enhancement of CO2 capture by using synthesized nano-zeolite	CO2 adsorption experiments using CO2/N2 mixture	Carbon capture	Superior adsorption capacity with only 6.33 % reduction after 10 cycles regeneration	[17]
Zeolite-supported silver as antimicrobial agents	polymer fabrication, metal coatings, textiles and polymers.	Antimicrobial surface coatings	Long-lasting antibacterial activity and durability in medical and industrial applications	[18]
Physiological and biochemical response of strawberry cv. diamond to nano zeolite soil application and cinnamic acid foliar application	Applied to the soil through irrigation	Crop's yield and quality of fruits	Decreased electrolyte leakage, transpiration rate, and malondialdehyde, and enhanced chlorophyll content, net photosynthesis rate, yield, and fruit quality parameters	[19]

Nano zeolite and applications

Drug Delivery Systems

Nano zeolites have emerged as highly advantageous candidates for drug delivery systems owing to their distinctive attributes, including an extensive surface area, hydrothermal stability, and non-toxic characteristics. These features render them appropriate for a multitude of biomedical applications, encompassing drug delivery and antibacterial interventions. The porous configuration and pH-sensitive properties of zeolites facilitate the efficient entrapment and selective release of pharmaceuticals, particularly in targeted environments such as the acidic tumor microenvironment [20]. Nano zeolites are also being investigated as carriers within drug delivery systems. For instance, synthetic nano zeolite sodalite has been utilized to adsorb and subsequently release cetirizine, which serves as a model drug [21, 22]. The investigation revealed that nano zeolite sodalite could proficiently adsorb cetirizine and release it under meticulously controlled conditions, thereby establishing itself as a promising candidate for drug delivery applications [22]. The capability to modify the nano zeolite with cationic surfactants further augments its drug-carrying capacity, thus providing a versatile platform for pharmaceutical applications [23].

Cancer Therapy

Zeolites and zeolitic imidazolate frameworks (ZIFs) are currently under investigation as drug delivery systems for pharmaceuticals aimed at augmenting the specificity and efficacy of anticancer agents [24]. Their inherently porous architectures and pH-sensitive characteristics facilitate the precise release of therapeutic agents in the acidic microenvironment's characteristic of tumors, thus presenting promising alternatives to established cancer treatment modalities. Comprehensive studies regarding their application in oncology have revealed their substantial potential as nanoplatforms for enhancing the delivery and effectiveness of well-established anticancer pharmacological agents, including doxorubicin, 5-fluorouracil, curcumin, cisplatin, and miR-34a [20, 23]. These innovative systems effectively address significant limitations associated with conventional treatment strategies by enhancing drug targeting, minimizing adverse effects, and improving overall therapeutic efficacy. An extensive review of these developments emphasizes the transformative capabilities of zeolites and ZIFs as pioneering instruments in cancer treatment, thereby highlighting their significance as credible alternatives to traditional therapeutic methodologies [25].

Pharmaceuticals

The extensive utilization of nanosized zeolites within the pharmaceutical sector is proliferating as a result of advancements in their synthesis and processing methodologies. These materials are being incorporated into a range of pharmaceutical formulations owing to their distinctive characteristics, including elevated surface area and adjustable porosity. Nano zeolites, exemplified by clinoptilolite, have demonstrated considerable promise as catalysts in the synthesis of pharmaceutically active compounds [6]. For example, nano zeolite clinoptilolite has been proficiently employed as a heterogeneous catalyst for the synthesis of 2-amino-4H-chromene derivatives in aqueous environments [26, 27]. These derivatives possess significance due to their varied pharmacological properties. The nano zeolite functions as a sustainable, reusable catalyst, underscoring its environmental viability and efficacy in organic synthesis processes. The continual exploration and advancement in this domain are facilitating the emergence of innovative applications in medicine and pharmaceuticals, such as drug delivery systems and excipients in formulations. Zeolites are esteemed for their adsorption capabilities, rendering them effective carriers for drug delivery systems (DDS) involving various pharmacologically active agents, thereby enhancing the specificity and efficacy of drug administration.

