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Recent advances in nanoparticle-modified zeolites: functionalization strategies and diverse applications

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Nanoparticle-modified zeolites (NPZs) are multipurpose materials that combine the special functions of nanoparticles with the structural benefits of zeolites. They present a variety of applications in energy, environmental remediation, adsorption, and catalysis. Surface area, porosity, ion-exchange capacity, stability, and other physicochemical properties are enhanced by structural alterations and nanoparticle incorporation, as highlighted in this review of recent developments in the design, synthesis, and use of NPZs. Because pore size, Si/Al ratio, framework type, and natural or synthetic origin all have a significant impact on performance, special attention is paid to how zeolites are classified. Rather than offering an exhaustive survey, the review highlights representative and application-relevant examples that demonstrate how rational nanoparticle incorporation significantly enhances adsorption capacity, catalytic activity, and selectivity. Key application domains-including CO_2 capture, pollutant removal, catalytic conversions, hydrogen production, and selected biomedical uses-are discussed to illustrate the multifunctionality of NPZs while maintaining a clear thematic focus on performance enhancement mechanisms. Current challenges, such as nanoparticle leaching, diffusion limitations, high synthesis cost, and scalability constraints, are critically assessed. Emerging strategies to address these issues, including hierarchical zeolite structuring, green and template-free synthesis approaches, and hybrid nanocomposite engineering, are also examined. In addition, a concise techno–economic perspective is presented to evaluate the feasibility of large-scale implementation and industrial translation. By integrating fundamental structural insights with application-driven considerations, this review clarifies key design principles and outlines future research directions for the sustainable development and commercialization of nanoparticle-modified zeolites.

1 Introduction

The growing demand for advanced functional materials capable of addressing critical challenges in environmental remediation, sustainable energy, catalysis, and healthcare has driven intense research into hybrid and multifunctional systems.[1,2] Conventional materials often fail to meet these complex requirements due to limited tunability or single-function performance. In this regard, zeolites-crystalline microporous aluminosilicates with distinct pore architectures, strong temperature stability, and the ability to exchange ions-have long been acknowledged as useful materials for separation, catalysis, and adsorption processes.[3–5] Due to these properties, zeolites have found applications in gas separation, environmental clean-up, petrochemical processing, and detergent detergency.[6] Moreover, due to their ion-exchanging properties and natural biocompatibility, both synthetic and natural materials derived from zeolites were studied for biomedical purposes.[7] In addition, distribution of Lewis and Brønsted acid sites of zeolites is to a large extent governing the catalytic activity which is not always satisfactory for complex reactions.[8] Pure zeolites lack important functional tunability and their antimicrobial effect is relatively low in biomedical applications.[9] These properties have influenced scientists to develop techniques to enhance the properties of zeolites including surface modification, structuration, and hybridization with most advanced nanomaterials.[10] However, the efficacy of pristine zeolites in advanced catalytic, biological, and environmental applications is limited by their constant acidity and limited functional diversity, and their

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inherent microporosity can hinder mass transport of bulky molecules.

To overcome these limitations, the integration of nanoparticles (NPs) into zeolitic frameworks has emerged as a powerful and versatile strategy. Nanoparticle modified zeolites, referred to as nanoparticle doped or zeolite-nanoparticle composites, provide a synergistic combination of the unique physicochemical properties of the nanoparticles and the stability, porosity, and ion-exchange of their zeolite hosts.[11] Nanocarriers based on zeolitic constitution have incorporated metal nanoparticles such as Ag, Au, Pt, Pd, and Ni, metal oxides such as TiO_2, ZnO, and FeO_4, and carbon-based nanostructures like graphene oxide and carbon nanotubes.[12] These hybrid architectures exhibit significantly improved adsorption capability, catalytic activity, broad-spectrum antibacterial activity, photocatalytic degradation, and drug delivery.[11] Multi-functionality of NP-modified zeolites has motivated interest across different sectors. They are good candidates for adsorbents and wastewater treatment catalysts in applications to environmental technology, eliminating dyes, heavy metals and persistent organic pollutants effectively.[13] It can even simultaneously combine adsorption and the catalytic degradation so that they are particularly suitable for advanced water purification technologies.[14] For instance, TiO_2- or FeO_4-modified zeolites show an enhanced photocatalytic degradation of pollutants upon light irradiation,[15] and Cu- or Ag-doped zeolites have a high antibacterial activity, making them attractive for water disinfection applications.[16] Then, the adsorbent can be recovered and reused easily when magnetic nanoparticles such as FeO_4 were adopted, which can reduce the cost and environmental burden of the adsorbent.[17]

Recent developments have greatly broadened the range of applications for zeolites functionalized with nanoparticles in energy conversion,[25,26] biomedicine,[19,20] heterogeneous catalysis,[21,22] environmental remediation,[11,15] and sensing.[32,33] Their multifunctional potential is highlighted by their capacity to distribute therapeutic compounds in a stimuli-responsive way, stabilize active metal sites against sintering, permit controlled antibacterial ion release, and combine adsorption with catalytic degradation. Even though this field is expanding quickly, evaluations that have already been written tend to concentrate on certain applications or particular nanoparticle systems rather than providing a comprehensive analysis of functionalization techniques, structure–property connections, and cross-sectoral performance.

In the future, nanoparticle-functionalized zeolites will be crucial in solving worldwide sustainability, energy and health problems. Their practical application will require not only research in material fundamentals, but also large-scale synthesis, longevity studies and toxicity testing for biomedical utility. Hybrid strategies that integrate different modification methods and the use of newly developed nanomaterials, such as 2D nanosheets and quantum dots, are anticipated to broaden the applications of zeolite-based composites. In the end, cost-efficient, energy scalable and environmentally friendly synthesis of these materials will be needed to translate the promise of nanoparticle-modified zeolites into practical applications. Focusing on their functionalization methods, modification structures, and a variety of applications in the environmental, catalytic, and medical areas, this review provides a comprehensive overview of the development of nanoparticle-modified zeolites. The intention of the article is to discuss the various role of these hybrid materials and inspire future lines of research toward sustainable materials for technological applications taking into account the novelties present in recent research. In order to provide a cohesive roadmap for the sustainable design, scalability, and commercialization of nanoparticle-modified zeolites, this review uniquely combines structure–property relationships, cross-sectoral applications (from biomedicine to energy and environmental remediation), and a critical techno–economic assessment. Over the last decade, there has been an exponential increase in publications on nanoparticle modified zeolites, demonstrating sectorial interest in this science as shown in Fig. 1. As shown, the number of annual publications grew from less than 12 articles on the year 2015 to nearly 145 papers on the year 2024, a clear indication of the growing importance of these materials in numerous fields. This increasing trend appeals to the need and importance of this current review.

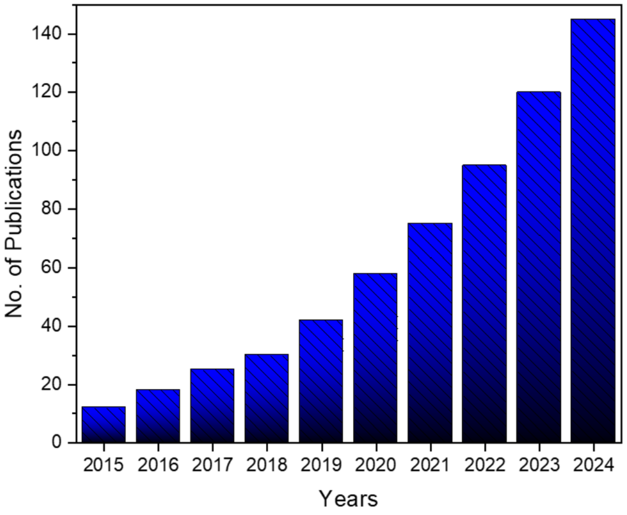


Fig. 1 Publication trend in nanoparticle modified zeolites from 2015 to 2024 using keywords like "nanoparticle modified zeolite", accessed on 28 September 2025, and information obtained from Google Scholar.

2 Methods for the controlled formation of zeolites

The synthesis of zeolites is an area of great interest due to the enhanced properties that these nanostructured materials exhibit compared to their bulk counterparts, such as higher surface areas, increased reactivity, and faster diffusion properties.[18] Interest in synthetic zeolites has increased as newer possibilities for their application in various industrial fields have been discovered. Modern synthesis techniques make it possible to obtain zeolite material with specific parameters that can be modelled and adapted for different application. Here for

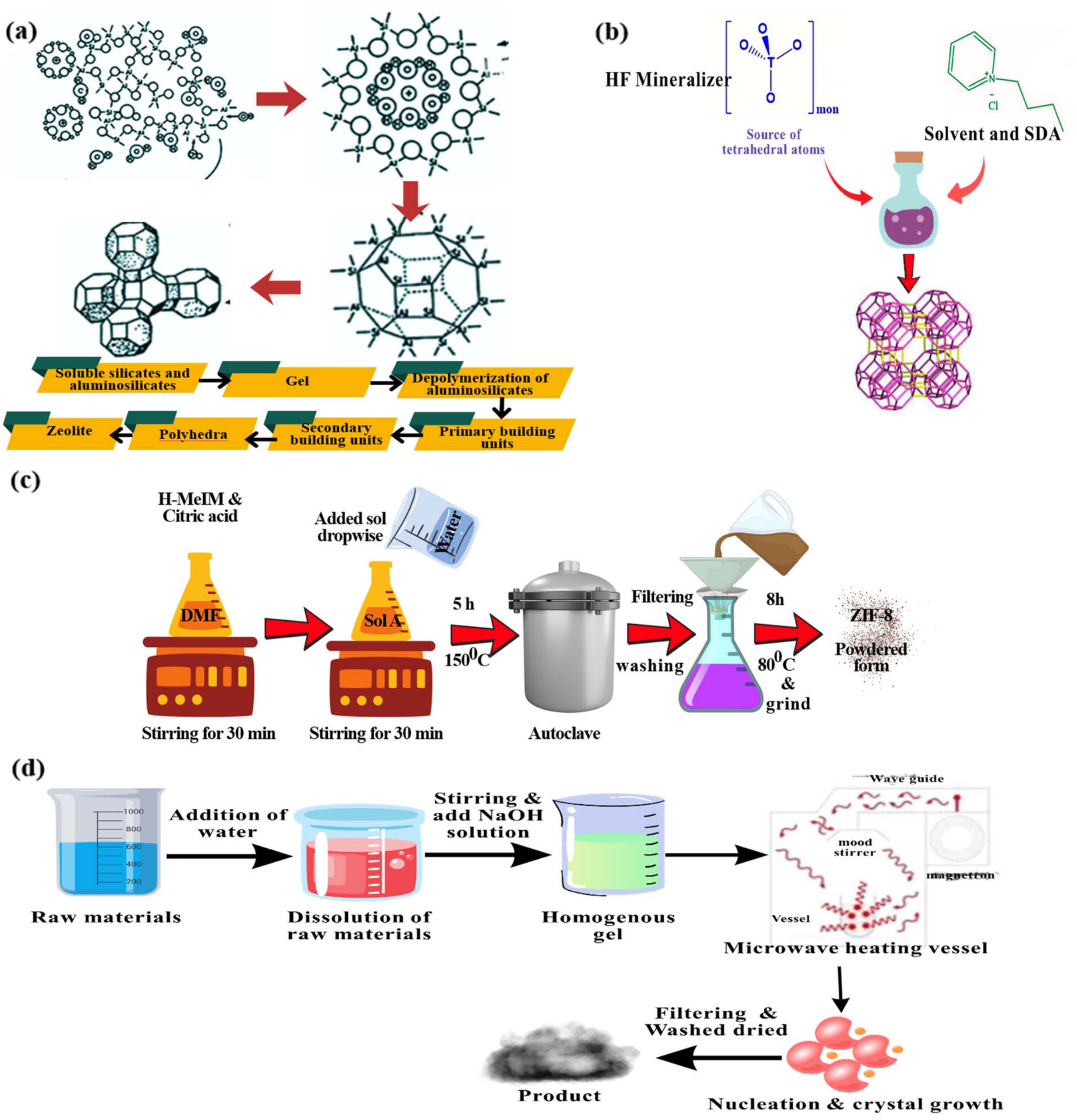


Fig. 2 (a) Hydrothermal synthesis model for zeolite, (b) inothermal synthesis of zeolites using ionic liquids. Reproduced from ref. 38, copyright 1998. (c) Solvothermal synthesis method for zeolite, (d) microwave synthesis method process of zeolites, reproduced from ref. 39, copyright 2020 with permission from Elsevier.

the synthesis of nanoscale zeolites comprehensively reviews the diverse methodologies employed for the fabrication of nanostructured zeolites.

2.1 Hydrothermal synthesis

The hydrothermal synthesis method is widely regarded as the most effective and versatile method for preparing zeolites, particularly for nanoscale structures.[19] In this process, zeolites are synthesized by mixing silica and alumina sources, often with a structure-directing agent, in an aqueous solution under high pressure and temperature.[20] The combination of presence of temperature, pressure, pH, and time controls the formation of zeolite crystals with desired sizes and properties.[21] The synthesis of zeolite nanoparticles with tailored characteristics, including enhanced surface area, pore volume, and ion exchange capacity which help to reduce wastewater treatment and removal of heavy water.[22] The process allows for control over crystal size and morphology by adjusting parameters such as temperature, time, and pH. The hydrothermal synthesis technique for zeolites offers precise control over crystal size, shape, and structure, resulting in high yields as shown in Fig. 2(a).[23] It allows the creation of diverse zeolite types with tailored properties, and is energy-efficient, making it ideal for large-scale production. This versatility supports applications in catalysis, adsorption, and ion-exchange.[24]

The crucial hydrothermal synthesis parameters (such as the Si/Al ratio, temperature, time, pH and structure-directing agent) are presented in Table 1. All these factors influence the framework structure, nucleation rate, crystallite size, phase composition, and zeolite topology.

2.2 Ionothermal synthesis

Ionothermal synthesis represents an environmentally friendly and powerful approach for the synthesis of zeolites and zeotype materials using ionic liquids (ILs) as solvents and structure-directing agents (SDAs).[25] This method provides a green and safe route compared to hydrothermal process.[26] The process is depicted in the attached figure and starts from a source of tetrahedral atoms (usually silicon or aluminum) that is introduced in an ionic solvent, mainly imidazolium based salts such as 1-ethyl-3-methylimidazolium bromide (EmimBr).[27] These ionic liquids are essential to dissolve reactants, direct the synthesis of the framework and regulate the structure of zeolite formed. Furthermore, mineralizers and solvents may be used to improve the process. In a general ionothermal synthesis, not only the framework directing species (silica or alumina precursors) but the ionic liquid (sometimes in conjunction with mineralizers or small co-templates) are combined together with the precursor. The mixture is then heated for a few hours to days in a sealed vessel at moderate temperature (typically 150–200 °C) shown in Fig. 2(b).[28] The benefit of employing ionic liquids in this approach for this method is the influence on the architecture of the zeolite produced, creating zeolites of complicated framework types.[29] As an example, the germanosilicate zeolites with double-four-ring units, STW and IRR, can be ionothermally synthesized effectively. The approach can also be extended to siliceous TON zeolites and further, has general applicability in material science and catalysis.[25]

2.3 Solvothermal synthesis

Solvothermal synthesis is a generalized form of hydrothermal synthesis, which can be performed at either higher temperatures and shorter reaction times or at lower temperatures and higher times compared with hydrothermal synthesis.[30] This enables the properties of the resulting zeolites (*e.g.*, framework type, and pore volume) to be well-controlled by careful selection of the solvent and synthesis conditions.[31] Organic solvents, such as alcohols (*e.g.*, methanol, ethanol), are usually employed together with a structure-directing agent (SDA) to achieve uniform mixing of silica and alumina precursors.[32]

Organic solvents, such as alcohols (*e.g.*, methanol, ethanol), are usually employed together with a structure-directing agent (SDA) to achieve uniform mixing of silica and alumina precursors. The mixture is then loaded into an autoclave, heated at a temperature from 100 °C to 250 °C under autogenous pressure for a given period showed in Fig. 2(c).[33] The solvent, temperature and time are essential parameters in the nucleation and growth of the zeolite crystals and can be employed respectively to control the pore size and the crystal morphology. This process is desirable, especially for the formation of specific zeolites having particular properties. For instance, have reported the successful preparation of highly dense NaX zeolite membranes from a mixture of water and an organic solvent, which showed high performance in the pervaporation separation of aqueous methanol and MTBE mixtures.[34] Being able to tune the synthesis by selecting a solvent and other parameters, the solvothermal synthesis allows a fairly easy tuning of the zeolite properties for particular applications, such as separation or catalytic process. Its versatility endows the solvothermal method a useful role in material science to prepare zeolites possessing superior properties.

2.4 Microwave-assisted synthesis

Microwave-assisted synthesis of zeolites is a recently developed process in which microwave irradiation is employed speed up the crystallisation of the zeolite framework by giving rapid, uniform heating, as in Fig. 2(d). Preparation of zeolite crystals by this process takes much less time than with conventional methods, and zeolite crystals are obtained much more rapidly.[35] One advantage in microwave heating is that a uniform heat is provided, leading to zeolite particles become more uniformly homogenized. Such uniform heating enables good control of particle size and morphology, providing more uniform and higher quality zeolite products.[36] Microwave-assisted synthesis in a typical microwave synthesis, sources of silica and alumina are mixed with alkaline solution and structure-directing agent to produce a clear gel. The resulting mix is then microwaved exposed at a controlled power and time to induce fast nucleation and growth of crystals.[37] This methodology has also used in the preparation of zeolite A and the metakaolin, that is the product of the calcination of kaolin ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$), is an alternative source of silica and alumina. The resulting microwave-assisted synthesized zeolites have also been reported to perform remarkably well for applications, *e.g.*, removal of VOCs due to its high surface area and hydrophobic

Table 1 Key parameters affecting hydrothermal synthesis

Si/Al ratio	Determines the framework structure and acidity	Higher Si/Al ratios improve stability
Temperature	Affects crystallization rate and phase selectivity	Optimal temperature is crucial for phase purity
Time	Influences crystal size and yield	Longer times may lead to larger crystals
pH	Controls solubility of precursors and phase formation	pH variations affect phase transitions
Structure-directing agent	Guides specific zeolite topology	Different agents yield different topologies
Pressure	Affects reaction rate and phase stability	Higher pressure can improve crystallization efficiency

nature. The quick and controlled microwave irradiation is conducive to prepare zeolites with improved properties and the method is expected to be used for a broad range of industrial applications.

2.5 Sol–gel method

The sol–gel process used to synthesize zeolite accounts for the preparation of a gel, a sol (a colloidal solution of particles in a liquid) and for the conversion of the gel into a zeolite framework, stressing frequently the decrease of the organic templates and even removing solvents.[40] This process involves, as indicated in the attached Fig. 3(a), first mixing 30 g water with 5 g ZSM-5 and stirring them for 30 minutes to create gel A and mixing another solution of 30 g water with 4.6 g pseudobohemite and 6.2 g di-*n*-propylamine at the same time.[41] The thus-obtained mixed solution is stirred for 30 minutes to give gel B, which is in turn mixed with 3.0 g of silica sol aliquot under stirring to give gel C, this final gel being stirred for an extended period of 150 minutes. The synthesis is then finished off in a calcination step at 600 °C for 6 h; converting the gel to zeolite.

The parameters, such as the pH, temperature, and agitation time, involved in the sol–gel process of zeolites can be varied to obtain certain structural properties of zeolites. The technique offers the advantage of a dramatically lowered dependence upon organic templates, a common issue in traditional zeolite synthesis, and also has the potential for elimination of toxic solvents.[42] It is shown that the gels experience several evolution

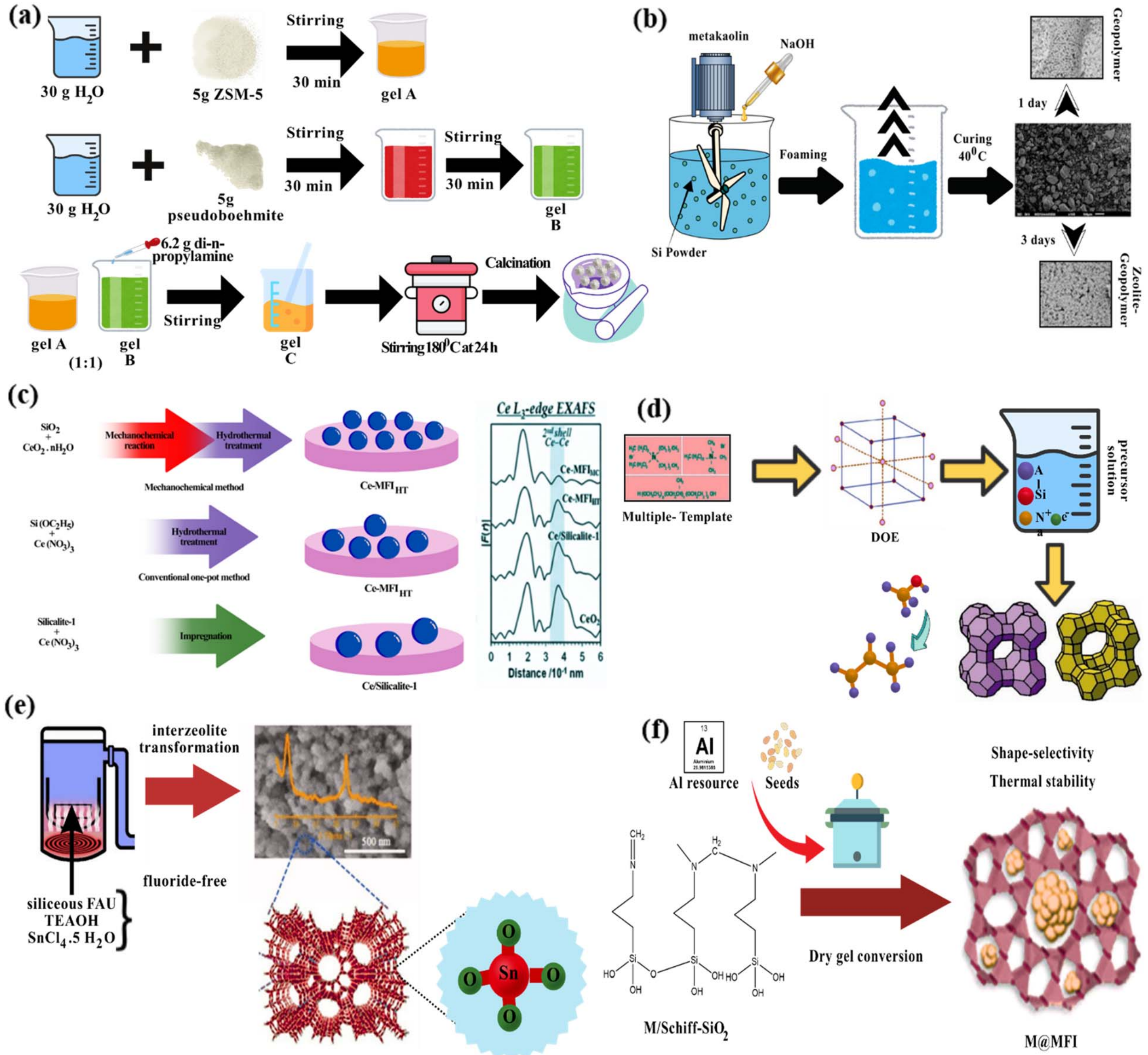


Fig. 3 (a) Sol–gel method process of synthesis of zeolites. (b) Zeolite-based monoliths for water softening by ion exchange/precipitation process. (c) Mechanochemical synthesis process of zeolites, reproduced from ref. 47 with permission from ACS, copyright 2021. (d) Temple-directed synthesis of zeolites. (e) Fluoride-assisted method for zeolites synthesis, reproduced from ref. 49 with permission from Wiley, copyright 1999. (f) Dry-gel conversion method for zeolites synthesis, reproduced from ref. 50 with permission from De Gruyter, copyright 2023.

steps before obtaining the final zeolite product, which is essential for tuning the properties of the material (porosity, catalytic activity).

2.6 Ion exchange method

The zeolite synthesis based on ion exchange is a procedure where the cationic sites occupied by cations in a natural or synthetic zeolite are exchanged by other metal ions, usually with aqueous solutions of salts. This method greatly influences the physicochemical properties of the zeolites (*e.g.*, acidity, pore diameter, and ion exchange capacity), which is important for processes such as catalysis and adsorption.[43] In general, zeolite exchange is carried out by immersing the zeolite in a solution of exchangeable ions (*i.e.*, Na^+, K^+, Ca^{2+} or metal cations such as Cu^{2+}). The zeolite is washed and dried subsequent to the soak to extract excess ions and effectively prepare the modified zeolite lattice.[44] This strategy is frequently applied for enhancing catalytic, adsorptive, or ion-exchange performance of zeolites in several environmental and industrial applications such as water and air purification, and catalysis.