Agricultural Applications

Nano zeolites present substantial potential in agricultural applications through the augmentation of crop growth, the optimization of stress management, and the facilitation of precision nutrient delivery. Their distinctive characteristics as ion-exchangers and adsorbents render them invaluable instruments for the advancement of sustainable agricultural methodologies.

Nano-Fertilizers

Zeolites serve as carriers for nano-fertilizers, thereby promoting sustainable agricultural practices by enhancing nutrient delivery systems and preserving soil productivity. Their inherent ion-exchange characteristics and adsorption capabilities render them particularly effective for the application of pesticides, insecticides, and fertilizers. Nano zeolites have shown significant potential in improving nutrient delivery to plants [28]. Their high surface area and porous structure enable them to adsorb, store, and gradually release essential nutrients, minimizing nutrient loss and enhancing plant uptake efficiency. Nano zeolite-based fertilizers contribute to sustainable agriculture by reducing the need for excessive chemical fertilizers. Their slow-release properties ensure prolonged nutrient availability, reducing the environmental impact of nutrient leaching and runoff. Studies highlight that nano zeolites improve soil moisture retention and aeration, which are critical for plant growth [29]. Their ability to regulate water content also enhances the bioavailability of nutrients in the soil. The application of nano zeolites as nano fertilizers allows for reduced fertilizer dosage, making them a cost-effective alternative for farmers [30]. Their efficiency ensures that smaller quantities of fertilizers deliver optimal crop yields. Nano zeolites act as carriers for nitrogen, phosphorus, and potassium (NPK) fertilizers. By reducing the excessive use of traditional fertilizers, nano zeolites help mitigate soil and water pollution, contributing to environmental conservation [31]. Research indicates that nano zeolites can enhance the activity of beneficial soil microorganisms [29]. Several studies have reported that the use of nano zeolites in fertilizers improves crop quality, including increased nutritional content and better stress tolerance [32, 33]. As an eco-friendly material, nano zeolites align with global efforts to promote green and sustainable agricultural practices.

Plant stress management

The implementation of nano zeolite in agricultural systems also plays a significant role in the management of plant stress. A relevant study conducted on maize indicated increased levels of stress-related enzymes, such as catalase, peroxidase, and superoxide dismutase, in flora treated with nano zeolite. These enzymes are instrumental in alleviating oxidative stress, thus implying that nano zeolite can bolster the resilience of crops against environmental stressors. Nano zeolites have been shown to alleviate abiotic stress in plants, such as drought and salinity, by improving water use efficiency and nutrient availability [34]. Nano zeolites play a significant role in alleviating plant stress, particularly under abiotic stress conditions such as drought, salinity, and nutrient deficiency [29]. Their porous structure and high surface area enable efficient water retention and gradual

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nutrient release, ensuring a consistent supply of essential resources [35]. Nano zeolites also enhance soil cation exchange capacity, improving nutrient bioavailability while mitigating harmful ion accumulation, such as sodium in saline soils [36]. Furthermore, they improve root zone aeration and water use efficiency, fostering plant growth in challenging conditions [37]. By enhancing the activity of beneficial microorganisms, nano zeolites contribute to stress resilience, promoting healthier plant development and improved crop yields [38].

Precision Agriculture and Controlled Delivery

The integration of nanotechnology, especially the utilization of nano zeolites, is crucial in the realm of precision agriculture. Nano zeolites function as carriers for agrochemicals, enabling site-specific and controlled delivery of nutrients and pesticides [37, 39]. This targeted methodology not only improves the efficacy of agricultural inputs but also reduces environmental repercussions, thereby contributing to sustainable agricultural practices.

Nanozeolites are highly effective in precision agriculture due to their porous structure, high surface area, and ion-exchange capacity, enabling controlled delivery of nutrients and agrochemicals [40]. They act as carriers for fertilizers and pesticides, ensuring gradual release in sync with plant needs, reducing nutrient loss and environmental pollution [37]. Nanozeolites improve fertilizer use efficiency, mitigate leaching, and enhance soil health while supporting site-specific applications tailored to diverse crops and soils [41]. Additionally, their water-retention properties and ability to alleviate stress conditions, such as drought and salinity, promote resilience and improve crop yields [42]. This eco-friendly approach advances sustainable and efficient farming practices.