A recent alternative zeolite-based process is presented in Fig. 3(b) where the generation of geopolymer and zeolite–geopolymer composites is described. The preparation begins with the mixing metakaolin with NaOH and Si powder to get a foaming mixture.[45] This feed is then aged at 40 °C for different times, yielding a geopolymer after one day and a zeolite–geopolymer composite after three days. The corresponding scanning electron microscope (SEM) images are unambiguously indicating the morphology development, and particularly a more complex, porous structure of the zeolite–geopolymer composite which is beneficial for different applications such as water softening, ion exchange *etc.*

2.7 Mechanochemical synthesis

Mechanochemical synthesis is a process that is used to prepare zeolites by directly grinding or milling the raw materials, and stimulating the chemical reactions on them.[46] Depending upon the method and reactants employed, the method for performing the same is illustrated in the appended Fig. 3(c). For instance, a mechanochemical method could be carried out by grinding SiO_2 and $CeO_2 \cdot nH_2O$ to obtain Ce-MFI (Ce-repirumaning MFI-type zeolite). Then, a hydrothermal treatment is conducted to even purify the zeolite structure. Furthermore, when $Si(OC_2H_5)_4$ and $Ce(NO_3)_3$ are combined by a classical one-pot approach Ce-MFI is formed, the synthesis being latter concluded under hydrothermal treatment. A derivative of the synthesis described above is instead impregnating Silicalite-1 with $Ce(NO_3)_3$ to obtain a Ce/Silicalite-1 product. The Ce L_3-edge EXAFS spectra shown in the figure emphasize the difference in the product structure and show the different Ce–Ce distances in Ce-MFI and Ce/Silicalite-1 in comparison with CeO_2, which is useful for elucidation of the local cerium environment in these zeolites.[47]

Compared to traditional organic templates, the use of high temperatures in addition to chemical equipment can be avoided in zeolite synthesis by applying mechanochemical approaches. This grinding not only promotes the required chemical reactions but also promotes the introduction of effective metal sites into the zeolite lattice. By controlling the conditions of grinding and treatment, zeolites can be prepared with desired properties for particular applications.[48]

2.8 Temple-directed synthesis

In structure-directing synthesis, an organic template serves as a guide for zeolite crystallization. Usually, the OSDA is a quaternary ammonium cation or an cation of the organic and serves several functions during the formation of the synthesis.[22] The OSDA does not only balance the framework charge, but also fills the space between the pores and serves as structure directing agent for the crystallization of particular topologies, *e.g.*, MFI, BEA or CHA.[51] The interaction between OSDA and framework is essential: the size and shape and actual interaction sites of OSDA with the nascent cavities play a dominant role in influencing factors such as nucleation, phase-selectivity and the final crystal growth habit.[52] For example, tetraethylammonium (TEA^+) is commonly used for the preparation of BEA-type zeolite and tetrapropylammonium (TPA^+) is used for the preparation of MFI-type zeolite. Small bicyclic or cyclic ammonium cations can also be used for the synthesis of nanoscale MFI or Beta zeolites.[22,53] As described in the attached Fig. 3(d), the synthesis process of the SAPO molecular sieve starts from a precursor solution containing necessary aluminum and silicon sources, organics templates and mineralizers. It is also emphasized how the multiple-template approach (MTP) is able to keep control over selectivity, as can be seen from the selectivity plot of several compounds.[54] The dual-OSDA strategy is exploited in this approach, which better control phase competition and intergrowth leading to well-ordered, defect-free zeolite crystals. This strategy can largely optimize the Si/Al distribution and the overall performance of the zeolite materials.

2.9 Fluoride-assisted synthesis

Fluoride-promoted synthesis is employed extensively in the preparation of high-quality zeolites, especially in hydrothermal systems where fluoride ions act as mineralizers along with hydroxide. The fluoride in the system greatly affects nucleation and crystal growth, which can result in larger and more uniformed crystals than that produced from typical alkaline routes.[55] Furthermore, fluoride offers a stabilizing medium under acidic ambient that is essential for the efficient incorporation of foreign atoms such as Sn and Ti into the zeolite structure, giving rise to Sn-Beta, Ti-Beta, *etc.* These heteroatom-substituted zeolites are excellent catalysts for applications including Baeyer–Villiger oxidations and Meerwein–Ponndorf–Verley reductions.[49] However, this practice causes environmental and safety problems for fluoride is a strongly corrosive substance and produces toxic waste, and so it has prompted the research of fluoride producing methods. In Fig. 3(e), the fluoride-free transformation pathway was established while using siliceous FAU as a parent, TEA as a structure-directing agent, and $SnCl_4 \cdot 5H_2O$ as the tin source.[56] In the meanwhile, the use of toxic fluoride salts is eliminated and Sn is still

Table 2 Comparative analysis of synthesis methods of zeolites

Technique	Description	Advantages	Challenges	Ref.
Hydrothermal synthesis	Hydrothermal synthesis for zeolites involves heating a silica–alumina gel in an autoclave under high temperature and pressure to crystallize zeolites	Versatile, scalable, control over particle size, morphology and efficient production	Controlling crystal size, preventing impurity formation, and optimizing reaction conditions for desired zeolite structure and yield	63
Solvo-thermal synthesis	Solvothermal synthesis of zeolites involves crystallizing silica and alumina in a solvent under high temperature and pressure	Structure, high crystallinity, and scalability for various catalytic and adsorption applications	High energy consumption, complex process control, expensive reagents, and difficulty in achieving desired crystallinity and purity	64
Microwave-assisted synthesis	Microwave energy to accelerate the formation of zeolites, enhancing efficiency, crystallization, and structural properties	Faster reaction times, energy efficiency, better control over crystallization, and enhanced zeolite properties	Uneven heating, limited scalability, control over reaction parameters, and potential degradation of zeolite structure	65
Sol–gel method	Converting a liquid precursor into a gel, which is then heated to form zeolites	Composition, uniformity, and particle size, enhancing zeolite structure and performance	Long processing times, difficulty controlling pore structure, and potential for low crystallinity or incomplete gel formation	66
Mechanochemical synthesis	Mechanical force to induce chemical reactions, promoting zeolite formation without requiring high temperatures or solvents	Energy efficiency, environmentally friendly process, reduced reaction time, and no need for high temperatures or solvents	Difficult to controlling particle size, scalability issues, and potential for inconsistent product quality due to variable mechanical forces	50
Ion exchange method	Replacing cations in zeolite structures with desired ions, modifying properties for specific catalytic or adsorption functions	Precise control over ion composition, enhanced catalytic properties, and the ability to tune zeolite performance for specific applications	Slow ion exchange rates, incomplete ion exchange, and difficulty achieving uniformity in ion distribution within zeolite structures	67
Ionothermal synthesis	Ionic liquids as solvents and structure-directing agents to synthesize zeolites at lower temperatures and reduced pressures	Faster crystallization, lower temperatures, reduced energy consumption, and environmentally friendly solvents for zeolite production	High cost of ionic liquids, limited scalability, and difficulty in recovering solvents for reuse	28
Temple-directed synthesis	Organic templates to guide zeolite formation, influencing pore structure and crystallinity during hydrothermal or sol–gel processes	Precise control over zeolite structure, pore size, and morphology, enabling tailored properties for specific applications	High cost of organic templates, difficulty in template removal, and potential environmental concerns with template disposal	68
Fluoride-assisted synthesis	Uses fluoride ions to accelerate zeolite crystallization, promoting lower temperature formation and enhancing framework stability and structure	Faster crystallization, lower synthesis temperatures, improved framework stability, and reduced energy consumption during zeolite formation	Handle of fhazardous fluoride compounds, controlling crystallization, and potential environmental impact from fluoride waste during zeolite synthesis	49
Sonochemical synthesis	Uses ultrasonic waves to induce cavitation, promoting rapid zeolite crystallization with enhanced nucleation and energy efficiency	Fast crystallization, energy efficiency, enhanced nucleation, and improved control over zeolite morphology and particle size	Equipment cost, difficulty in scaling up, inconsistent crystallization, and limited control over zeolite structure and morphology	60
Dry-gel conversion (DGC)	Heating a dry gel precursor to form zeolite, offering energy efficiency and shorter synthesis times	High purity, controlled porosity, and efficient production of advanced materials like ceramics	High cost, complex processing conditions, risk of cracks, and difficulty in scaling up production efficiently	69

successfully introduced into the zeolite framework. The schematic explains the lattice rearrangement that results in a crystalline structure, micrograph proves the presence of particles of good crystal nature with features in nanometer regime.[57] The Sn-modified zeolite has isolated Sn sites, as is evidenced by the Sn–O coordination environment that are active for selective oxidation reactions. Therefore, the fluoride-free approach not only provides a more environmentally friendly alternative but also preserves the high crystallinity and functionality of fluoride-mediated systems.

2.10 Sonochemical synthesis

Ultrasound induced nucleation and crystallisation of zeolites in sonochemical syntheses of zeolites was based on acoustic cavitation. It is based on the explosion of microscopic bubbles in a liquid, which results in the formation and collapse of bubbles, and thus in very high temperatures and pressures developed locally. These conditions favor the dissolution and reorganization of the aluminosilicate precursors and result in the preparation of highly porous zeolites.[58] As a result, the sonochemically synthesized zeolites present unique attributes of a high external surface area, low diffusion limitations and hierarchically porosity, all of which render them highly valuable for many industrial applications. Higher efficiency in the adsorption and conversion of VOCs was reached by the ZSM-5 nanosize zeolite such as ZSM-5 obtained by ultrasound methods in catalytic processes in comparison with traditional catalysts.[59] This enhancement arises from the enlarged exposure of their active centers associated with the nanometric size and high SSA. Furthermore, sonochemically synthesized zeolites such as NaA and NaP have already showed to have specific application in water softening, wastewater treatment and removal of heavy metal ions. Their superior ion exchange ability and fine particle size make them be effective in such environmental remediation.[60] Therefore, sonochemistry becomes an attractive tool in zeolite preparation to tailor their properties for being useful catalysts and materials, in industrial and environmental applications.

2.11 Dry-gel conversion (DGC)

The DGC method has been developed as an efficient and environmentally benign procedure for preparation of zeolites by crystallization of the dehydrated gel with solvent vapor as the medium instead of the liquid phase. In this process, a synthesis gel comprising silica and alumina precursors and molecular templates (SDAs) is dried into a "dry gel" firstly and then calcined in a reactor under mild temperature and pressure.[24] Solvent and SDA vapors diffuse in the dry gel, and crystal growth is considerably enhanced without using water, solvent, or organic template to a great extent. This not only promotes nucleation and crystallization, but also reduces the generation of waste, in contrast to traditional hydrothermal synthesis. Consequently, DGC frequently produces nano zeolite particles of high crystallinity, improved porosity and adjustable morphology. BKC is employed to DGC process, where Schiff-base modified silica (M/Schiff-SiO_2) is doped Aluminum source and zeolite seeds to synthesize M@MFI zeolite (Fig. 3(f)).[61] The process includes the step (dry gel to zeolites) which produces zeolites with uniform pore structures and excellent shapes selectivity and thermal stability, as schematically depicted. In addition, incorporation of metal species in the silica structure also improves the catalytic properties of the resultant zeolites, rendering them suitable for hydrocarbon cracking, selective oxidation and isomerization reactions. In particular, MFI mesoporous zeolites prepared by DGC involving metal oxides, such as ZnO, have shown enhanced catalytic performance for model cracking reactions.[62] Hence DGC is highlighted as a scalable and eco-compatible approach to tailor cutting-edge zeolite materials with high structural strength and advanced catalytic performance.

This is an overview of the comparative study of the zeolite synthesis techniques shown in Table 2. The table lists each approach's benefits, challenges, and suitability for real-world uses.

3 Modification techniques for nanoparticle-doped zeolites

Zeolites, a class of crystalline aluminosilicates with well-defined microporous structures, are widely recognized for their exceptional thermal stability, ion-exchange capacity, and catalytic activity.[70] However, their performance in advanced applications such as environmental remediation, energy storage, biomedical delivery, and catalysis can be significantly enhanced through the incorporation of nanoparticles.[71,72] Doping zeolites with nanoparticles provides a synergistic effect, combining the molecular sieving ability and stability of zeolites with the unique electronic, optical, or magnetic properties of nanoparticles.[14] To accomplish this integration effectively, several modification techniques have been developed, each with distinct mechanisms, benefits, and limitations.[3]

The Fig. 4 shows several methods of modifying zeolites to improve their structural and functional characteristics, such as hydrothermal, sol–gel, ion exchange, impregnation, and surface functionalization.[73]

3.1 Ion exchange method

The ion exchange is well known and simple method of metal nanoparticles modification as well as the most popular, due to its simplicity and scalability.[74] In the latter case, transition or precious metal ions (for example Au^+, Ag^+, Cu^{2+}, Zn^{2+} or Fe^{3+}) can be inserted into the zeolite structure by exchanging native cations (such as Na^+ or K^+) with other ions of metallic nature *via* treatment in aqueous solution.[75] This exchange takes place at the active sites in the zeolite catalysts where the metal ions substitute for known cations to fill up empty spaces. Upon completion of this interaction, the metal ions are reduced by some combination of thermal and/or chemical methods in order to form metallic nanoparticles.[76] These metal nanoparticles reside either in the pores or on the surface of the zeolite depending upon the reaction conditions adopted for reduction. The ion-exchange approach is especially interesting

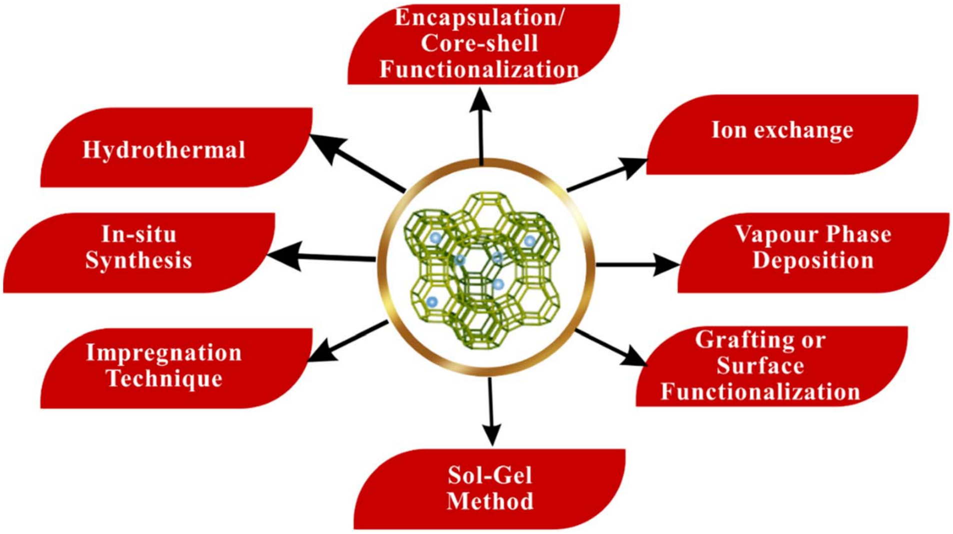


Fig. 4 Modification methods of zeolite.

for controlled catalytic activity, such as in antibacterial materials, redox and catalysis.[77] Uniform metal nanoparticle dispersion in the zeolite matrix has been proven to be beneficial for better catalytic utilization and it is broadly applicable for various industrial sector, such as environmental remediation and energy generation. But this approach has its own drawbacks. The method is limited to ion exchangeable metals and in order to obtain complete ion exchange several processing steps may be necessary, which possibly will render the process more complicated.[78,79] The ion exchange process is shown in the phenomenon that K^+ ions originally in the zeolite framework are exchanged by metal ions (such as Au^{3+}), and then autoreduction occurs to generate metallic Au nanoparticles (Fig. 5(a)). This technique provides a rational route to prepare zeolites containing metal cations that would be difficult to introduce into crystalline frameworks by the conventional ion-exchange method.

3.2 Impregnation techniques

Impregnation, such as wet impregnation and incipient wetness impregnation, is a commonly used technique to modify zeolite with metal nanoparticles.[80] In this method the zeolite to be treated is contacted by washing or impregnation with a solution of a precursor(s) of metal. The material is then dried and subjected to calcination or reduction reactions where the metal precursors are converted into nanoparticles.[81] It enables a high metal loading, which is especially advantageous for catalytic purposes. Very well scaling here is also easy, that's why is the favourite method for industrial processing.[82] However, the partial shortcoming to this method is that in most a cases dispersion of nanoparticles is confined on the external surfaces or major pores of zeolite and can prohibit its potential applications with less efficiency. Despite these drawbacks, impregnation is still one of the most widely used techniques particularly for synthesis of catalysts containing precious metals, such as platinum (Pt), palladium (Pd) and gold (Au), because it is cost-effective and quite simple.[83] But, uneven nanoparticle distribution and possible pore plugging can be drawbacks under certain circumstances. The Fig. 5(b) below also describes in a simplified way the impregnation procedure: in which a metal precursor solution is co-mixed with methanol and polyethyleneimine (PEI) to allow for impregnation into the zeolite (13X) structure. This procedure results in metal-loaded zeolite composites that can serve as adsorbents or catalysts for a number of applications.[84,85]

3.3 *In situ* synthesis, co-precipitation and sol–gel technique

The methods involving the *in situ* formation of zeolite combined with metal nano-particles and simultaneous formation of zeolite because modification by direct presence within the particle or surface after crystallization time.[86] In this way of preparation, metal precursors are loaded in the zeolite combining solid state chemistry and formation of NPs inside the framework. This promotes a more even distribution of nanoparticles within the zeolite, which can enable greater control over particle size, its location and also density. Zeolite structures and nanoparticles can be co-generated *in situ* along with co-precipitation, leading to the formation of nanocomposites where the zeolite matrix and the nanoparticles are stable and integrated, exhibiting strong interaction between it.[87,88] This interaction results in better thermal and chemical stability that is highly desirable for applications in catalysis, environmental remediation, and energy. The conditions of synthesis are often complex and involving stringent controls on temperature, pH and the concentration of metal precursor.[87,88] Furthermore, the presence of nanoparticles embedded in zeolite framework can change the crystallinity of zeolite leading to loss or reduction in its catalytic and adsorption performance. However, despite such drawbacks, they are both powerful methods for obtaining advanced nanoparticle-doped zeolites.[89] Researcher illustrates the process of co-precipitation, where Na-zeolite is contacted with a solution of NaOH and subsequently

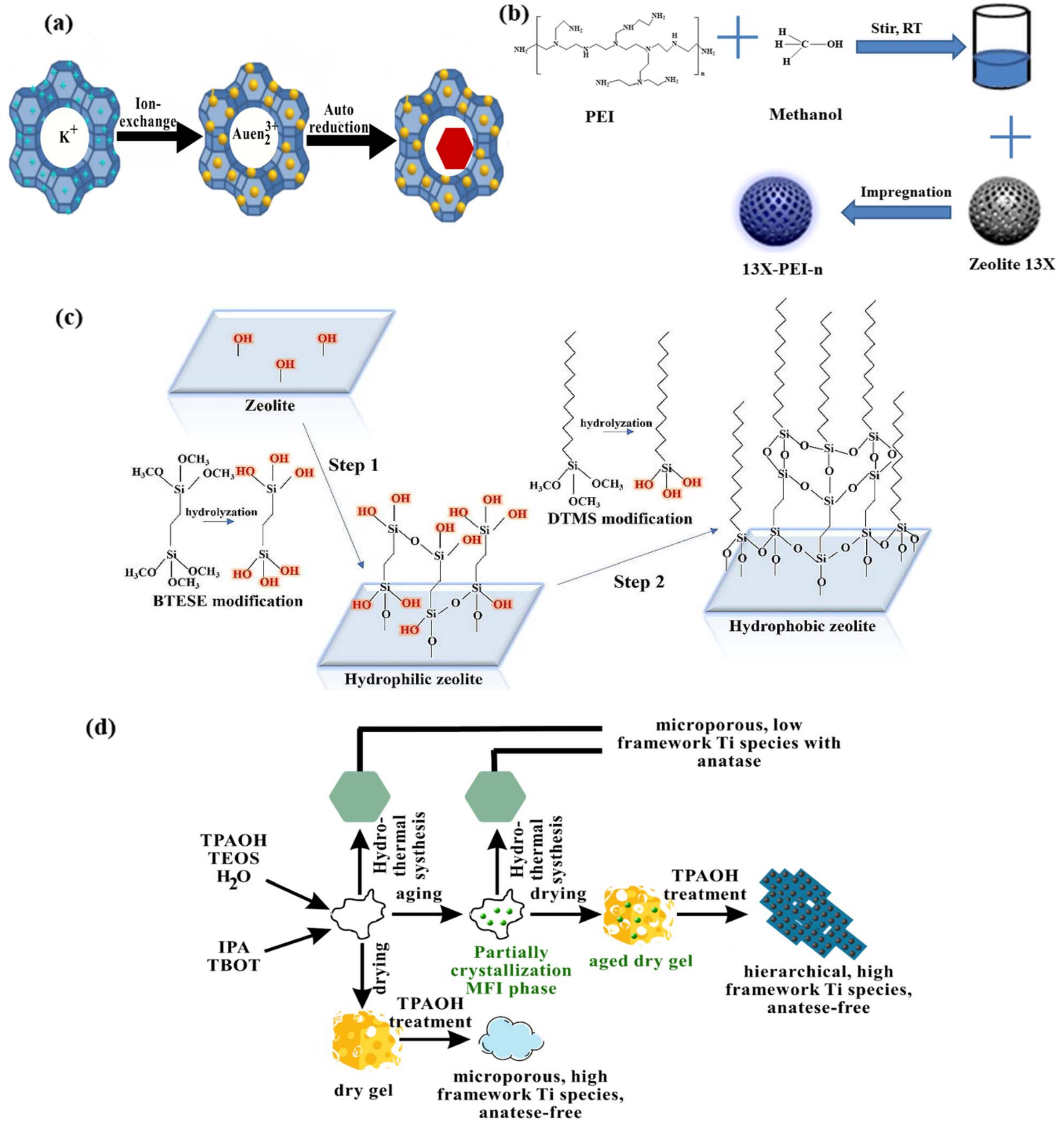


Fig. 5 (a) Ion exchange method of nanoparticle modified zeolite, reproduced from ref. 103 with permission from Elsevier, copyright 2014. (b) Schematic representation of adsorbent preparation by impregnation method, reproduced from ref. 85 with permission from ACS, copyright 2019. (c) Modification strategy for improving surface hydrophobicity of zeolites, reproduced from ref. 104 with permission from Elsevier, copyright 2023. (d) Schematic representation of preparation by hydrothermal method, reproduced from ref. 102 with permission from ACS, copyright 2023.

iron salts ($FeCl_3$ + $FeSO_4$) are added. As a result, magnetic nanoparticle modified zeolites were prepared and have been utilized for the highly efficient adsorption/separation of heavy metals from aqueous environments.[90] In addition, the sol–gel method is a proven way to embed metal nanoparticles at the molecular level in zeolite matrices. It provides exact control over the size, shape, and uniform distribution of the nanoparticles, especially in systems that are rich in silica or alumina.[76,91] The sol–gel procedure is a popular method for creating stable, high-performance nanoparticle-doped zeolites because it maintains structural stability while greatly improving catalytic and adsorption performance, despite being time-consuming obtaining products with desired characteristics[92,93] and sensitive to synthesis conditions.[94]

3.4 Surface functionalization and grafting

Surface-functionalization or grafting are important methods to modify zeolites by incorporating specific organic or inorganic groups on their surface. This enables the nanoparticles to be immobilized and anchored, thereby further improving the property of the material for different uses.[95] Amines, thiols or silanes are the most widely used ligands or chemical anchors for metal or metal oxide nanoparticles.[96] These clusters also play important role on enhancing the interaction of the nanoparticles with zeolite matrix, especially when strong bonding is needed to bridge between catalyst particles and/or sensor-surface.[97]

In surface functionalization, the presence of such groups gives a greater control on the chemistry of the zeolite surface that influence parameters as nanoparticle dispersions, stability and reactivity.[98] For example, surface modification by silane compounds like BTSE and DTMS may change the surface hydrophobicity of zeolites dramatically. It is two steps reaction that the modification with BTSE was first to make hydrophilic sites in the cellulose chains and then DTMS modification to provide hydrophobic sites showed in Fig. 5(c). It is due to this method that more active zeolites are created, which can be used in industry as well as for environmental protection.

Nonetheless, such a method is not without its drawbacks, such as complicate of the synthetic procedure and multiple steps required to obtain homogeneous functionalization. Furthermore, modification of surface properties may not always provide a homogenously distributed nanoparticles that can influence the behaviour of the material.

3.5 Hydrothermal and post-synthetic treatments

Synergistic features few techniques have capability of doping single crystal zeolites with nanoparticles, besides the hydrothermal treatment in common presence of metal salts and nanoparticles is a very effective way, as they eventually lead to hierarchical or mesostructured zeolite formation. This method is useful for loading larger nanoparticles or nanoparticle aggregates into zeolite network, which ultimately intensifies the functionality of the material in different domains.[99] The procedure usually involves controlled temperature, pressure and pH applications for zeolite treatment, where nanoparticles are attached to the surface of zeolite materials.[100] Such flexibility enables users to tune the surface chemistry (*e.g.*, porosity), which is definitely important for a customized material developed for particular application in catalysis, adsorption and sensing.[101]

A clear merit of this method is the high degree of ordered structures and stable nanoparticle loading. As illustrated in the Fig. 5(d), adjusting the hydrothermal activation of zeolites can affort to various levels of crystallinity with nanoparticle, leading to their selective tuning in structure and function. It reveals that the various treatments including different aging and drying processes might develop different products, micro-porous to hierarchical zeolite structures decorated with differing titanium species (Ti) content of the treatment conditions.[102] This technique has been widely employed to impregnate titanium and other metal nanoparticles, boosting the catalytic activities of zeolites. Moreover, the extent of crystallization and particle size distribution can also be tuned by tuning parameters such as metal salt concentration and hydrothermal process condition for an optimum material performance.

3.6 Vapor phase deposition, encapsulation and core–shell structures techniques

Vapor phase deposition techniques, including chemical and physical vapor deposition (CVD), physical vapor deposition (PVD),[105,106] are innovative methods for depositing nanoscale particles on pure or functionalized zeolites film.[107] They provide precise control over thickness and uniformity, enabling thin, uniform nanoparticle films that impart tailored catalytic, adsorptive, and sensing properties, especially valuable for high-surface-area applications and devices.[108] Moreover, these methods are used to deposit a wide range of materials like metals, metal oxides and polymers that can be customized in order to fulfil specific applications. Nevertheless, the two main limitations of these techniques are the high costs and sophisticated equipment, which impedes their general use for most high-end industries and research areas. Furthermore, these processes are generally complicated and turnkey temperature control, pressure conditions and precursor compositions can be necessary limiting the applicability in large scale or mass production. Although vapor phase deposition is a viable option to prepare state of the art nanoparticle-doped zeolites, its cost and technical requirements restrict its use to selected high-end applications.