Environmental Applications

Wastewater Treatment

Nano-zeolites can be used in the treatment of water and wastewater, facilitating processes such as ion-exchange, sorption, and membrane separation. Their efficacy in contaminant removal is attributed to their distinctive structural characteristics and advanced preparation methodologies [43]. Nano zeolites have demonstrated exceptional proficiency in the adsorption and ion-exchange mechanisms essential for eliminating heavy metals and dyes from wastewater streams [44]. The elevated surface area and increased porosity of nano zeolites substantially augment their adsorption capabilities in comparison to traditional zeolites [45]. For instance, nano zeolite X synthesized from fly ash exhibited a superior adsorption capacity for metals such as Pb^{2+} as well as dyes like methylene blue, surpassing the performance of commercially accessible zeolites [46]. Furthermore, nano zeolites have been successfully applied to the extraction of radioactive caesium from high-salt wastewater, achieving rapid adsorption kinetics [47]. Additionally, nano zeolites are employed in photocatalytic applications and as integral components within membrane separation technologies [48]. They function as nano catalysts in heterogeneous photocatalysis, facilitating the degradation of organic pollutants [49, 50]. In the realm of membrane technology, nano zeolites can be integrated into polymer matrices to enhance both the mechanical integrity and hydrophilicity of membranes, thereby improving their efficacy in water purification [51]. Similarly, the synthesis of nano zeolites utilizing industrial and agricultural waste products, such as fly ash and rice husk ash, exemplifies a sustainable methodology for the fabrication of these materials [52]. This approach not only presents a cost-effective strategy for nano zeolite production but also contributes positively to waste management initiatives and promotes environmental sustainability. The utilization of ultrasound-assisted hydrothermal synthesis has been recognized as an effective technique for generating high-purity nano zeolites characterized by superior adsorption properties [53].

Gas Delivery Systems

Nano zeolites have arisen as innovative materials within the domain of gas delivery systems, particularly attributable to their distinctive attributes such as extensive surface area, hydrothermal stability, and non-toxic composition. These properties render them suitable for a multitude of biomedical applications, including the transport of gases such as nitric oxide (NO) and carbon dioxide (CO2) [54, 55].

Gas Adsorption Properties

Investigations have demonstrated that various types of nano zeolites present differing efficiencies regarding gas adsorption [56]. For example, sodium-containing nano zeolites (Na-X) have exhibited an enhanced adsorption capacity for carbon dioxide [57, 58]. Conversely, copper-exchanged FAU nano zeolites (Cu-X) demonstrate superior efficacy in the adsorption of nitric oxide [57]. This variability in adsorption capability is imperative for the customization of nano zeolites for targeted gas delivery applications within the biomedical sector.

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Biomedical Applications

The non-toxic characteristics of nano zeolites, corroborated by cytotoxicity assessments, render them appropriate candidates for biomedical applications. They can function as carriers for gases that are essential in medical interventions [6, 59, 60]. For instance, nitric oxide serves as a crucial molecule in numerous physiological processes, and its effective delivery can be instrumental in averting life-threatening conditions [61, 62]. Likewise, the administration of carbon dioxide can hold significant relevance in specific therapeutic scenarios [63, 64].

Potential in Therapeutic Strategies

The potential applications of nano zeolites transcend mere gas delivery functions. They are currently being investigated for their effectiveness in antimicrobial therapies and the reoxygenation of tumor tissues [57]. The ion-exchange properties of nano zeolites facilitate the incorporation of diverse cations, thereby enhancing their functionality in these applications. For example, copper-modified nano zeolites have demonstrated efficacy against ESKAPE type bacteria and possess potential applications in tissue oxygenation and visualization through magnetic resonance imaging (MRI) [65].

Synthesis and Structural Properties

Nanosized and Hierarchical Zeolites

Nanosized and hierarchical zeolites signify considerable progress in zeolite technology, thereby augmenting their efficacy in various applications, including catalysis and adsorption. These advancements effectively mitigate the constraints associated with conventional zeolites, such as diffusional limitations and restricted accessibility of active sites, which enhances their versatility and efficiency [66].