In parallel, encapsulation techniques are a more sophisticated approach of zeolites modification, whereby the nanoparticles are incorporated inside the framework of an existing zeolite or in a core–shell morphology where nanoparticles constitute the core and amorphous zeolite is the shell.[109] This configuration has a number of merits such as improved thermal and chemical stability, the prevention of nanoparticle leaching during growth process, and the inhibition of nanoparticle agglomeration.[110] These advantages render encapsulated nanoparticle-ZL composites as highly attractive in catalysis and biology, where long-term stability and triggered release become indispensable. It can, for example be used as a stabilizing shell on the nanoparticle core in catalytic processes to stabilize and prevent sintering and/or degradation of the nanoparticles such that this activity is preserved over lengthy periods.[111] The application of nanoparticles inside the zeolite matrix opens a new era in materials science, providing opportunities for multifunctional systems capable to play different roles in distinct disciplines ranging from energy conversion, pollution treatment to drug delivery.[112,113] The choice of a suitable modification process is critical and will be influenced by several parameters such as the desired final physicochemical properties, the size of particles, the host nanoparticles position (inside or outside sterile), the goal application and scale-up of the treatment.[114] Hybrid modification approaches are attracting more attentions with the development of the research. These techniques include using surface functionalization with *in situ* methods of growth that are expected to allow the fabrication of next generation nanoparticles–zeolite composites that will be able to provide improved properties.[112,115] These advanced materials are aimed to address future technological and environmental challenges with enhanced performances in a variety of breakthrough applications.[116]

4 Application of nanoparticle-doped/modified zeolites

Nanoparticle-modified zeolites have garnered significant attention across diverse scientific and industrial fields due to the synergistic combination of the intrinsic properties of zeolites with the unique physicochemical characteristics of nanoparticles. Zeolite has a crystalline aluminosilicate structure, and it presents the advantage of high regular micropore system, ion-exchange capacity, thermal stability and molecular sieving properties,[43] these characteristics make it suitable for many applications. On their own, these composite materials offer multiple advantages (compared with Parental polymers) due to high surface-area, exceptional porosity and tunable surface chemistry; and when compounded or functionalized using nanoparticles such as metals (*e.g.* silver, gold and iron), metal oxides (*e.g.* TiO_2, ZnO) or carbon-based nanomaterials.[117] This character is beneficial for spl vehicle, pollutant adsorption and other special area.

These nanoparticle-modified zeolites may also have their electric and optical properties tuned to react to external stimuli like pH, light (*e.g.*, UV), or magnetic fields, as such becoming multifunctional systems.[118] Their fouling or deactivation resistance allows for application in more severe industrial conditions, broadening their potential applications.[119,120] For instance, the modified zeolites proved to be very efficient in removing heavy metals, dyes and organic pollutants as well.[121,122] In the bio-medical area, zeolites containing nanoparticles *e.g.* silver, copper or zinc show promising antimicrobial activity which is resistant toward MRSA. In the area of pharmaceuticals, they function as novel drug carriers providing controlled release and greater efficacy at lower toxicity. Furthermore, in catalysis, there are also nanoparticle-encapsulated zeolites like Ni-decorated zeolite; they have been shown to greatly promote CO_2 methanation for renewable energy applications.[123] Gold nanoparticle assembled zeolites are also good supports for enzyme immobilization and the resultant bio-catalysts present reusability and stability in bio-catalysis.[124] The broad applications of nanoparticle-modified zeolites exemplify their significant contribution to environmental sustainability, healthcare and industrial catalysis.

The Fig. 6 shows how nanoparticle-modified zeolites can be used for a variety of purposes, from energy, gas separation, and catalysis to biomedical applications like antibacterial surfaces and drug delivery. This is supplemented by Table 3, which summarizes these applications and highlights their versatility, effectiveness, and potential in the industrial, healthcare, and environmental domains.

4.1 Water treatment

Nanoparticle-modified zeolite has been proven to facilitate water treatment through their improved adsorption,[125] catalytic,[132] and ion exchange capability.[133] The embedding of nanoparticles in the zeolite framework greatly enhances their capability to eliminate a plethora of pollutants, rendering them suitable for highly efficient water purification applications. An outstanding application of such materials is in the area of wastewater treatment, zeolites modified with nanoparticles like TiO_2 and Fe_3O_4 have demonstrated excellent adsorption/photocatalytic–degradation activity. They demonstrate excellent performance in degrading dyes and heavy metals (such as Pb^{2+}

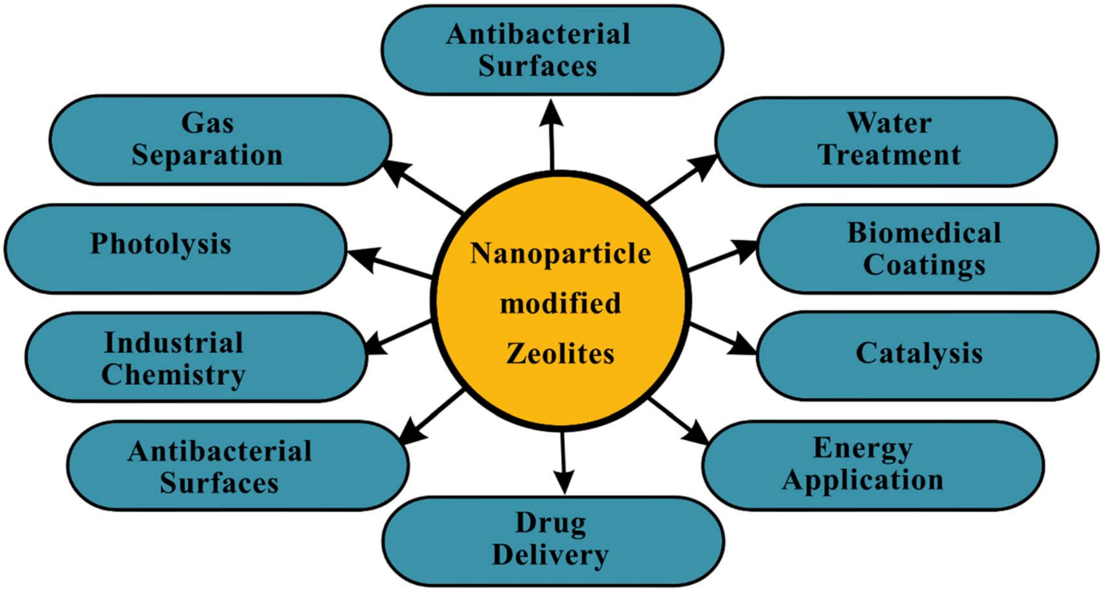
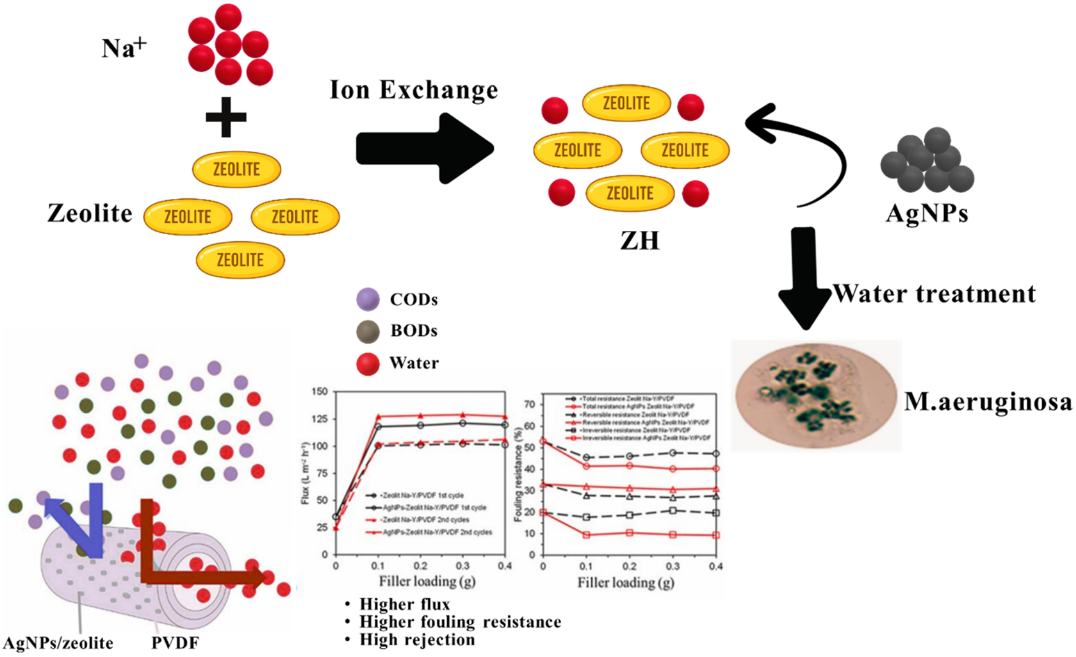


Fig. 6 Key application of nanoparticle modified zeolite.

Table 3 Application of nanoparticle modified zeolites

Application area	Description & function	Ref.
Water treatment	Nanoparticle-modified zeolites (*e.g.*, Ag, Fe, TiO_2) act as adsorbents and photocatalysts for pollutants like dyes, heavy metals, and organic toxins	125
Antibacterial surfaces	Silver nanoparticles embedded in zeolites show strong bactericidal effects against *E. coli*, *S. aureus*, and multidrug-resistant strains	126
Catalysis	Metal nanoparticle-loaded are widely as catalyst in petrochemical refining, green synthesis; hydrogenation and C_1 chemistry	127
Drug delivery	Zeolite-based nanoparticles offer pH-responsive, controlled-release drug delivery for antibiotics, anticancer drugs, and vaccines	128
Photocatalysis	TiO_2–zeolite nanocomposites are efficient under UV light for degradation of pollutants like dyes and pharmaceuticals in wastewater	129
Environmental sensors	Modified zeolites can detect gases (*e.g.*, NO_2, CO) due to changes in conductivity or fluorescence when interacting with nanoparticle surfaces	130
Biomedical coatings	Zeolite nanoparticles functionalized with bioactive agents serve in dental and orthopedic implants for long-term antimicrobial effects	131

and Cr^{6+}) from aqueous solution, offering green alternative materials for advanced water treatment.[134] As a natural material, halloysite and zeolites are potential materials for adsorbing pollutants because they possess the microporous structure and three-dimensional interconnected channel system. Their negatively charged structure and ion-exchange characteristic improve their ability to adsorb pollutants. Numerous industrial processes, such as fuel production, metallurgy and processing of metal surfaces, produce materials with heavy metals in them that are disposed into the natural environment without being properly treated and thus create a serious risk for human health and at the same time threaten ecosystems.[135] Heavy metals, including Pb, Cd and Cr are non-bio-degradable and can be deposited in aquatic systems posing a long-term environmental risk.[136] Nanoparticles (*e.g.* iron oxide) embedded in zeolites enhance the heavy metal ion adsorption more efficiently due to increased nanoparticle–interface interaction.[12] The surface area rises and it creates active sites for the interaction with metal ions which lead to the high adsorption capacity.[137] It has already been shown in experimental work that zeolites with nanoparticle modification are especially more successful for removing heavy metals than traditional zeolites. The integration of nanotechnology and two-dimensional nanoparticles having very high surface-to-volume ratios greatly enhances resource utilization and advances water purification and monitoring.[138]



- **Higher flux**
- **Higher fouling resistance**
- **High rejection**

Fig. 7 Schematic of AgNPs/zeolite composites for water treatment, highlighting ion exchange and antibacterial properties, along with filtration performance showing improved flux, fouling resistance, and high contaminant rejection, reproduced from ref. 139 with permission from Elsevier, copyright 2023.

Some factors that can lead to sharing of teeth number incorporation of nanoparticles, like silver (AgNPs), on the zeolite structure endow them with improved adsorption and catalytic properties, then makes best use for water treatment. For example, AgNPs–zeolite composites show the high removal efficiency of contaminants such as heavy metals and organic pollutants, in addition to their antibacterial action which results in a successful water treatment. Modification of zeolite by nanoparticles like silver increases fouling resistance and filtration efficiency as it can be seen in the figures, by the improvement of flux and better recovery of membrane in case fouled. These superior properties impart an enhanced performance of the composites during water purification, which can be further optimized when used with PVDF membranes as filters. Additionally, the zeolites modified with NPs display good rejection for organic contaminants and thus can be a promising candidate for wastewater treatment.[139] Ion exchange processes occur in zeolite nanoparticles as shown in the Fig. 7, compounds up on such acts to increase their toxic waste extraction capability of materials for example Pb^{2+} and Cr^{6+} from water solutions. This makes them extremely effective for industrial wastewater treatment. These composites also have the antibacterial capacity which has an additional advantage in destroying a hazardous microorganism *M. aeruginosa* and thus increasing water safety.[140] As awareness of heavy metal contaminations increases, particularly from industrial and municipal effluents, zeolite modified nanoparticles have become a compelling remediation approach. Further development of such materials is expected and they will be used in the next generation of water treatment devices solving worldwide problem of clean drinking water. This will be of great importance to enhance water availability and safety globally, particularly in those regions with severe water quality problems.

4.2 Antibacterial surfaces application

Taking full advantage of the dual benefits that an ion exchangeable zeolite framework offers and inherent antimicrobial properties inbuilt from confined nanophases, NPZPs exhibit exceptional promise as durable antibacterial coatings.[141] The regular, crystalline and porous architectures of the prevalent zeolites-A/NAA, FAU-type X and Y (including K-X and NH_4-Y), EMT (IZA #7), natural clinoptilolite as well as MFI/ZSM-5 serve to stabilise guests while at the same time acting as dealers in a vast array of biocidal agents. Ag^+/Ag^0, Cu^{2+}/CuO, Zn^{2+}, TiO_2 and ferrite phases such as $CuFe_2O_4$ anchored inside cages, channels or on the external facets can be released in

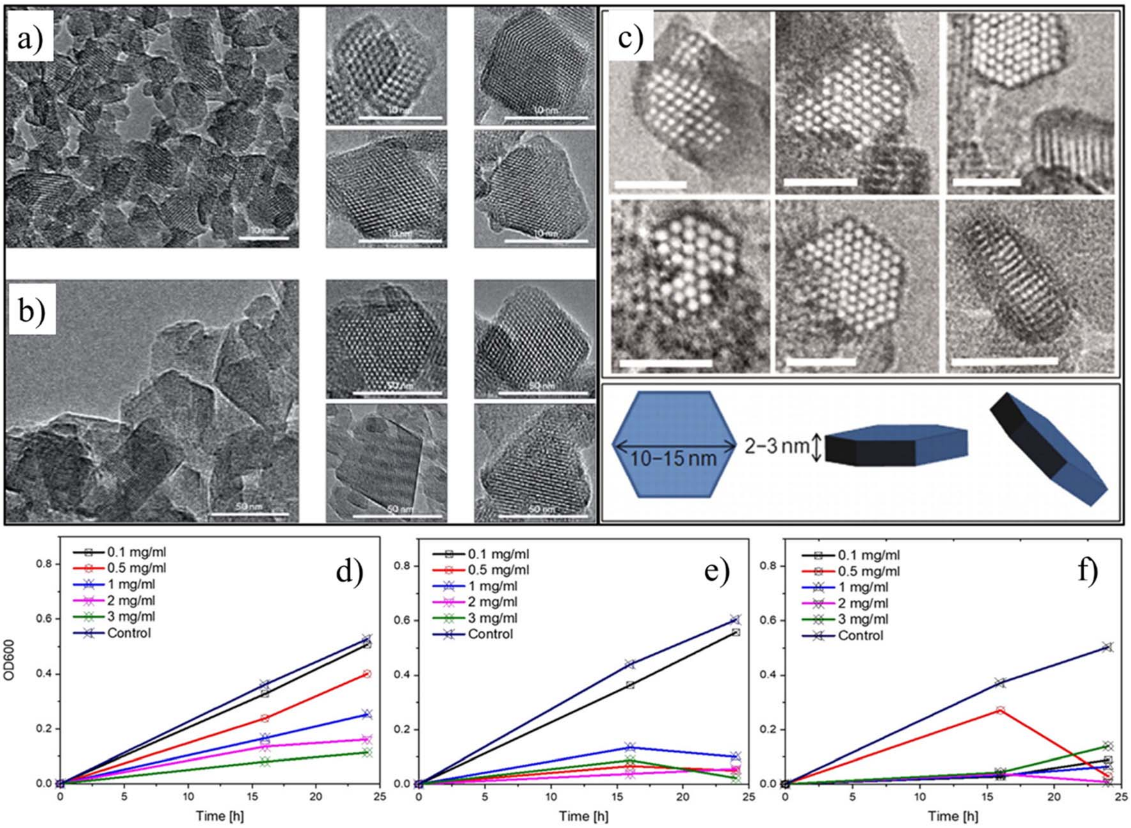


Fig. 8 High-magnification pictures of individual nanocrystals are displayed in the insets of TEM micrographs of FAU-type nanosized zeolites, Y-10 (9 nm) (a) and Y-70 (38 nm) (b). The Mintova group demonstrated the synthesis of ultrasmall EMT zeolites under mild conditions by obtaining an ultrasmall EMT-type zeolite from a template-free precursor suspension at 30 °C for 36 hours. (c). The antimicrobial activity of the following materials against *Staphylococcus aureus* is shown in terms of optical density at 16 and 24 hours: (d) Y-zeolite, (e) Ag/CBV-600, and (f) Zn/CBV-600, reproduced from ref. 143 and 146 with permission from Elsevier & ACS, copyright 2023 & 2024.

a slow controlled way that extends efficacy while minimizing systemic toxicity or *via in situ* formation.[142] The microstructural origin of this performance is apparent in the TEM overview shown in Fig. 8(a–c) in which dense fields of platelike crystallites with long range lattice order can be recognized; HRTEM panels show that periodic pores arrays, which confine nanoparticles to some nano-meter precision, are embedded at these crystallite surfaces-for a platelet dimension being 10–15 nm laterally and 2–3 nm thickness as seen on the inset drawing, most likely depicting hexagonal pores-corresponding to maximized surface *versus* volume ratios supporting short ion diffusion paths; anion framework integrity remains unaffected by such nanoparticle confinement.[143,144] These above nanoarchitectures lead directly to function. Among controlled release treatments, Ag-exchanged EMT or FAU (X) zeolites in water treatment architecture offer a textbook example: Ag^+ migrates from a framework to an interface microbial surface, absorbs at cellular envelopes, then crosses their wall and complexes thiol-rich enzymes to snap-condense nucleic acids until replication becomes impossible; meanwhile the loaded cages play the role of long-lived precursors trapped inside of them that will replenish this asuded-up ion under oxidative stimuli, further fin-stabilizing profile delivery shapes with shorter bact growth risk between services.[145] In keeping with this mechanism, the growth-kinetics Fig. 8(d–f) show a clear dose-dependant suppression of turbidity compared to the untreated control-such that even at sub-mg mL^{-1} loading the slope of the optical-density trace is notably shallower, and at 2–3 mg mL^{-1} growth is essentially halted over 24 h operational windows which intersect practical contact times in recirculating filters as well as point-of-use cartridges.[146] Copper-modified zeolites complete this playbook with an alternative oxidative pathway. Cu^{2+}/CuO stabilization on FAU-type supports: copper ions and surface redox couples catalyze generation of reactive oxygen species (ROS) at the cell interface; ROS cause lipid peroxidation, protein oxidation, nucleic-acid damage, and Cu^{2+} coordination inhibits essential metalloenzymes. In addition, these Cu-NPZPs are still effective against both Gram-positive and Gram-negative strains (including clinically significant ESKAPE strains), appealing for application in hospital touch-surfaces, HVAC filters, and high turn-over public infrastructural surfaces where broad spectrum effectiveness is critical.[147] Other low toxicity alternatives may be zinc–clinoptilolite systems, especially where there are regulatory restrictions for silver. Clinoptilolite-resident Zn^{2+} depolarizes pathogenic *H. pyloriand*, *V. cholerae* membranes and disrupts ion homeostasis, but zinc is also inert in the environment and safe for direct human consumption, making it applicable for deployments lasting years or even decades in environmental remediation, aquaculture, or potable-water polishing. TiO_2/ZnO dispersed in 4A or ZSM-5 matrices can produce ROS under ambient or UV-A illumination, causing photocatalytic sterilization that is active against *Listeria monocytogenes*, *Pseudomonas aeruginosa*, *E. coli* and *Staphylococcus aureus*.[148] When compared to undoped ZnO and Ag/ZnO nanoparticles alone, zeolite-supported Ag/ZnO nanoparticles show much higher antibacterial activity. Zeolite increases efficacy, especially against Gram-positive bacteria like *S. aureus*, but ZnO and Ag/ZnO exhibit limited effects. Higher doses do not significantly increase antibacterial activity, indicating effective suppression even at lower concentrations. All of the nanoparticles, which were created using precipitation and incipient wetness impregnation techniques, retain their hexagonal wurtzite crystalline structure. According to the study, zeolite-supported Ag/ZnO composites are prospective antibacterial agents that might be further morphologically and surface characterized, optimized, and evaluated against various bacterial and fungal strains.[149] Here, the zeolite does more than prevent agglomeration of NPs, which in turn preserves active surface but instead it also modulates the interfacial charge environment that increases photogenerated radical lifetimes and their directionality to adhered cells or biofilms. The same conceptual logic can be applied to reusability and sustainability. Bead or film formed composites as Ag- or Cu-zeolite@alginate are an example of the combination of microbicidal activity from inorganic part and biopolymer malleability and soft conditions. Such constructs can be cycled which minimal deterioration of activity, thus reducing waste streams and overall cost to own in high volume process.[148] For bedside or machine coating applications, ferrite-supported zeolites ($CuFe_2O_4$ on FAU or EMT) offer two additional advantages: magnetic recoverability for fast retrieval from treated fluids and excellent mechanical dispersion in polymer matrices. Realization into practice $CuFe_2O_4$-NPZPs consistently realize ∼98% kill of *E. coli* in batch tests, and repeat the performance for at least seven regeneration cycles making them particularly suitable for wound dressings, catheter coating or rinse-off surgical instruments where repeatability of efficacy and easy cleaning is critical.[146] Apart from the laboratory numbers, the numbers point to practical design cues. The regularly arranged bright/dark contrasts in the high-resolution images correspond to well-registered nanoparticle arrays or pore channels – signs of a synthesis that affords narrow size distributions and intimate host–guest contact (both factors are expected to sharpen release kinetics and reassure against any "burst-and-fade" profile characterizing loosely suspended colloids). In the meantime, growth curves of bacteria do give not just direct dose response but clear "knee" point's likely indicating sweet spots for formulations that allow us to hit minimum inhibitory concentrations without wasting material or causing cytotoxicity in sensitive environments (*e.g.*, films meant for food contact).[150] Together, these data illustrate why NPZPs perform so well in the context of diverse applications: as a food-packaging additive they inhibit biofilm formation on moist surfaces; when coated onto medical devices or suture material they deliver on-contact prophylaxis; within wound dressings they retain a local microbicidal field that does not impede re-epithelialization; and as part of potable-water systems they serve both shielding and absorbent functions-adsorbing endotoxins while dispensing a controlled stream of ions that sterilize elapsing microbes. Equally critical, the zeolite scaffold inhibits resistance by avoiding sublethal, pulsatile events; instead cells are subjected to a constant hostile micro-environment that would prevent adaptive responses.[143]

Last, the built-in bay for comparing silver- and zinc-exchanged Y-zeolites was that no one should doubt these zeolitic ion exchange products signed a document of performance: base zeolites themselves exhibit by strictly physical means modest bacteriostasis through adsorption and pH/ionic considerations, but judicious loading with Ag^+ or Zn^{2+} raises killing power by orders of magnitude at room temperature in a way convenient to control, wash away and last. With resistance mounting, the zeolite-embedded nanoparticle microrockets provide an industry-scalable, regulatory-compliant platform-one that combines defined microstructure, predictable kinetics and broad-spectrum biological impact-establishing NPZPs as a foundational technology for future antibacterial surfaces in healthcare, agriculture and drinking supply.

4.3 Catalysis application

Zeolites modified with nanoparticles are shown to be high utility catalysts in both heterogeneous and functional catalysis. These classes of catalysts comprising zeolites in association with redox metal nanoparticles bear crucial advantages because they hold superior physicochemical properties like high surface area, tunable porosity, good thermal stability, and ion-exchange facilities. For catalytic applications, turnover frequency and conversion efficiency are now discussed to better reflect catalytic performance. To improve the redox and acid–base character of zeolite catalysts, NPZs are prepared using metal NPs including Pt, Pd, Au, Cu, Ni as well as transition metal oxides such as TiO_2, ZnO and Fe_3O_4. These metal nanoparticles are incorporated in zeolite structures such as ZSM-5, Y, Beta, Mordenite and SAPO-34.[151] Hybrid NPZ in which metal NPs and zeolite frameworks are assembled, have been widely studied for catalysis of petrochemical reactions (hydrocracking, isomerization and alkylation), biomass conversion (catalytic pyrolysis and hydrodeoxygenation), environmental remediation (catalytic oxidation of volatile organic compounds and reduction of NO_x) or energy application (water splitting, fuel cell or CO_2