Nanosized zeolites, characterized by particle dimensions typically below 100 nm, exhibit distinctive properties that expand their range of applicability [67, 68] . Their augmented surface area facilitates greater accessibility to active sites, thereby improving functionality. Furthermore, the enhancement of mass transfer due to reduced diffusion pathways significantly increases the efficiency of adsorption and catalytic processes, particularly for larger molecules. Their superior dispersibility promotes enhanced integration within diverse media, which is critical for mixed-phase systems. Such attributes render nanosized zeolites especially advantageous in fine chemical synthesis, pharmaceutical catalysis, and as substrates for metal nanoparticles in heterogeneous catalysis [69]. Conversely, hierarchical zeolites are meticulously engineered with multilevel porous architectures that integrate micropores (<2 nm) with mesopores (2–50 nm) or macropores (>50 nm) [70]. This structural design effectively addresses diffusional constraints while providing dual porosity for molecular sieving and mass transport, reducing diffusional resistance for the efficient processing of sizable molecules, and enhancing catalytic performance through improved reactant interactions and accessible active sites. Additionally, their sustainability and reusability are bolstered by superior thermal and hydrothermal stability, facilitating their reapplication [71]. Hierarchical zeolites are particularly proficient in applications such as biomass conversion and petrochemical refining [72, 73].

Therefore, both nanosized and hierarchical zeolites offer substantial enhancements over traditional variants, highlighting their essential roles in industrial, environmental, and biomedical advancements. Their unique structural and functional characteristics are instrumental in driving progress across multiple scientific disciplines.

Challenges and Future Prospects

Sustainability and Efficiency

The review elucidates the challenges associated with the large-scale implementation of nano zeolites across various applications, with particular emphasis on sustainability and energy conservation. The feasibility of substituting existing methodologies with optimized zeolite-based processes warrants thorough investigation.

Nanozeolites play a pivotal role in advancing sustainability and enhancing efficiency across various agricultural domains, attributable to their distinctive structural and functional characteristics. Within the realm of crop production, their regulated nutrient release mechanism guarantees a consistent provision of vital elements such as nitrogen, phosphorus, and potassium, thereby diminishing fertilizer overapplication and lessening environmental degradation. This gradual nutrient release minimizes the leaching of nutrients into aquatic systems, thereby alleviating eutrophication and safeguarding aquatic ecosystems [74].

In regions characterized by water scarcity, nanozeolites augment water retention capabilities and bolster water use efficiency, thereby supporting crops during periods of drought and decreasing irrigation demands [75]. Their elevated cation exchange capacity facilitates the replenishment of soil nutrients and the enhancement of soil structure, which is particularly advantageous for degraded or saline soils.

Furthermore, nanozeolites are instrumental in the implementation of site-specific and precision agriculture, whereby they facilitate the targeted delivery of nutrients and agrochemicals [76]. This method optimizes the utilization of inputs, amplifies crop yields, and endorses sustainable agricultural practices that are specifically attuned to particular crops and soil conditions.

Additionally, nano zeolites foster environmental sustainability by curtailing greenhouse gas emissions that are often linked to excessive fertilizer application [77]. Their adaptability to both organic and inorganic farming systems renders them versatile and environmentally friendly. Throughout varied agricultural landscapes, nano zeolites enhance resource efficiency, bolster plant health, and contribute to the long-term sustainability of agriculture, thereby ensuring a harmonious balance between productivity and environmental conservation [78].

Conclusion

In summary, nanoparticles significantly augment pharmaceutical bioavailability while concurrently mitigating systemic toxicity, thereby demonstrating their potential for the development of safer therapeutic modalities. Nevertheless, in the absence of suitable carriers, they are susceptible to challenges such as instability, uncontrolled release, and inadequate targeting, which end in suboptimal therapeutic results. Zeolites function as nanocarriers, effectively addressing these obstacles through their multifaceted applications in drug delivery, agricultural improvement, environmental remediation, and gas transport. Their distinctive structural and adsorption characteristics markedly enhance both process efficiency and specificity; however, obstacles pertaining to scaling and optimization persist.

Authors contribution

Mustapha Isah write major part of the review paper, both Mustapha Muhammed and Umar Abdulsalam revised the paper more deeply.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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