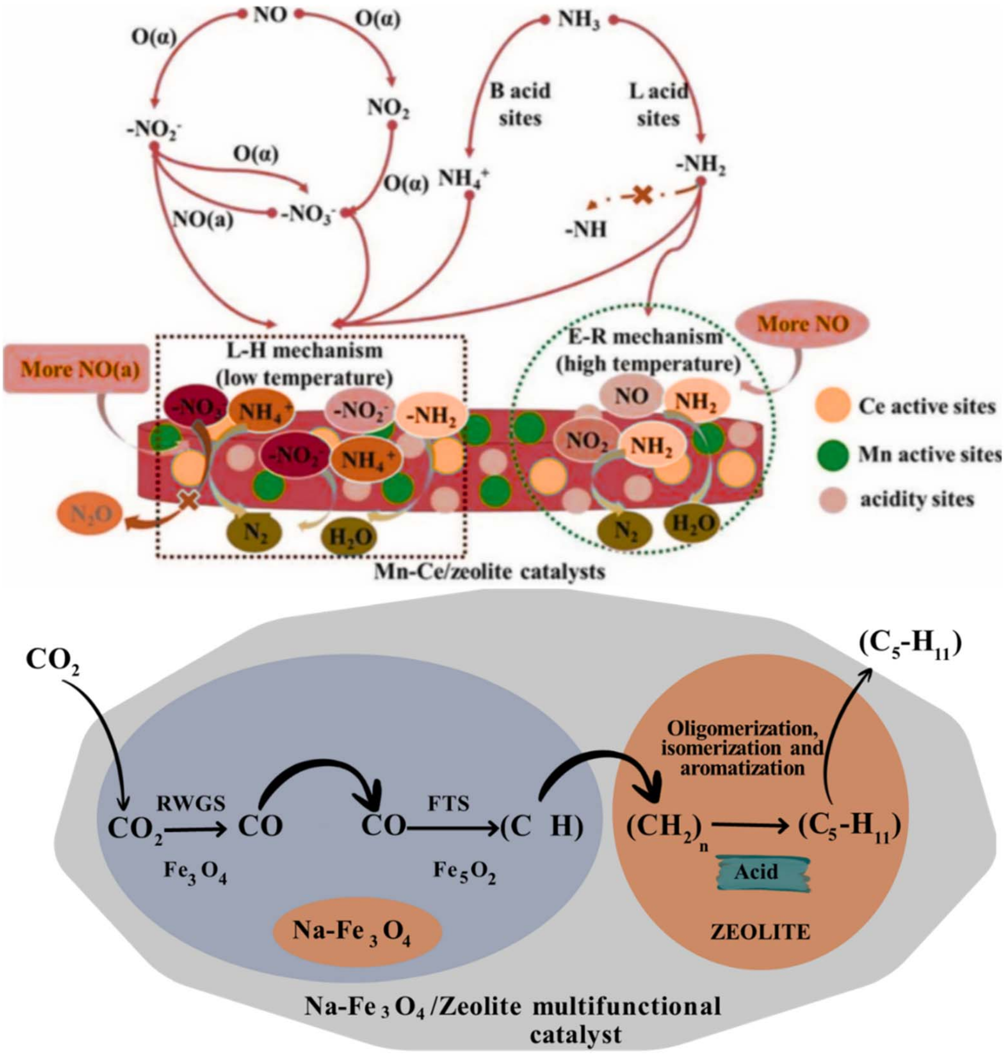


Fig. 9 Different zeolite supports and their catalytic performance over Mn–Ce catalysts for NH_3-SCR of NO at low temperatures. New uses for zeolites in host–guest assembly, separation, and catalysis, reproduced from ref. 113 and 163 with permission from Springer Nature & Elsevier, copyright 2021 & 2022.

hydrogenation).[152,153] For example, Pt/ZSM-5 catalysts show excellent naphtha reforming catalytic activity and coking resistance, while Ni-modified zeolites are efficient in hydrogenation reactions for bio-oils and syngas.[154,155] It has been reported that the interaction between metal nanoparticles and zeolite acidity is key to selective product formation as well as overall reaction pathways. Another example for catalytic oxidation, MTBE oxidation by H_2O_2 using Fe-ZSM5 and Fe-Beta zeolites at pH 7. MTBE degradation followed pseudo-first-order kinetics, with Fe-ZSM5 showing higher activity. Fe-Beta utilized H_2O_2 more efficiently due to stronger adsorption. Intermediates, including *tert*-butyl alcohol and *tert*-butyl formate, were also analyzed, confirming Fe-zeolites' catalytic potential.[156] Notably, by spatial confinement of metal nanoparticles inside zeolites their agglomeration and sintering at high temperatures can be prevented and catalytic lifetimes severely extended. Moreover, zeolite-stabilized metal nanoparticles are important in the context of cascade reactions and tandem catalysis, which demands both acidic and redox sites. Recent progress has been shown on hierarchical zeolites and mesoporous hybrid sets, enabling the alleviation of limitations in diffusion and facilitating access to reactants. The versatile properties and tunability of nanoparticle-decorated zeolites render them the candidate as new generation sustainable catalysts for fine chemical synthesis, green fuels and environmental protection. The position of metal species in zeolites can be classified into four types: (a) metal species supported on the outer surface of zeolite crystals; (b) metal species trapped inside the crystal, such as within the framework of zeolites, micropores cages and mesopores; (c) metal species confined in the hollow cavities of zeolite and (d) dispersed mixed with zeolite. The movement and collecting of metal species may occur in processes such as the calcining, the reducing process, and the catalytic process especially when adopting supported ions on external surface of zeolites. Nevertheless, by trapping the metal species in zeolite crystals or in cavities, we can ensure better metal stability.[157] These design techniques, along with adjustable redox and acid–base characteristics, highlight NPZs as next-generation sustainable catalysts with high turnover frequencies, enhanced conversion efficiency, and widespread use in environmental protection, green fuels, and precision chemical synthesis.

As for the preparation method, impregnation and ion-exchange methods have frequently been employed to prepare metal catalysts supported by zeolite. But, those processes easily result in the metal particles of a large size and with an uneven dispersibility, to make their catalytic activity and stability low.[158] Recent developments of synthesis strategies, including the ligand protected approach, metal-containing-seed directed synthesis and the impregnation–dissolution–recrystallization method have largely enhanced the dispersion of metal species in zeolite crystals. These methods also improve the confinement of metal nanoparticles which have implications in terms of catalytic activity, stability and shape selectivity. For instance, as shown in recent studies of Mn–Ce/zeolite catalysts used for NO_x reduction, the catalysis mechanisms and reaction pathways are manipulated by metal specie–zeolite interaction and by zeolite acidity.[159] In this example, NO_x reduction is achieved *via* the L–H reaction mechanism at low temperatures and the E–R reaction mechanism at high temperatures. Such a heterogeneous catalyst system demonstrates flexibility of zeolite-supported metal-based catalysts in various catalytic processes. ZSM-5 supported metal catalysts have received extensive interest in a wide range of catalytic systems such as C_1 chemistry, chemical hydrogen storage and biomass conversion.[160] In the past five years, a series of advances have been made in use of zeolite-supported metal catalysts for co hydrogenation, CO_2 hydrogenation, dehydrogenation, oxidation and selective catalytic reduction of no with NH_3.[161] These catalysts show high converting capability, good selectivity toward desired products and very good stability, being ready for the industrial use. For example, as can be seen in the accompanying figures, if Fe_3O_4 based catalysts are utilized for CO_2 hydrogenation and I\NO_x reduction, high effectiveness and selective product formation along with better stability can be achieved as shown in Fig. 9. These results highlight the feasibility of metal nanoparticle-supported zeolite catalysts for advancing environmentally friendly chemical processes. In the long run, the consumption of chemical industry, energy and environmental protection fields' demands zeolite-supported metal catalyst at will. Further development in the synthesis, characterization and utilization of such catalysts will be an important tool for overcoming current challenges and increasing the sustainability of industrial processes.[162]

4.4 CO_2 capture and photocatalysis application

Through synergistic modulation of pore architecture and surface chemistry, nanoparticle-modified zeolites constitute a flexible and high-performing class of functional materials that successfully combine CO_2 collection and photocatalytic environmental remediation. Ion exchange, amine functionalization, mobile cation incorporation, and nitrogen activation are examples of post-synthetic modifications that are essential for modifying the surface characteristics and active sites of zeolites in CO_2 capture applications. This results in significantly increased CO_2/N_2 selectivity and adsorption capacity. These materials' improved performance results from the synergistic improvement of surface chemistry and pore architecture, which together facilitate effective interaction between CO_2 molecules and the adsorbent framework. On zeolites modified by nanoparticles, CO_2 adsorption occurs *via* both physisorption and chemisorption processes.[164] Physisorption is driven by weak van der Waals forces, enabling CO_2 molecules to reversibly adsorb onto the zeolite surface and, under low-temperature conditions, form multilayer adsorption. This mechanism is strongly influenced by textural and structural properties such as pore size distribution, surface area, and the presence of exchangeable extra-framework cations, which induce local basicity and electrostatic fields that enhance CO_2 affinity. In contrast, chemisorption involves the formation of strong chemical bonds between CO_2 molecules and specific active sites on the modified zeolite surface, typically leading to monolayer adsorption with limited reversibility. Surface modifications-most notably amine

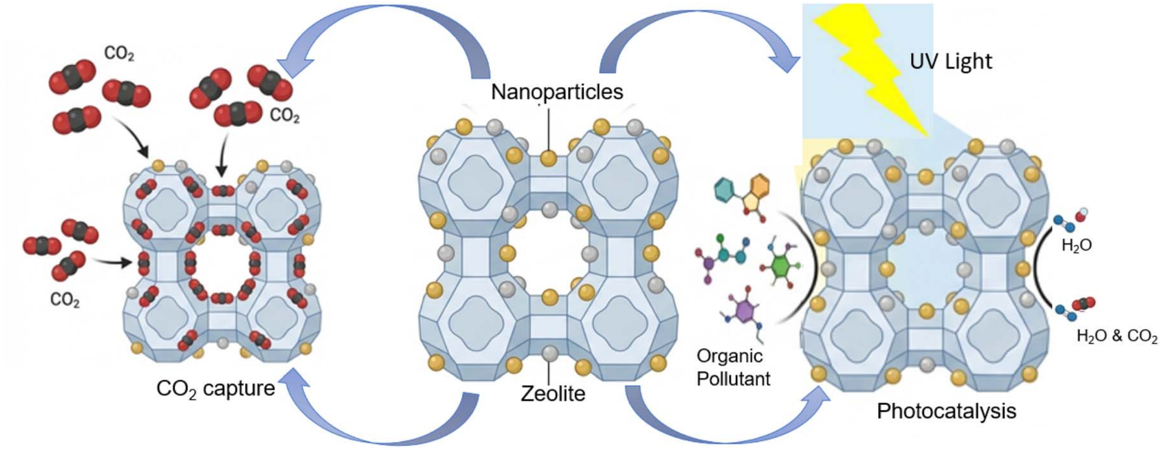


Fig. 10 CO_2 capture and photocatalysis application for modified zeolite, reproduced from ref. 173 and 174 with permission from Elsevier, copyright 2020 & 2024.

functionalization-facilitate chemisorption through carbamate formation, thereby increasing adsorption capacity and selectivity, albeit at the cost of higher regeneration energy requirements. The relative dominance of physisorption and chemisorption is highly dependent on operating conditions such as temperature, pressure, and the presence of competing species like water vapor. Understanding this mechanistic interplay is crucial for the rational design and optimization of efficient nanoparticle-modified zeolite materials for CO_2 capture applications.[165,166]

Quantitatively, under temperature swing adsorption conditions, nano-zeolites show a strong preferred affinity for CO_2 with a CO_2/N_2 selectivity of 18.65 (IAST) and a high CO_2 adsorption capacity of 4.81 mmol g^{-1} at 20 °C and 1 atm. Significantly, over 88% CO_2 removal is sustained across 10 adsorption–desorption cycles, demonstrating high regenerability and proving structural and functional stability.[167] When compared to pure zeolite materials, these findings demonstrate their potential for large-scale, sustainable carbon collection.

Zeolite-supported nanoparticles have become extremely successful photocatalysts for wastewater treatment, especially for the breakdown of colors and pharmaceutical pollutants, in addition to gas separation. Zeolites' inherent qualities-such as their large surface area, ion-exchange capacity, and adjustable porosity-make them perfect hosts for photocatalytic nanoparticles, guaranteeing better recyclability, reduced agglomeration, and increased dispersion. When it comes to visible light-driven photocatalysis, composite systems like zeolites loaded with Ag_2O or TiO_2 function better than unsupported nanoparticles.[168,169] Zeolite@Ag_2O nanocomposites, in particular, exhibit almost total Rhodamine B degradation under visible light, which is explained by effective charge carrier separation, the production of reactive oxygen species, and robust interfacial contacts that prevent electron–hole recombination is showed in Fig. 10.[170,171] Effective destruction of resistant dyes was made possible by highly oxidizing ROS, and photocatalytic activity was increased by the close zeolite–Ag_2O contact, which inhibited charge recombination.[170,172] Uniform Ag_2O deposition was verified by SEM studies.[173,174] The Zeolite@Ag_2O composite demonstrated little silver ion release, outstanding stability, and recyclability, making it appropriate for real-world wastewater treatment applications.[175,176]

Zeolite@Ag_2O nanocomposites serve as adaptable platforms for eliminating other organic contaminants under visible light, in addition to RhB degradation. Zeolites stabilize scattered Ag_2O nanoparticles, improve adsorption, and speed up reaction kinetics. These composites are effective, energy-efficient, and versatile for advanced wastewater cleanup due to their ion-exchange capability, which permits variable catalytic activity.[177] For example, new designs may incorporate bimetallic (oxy) oxides or plasmonic nanoparticles to widen the visible-light response and increase the suppression of electron–hole recombination. These approaches would broaden the applicability of zeolite-supported photocatalysts for treatment of more complex industrial effluents.[170,178] To conclude a combination between the adsorption and photocatalytic degradation in an integrated, structurally robust architecture as photocatalysis of nanoparticle-modified zeolites is seen as a highly promising perspective. Systems such as Zeolite@Ag_2O illustrate how the interplay between the porous zeolite host and the photocatalytic nanoparticles overcomes inherent limitations associated with materials on their own, providing enhanced performance in terms of efficiency, recyclability and eco-benignness. Not only such advancements provide a promising practical solution for applications in waste water remediation industries including textiles, pharmaceuticals, and dyes but they also pave the way for the future hybrid systems in green chemistry and sustainable environmental engineering.[179] Furthermore, leaching is avoided and long-term operational stability and environmental safety are guaranteed by the strong immobilization of nanoparticles within the zeolite framework. When combined, adsorption-driven CO_2 capture and photocatalytic degradation within nanoparticle-modified zeolites offer a viable and sustainable approach to wastewater remediation and carbon management, with great potential for future developments in green chemistry and environmental engineering.

4.5 Drug delivery application

Zeolites have received a great deal of interest in biomedical science over the last few years as universal nanocarriers for drug molecules, especially for controlled and targeted delivery. Their clear microporous and mesoporous structures, large surface area, controllable pore sizes distribution, and high framework stability render them more competitive than a lot of traditional carriers.[180] In addition, zeolite nanoparticles present chemical stability, ion-exchange capability and biocompatibility that permit the encapsulation, protection and slow release of a variety of drugs. Synthetic (*e.g.*, ZSM-5, NaX, Y and LTA) and natural (clinoptilolite) zeolites have been nanosized for delivery of small-molecule chemotherapeutic drugs, antibiotics and bioactive natural products optimised pharmacologically.[181,182] Proof-of-concept studies were first carried out showing that microporous zeolites like X and Y can enhance the solubility and oral bioavailability of poorly water-soluble drugs such as danazol and ibuprofen by encapsulating them in their crystalline cavities. These systems not only afforded improved dissolution but also sustained release profiles, and a reduction in dosing frequency. Based on this cradle, scientists developed more sophisticated approaches combining zeolites with NPs, polymers and responsive functional groups to obtain multifunctional delivery platforms. For example, zeolite has been combined with magnetic iron oxide nanoparticles for targeting under the magnetic field and persistent luminescent nanoparticles (PLNPs) for imaging-guided therapy and drug delivery.[183] A typical progress is the fabrication of PLNP-embedded ZIF-8 nanocarriers as a vehicle for the anticancer drug doxorubicin (DOX) in Fig. 11. These nanoplatforms demonstrated pH-responsive release of DOX, with accelerated liberation in the acidic microenvironments and real-time imaging of tumors based on luminescence. With loading efficiencies of ∼93% and tumor inhibitory ratios *in vitro*, their therapeutic effectiveness is evident. Phosphonates-conjugated zinc-exchanged zeolite X also showed minimal release of the drug at physiological pH and released about 88% in acidic tumor-like environment during 2 h-release time demonstrating selective and adaptive delivery. These examples highlight how NP modification and ion exchange transform zeolites from merely passive carriers to smart, stimuli-responsive nanodevices.[184]

Zeolites with nanocrystalline size (approx. 50–100 nm) have shown significant interactions with biological systems, as they exhibit excellent cellular uptake and low systemic toxicities. For instance, zeolite nanocrystals have acted as host carrier for inclusion of crocin, a natural generation antioxidant and anticancer agent with improved cytotoxicity profiles and synergistic therapeutic efficacy compared to the free drug in our previous studies. Similarly, clinoptilolite and NaX nanoparticles loaded with graphene oxide or Fe_3O_4 core–shells that were later electrospun into nanofibers provided a dual protection and magnetically controlled release of DOX, achieving both spatial targeting and controlled kinetics. These hybrid frameworks highlight substantial modularity feature of zeolites in the designing of multifunctional drug delivery systems.[186] The polymeric composites also constitute another promising route to modulate the properties of zeolite-based nanocarriers. Immobilization of zeolite nanoparticles in biodegradable or biocompatible polymers like PEG, chitosan and gelatin endows mechanical stability, modifies hydrophilic–hydrophobic balance, as well as controls the rates of release. For instance, PEG/zeolite Y composites, ZSM-5/chitosan system and gelatin–zeolite frameworks have all been investigated to encapsulate

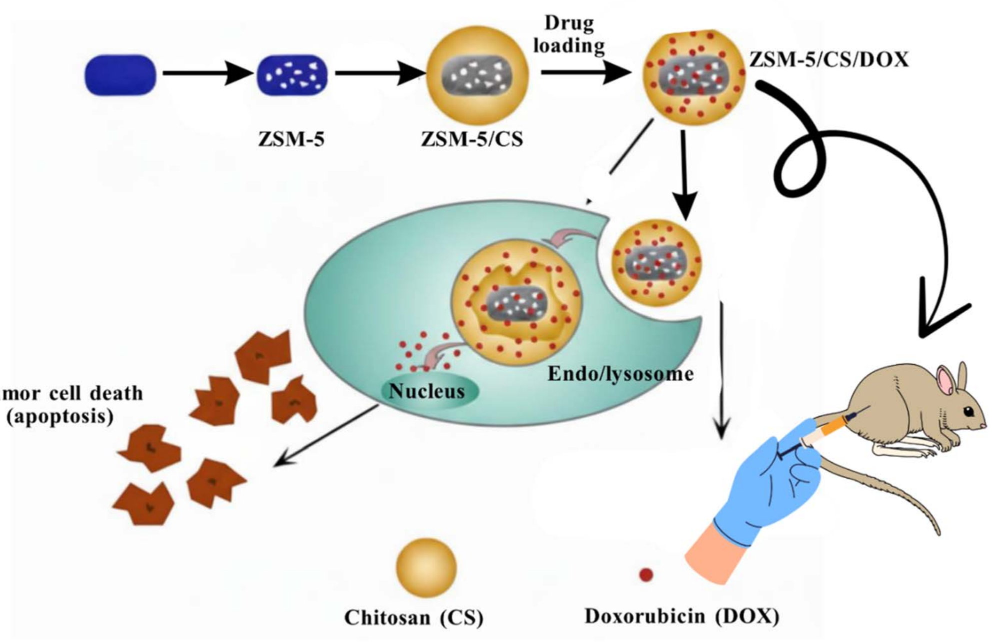


Fig. 11 Drug delivery application for modified zeolite, reproduced from ref. 185 with permission from Elsevier, copyright 2020.

hydrophobic anticancer drugs such as curcumin, paclitaxel and 5-FU.[187] This hybrid platform is useful not only in preventing drug from degradation prematurely, but also offers sustained and pH-dependent releases that would be beneficial for the treatment of tumors possessing an acidic microenvironment. Interestingly, ZSM-5 nano particles reinforced the delivery of paclitaxel to prostate and osteosarcoma cells using PLGA/chitosan matrices with enhanced selectivity and minimized systemic side effects.[188] An exciting application of micronized zeolites is their participation in oral chemotherapy preparations. To treat colon cancer, zeolite A NaX and ZSM-5 were prepared economically from kaoline and their potential use as 5-fluorouracil (5-FU) carriers has recently been investigated. These formulations had high surface areas (up to 578 $m^2 g^{-1}$) and showed dual pH-dependant release, with higher trading in strongly acidic gastric fluids (pH 1.6) than mildly acidic media (pH 5). The high selectivity of drug-loaded zeolites exhibited against colon carcinoma (CaCo-2) cells was compromised without significant toxicity due to the carrier. Given that colorectal cancer is one of the top three leading causes of cancer death worldwide, these low-cost, scalable and efficient drug delivery systems from natural resources are particularly attractive.[189]

Another avenue of recent development concerns hierarchical and mesoporous zeolite systems. Although microporous zeolites have provided proven the utility of delivery systems, they offer low versatility due to poor diffusion for bigger drug molecules. The post-synthetic approach, particularly alkaline desilication, has been applied to create mesopores, as presented in ZSM-5 frameworks.[190] For instance, loading DOX into the pores of porous ZSM-5 yielded a drug loading efficiency of 97.7% with consequent exceptional pH responsiveness.[185] As demonstrated in the schematics, the chitosan shell is protonated on the surface; at physiological pH, the pore inlets are sealed without the possibility of the pre-release. Upon acidification of the medium to the tumor microenvironmental value, the pore mouths become destructed because of barrier deprotonation on the carrier surface. The mechanism ensures cells around the tumor and in other tissues are not targeted beyond the desired range. *In vivo* test with osteosarcoma rats confirmed that the cancerous growth had been significantly suppressed compared to free DOX. Other innovative strategies involve twin-functionality when zeolites are used into luminescent or magnetic nanoparticles. For example, mesoporous ZSM-5 was functionalized with $NaYF_4:Yb^{3+}/Tm^{3+}$ nanocrystals, creating a theranostic platform whereby DOX precinct could be monitored through upconversion luminescence signals.[182] Electrospun nanofibers provide unique characteristics. Dexamethasone loaded in the luminal spaces of polycaprolactone–polyethylene glycol nanofibers with ZSM-5 nanocrystals, a noncovalent assemble role, provided continuous release retaining osteogenic differentiation effect.[191] For all this remarkable progress, there are still some challenges. After syneresis, the post synthetic treatments (*e.g.*, desilication) may however affect stability of zeolite framework under physiological conditions and might lead ti leaching of aluminum or structural breakdown. Thus, future studies should develop optimal pore inducible conditions along with the maintenance of structure. Furthermore, there are few studies about *in vivo* pharmacokinetics, long-term biocompatibility and elimination routes of zeolite nanoparticles compared to more conventional nanocarriers such as liposomes or polymeric nanoparticles. For clinical translocation it will be relevant to solve these issues.[192] Finally, nanoparticle engineered zeolites comprise a new frontier in the field of nanomedicine resulting in modular, multivalent and triggered platforms for targeted and sustained drug delivery to numerous diseases. Through further structural and functional development they are expected to move from proof-of-concept to the clinic as next-generation precision therapeutics.

4.6 Environmental sensors

NP–zeolites are emerging as multifunctional materials for environmental monitoring, exhibiting possibilities to combine adsorption selectivity and catalysis. The microporous crystalline nature, capability for ion exchange and tuning of hydrophilicity/hydrophobicity make zeolites an ideal material to pre-concentrate target analytes at the solid–fluid interface, with concomitant stabilization of catalytically active NPs in an organized high-surface-area framework.[180] This two-in-one function provides NP–zeolites with the opportunities to not only play a role of molecular sieves but also serve as active transducers, therefore realizing seamless integration between selective recognition and sensitive detection in gaseous-and/liquid-phase environments.[193] In gas detection, NP–zeolites often act as both host and sensor. On the other hand, these effect as molecular sieves, precluding interferents and controlling humidity cross-sensitivity to enhance the signal fidelity in practical environment. In addition, the impregnated nanoparticles are acting as a catalytic or recognition sites that generate an amplified response towards environmental and climate relevant gases like nitrogen oxides (NO/NO_2), VOCs, CO_2, methane, and even radioiodine.[194] This partitioning-catalysis synergy couples the shape- and charge-selector properties of the zeolite framework with the redox activity of nanoparticles for enhancing both sensitivity and selectivity. The result is a sensing material with good responses to trace-level toxic gases and excellent stability in complicated atmospheres.

In aqueous medium, and in the case of electrochemical sensing schemes, NP-zeolites serve as a stricty porous host matrix that allows for fast electron transfer process combined with an excellent resistance to fouling of electrode surface. Redox-active nanoparticles (*i.e.*, Fe, Ag, and Co) encapsulated within zeolite hosts can promote the interfacial charge transfer and extend the electrochemical window for the detection of ions, biomolecules, or pharmaceuticals in challenging aqueous samples.[195] A typical case is the Fe(II)-doped nano-zeolite X based carbon paste electrodes (CPEs) for the voltammetric determination of cysteine. The Fe(II)-NX/CPE system exhibited a significantly wider linear range (5.0×10^{-9} to 3.0×10^{-3} mol L^{-1}) and an ultralow detection limit of (1.5×10^{-10} mol L^{-1}) than that for the unmodified electrode. It also transferred the oxidation peak to a more positive potential

Table 4 Comparison of unmodified CPE and Fe(II)–NX modified zeolite CPE for analytical performance, reproduced from ref. 203 with permission from Elsevier, copyright 2015

Parameter	Unmodified CPE	Fe(II)–NX modified zeolite CPE	Analytical performance
Detection range	Not significant	5.0×10^{-9} M to 3.0×10^{-3} M	Broad and sensitive detection range suitable for trace analysis and higher concentration levels
Detection limit (LOD)	Not reported	1.5×10^{-10} M	Extremely low LOD indicates high sensitivity of modified electrode
Oxidation peak shift	No improvement	Shifted to more negative potential	Facilitates easier oxidation, suggesting better electron transfer kinetics
Current response	Low	High and linear	Improved signal intensity ensures reliability in quantitative analysis
Real sample detection	Not applicable	Confirmed in pharmaceutical samples	Demonstrates real-world applicability and validation in complex matrices
Stability & reproducibility	Not tested/reported	Good operational stability and reproducibility	Indicates suitability for routine analytical applications

(≈ -0.27 V) and much greater peak currents were observed.[196,197] With these improvements, a highly sensitive determination of trace cysteine was achieved in pharmaceuticals and biological fluids with good reliability and selectivity. Perhaps most significantly, the enhanced performance did not come at the cost of a deterioration in structure: Na^+ was exchanged with Fe(II) without loss of parent nano-zeolite granular morphology or porosity granting both reproducible access to active sites and stable sensing responses.

Maintaining morphology and textural quality is an important design-rule for NP-zeolite sensors. SEM is commonly used to confirm the dispersion of nanoparticles, crystal shape and film uniformity. SEM data demonstrated the preservation of porous granular structure of Fe(II)–NX in metal loaded state resulting in maintaining accessible surface area and reproducible response among sensors. Guaranteeing stability of the structure during modification is especially important for the reproducibility because nonuniform nanoparticle distribution, or pore collapse can cause substantial differences in analytical performance.[198] In addition to single-metal replacements, hybrid NP-zeolite composites combining conductive nanocarbons have emerged as a trend. These materials possess not only the permselectivity and absorption ability of zeolites but also the good conductivity and huge surface area of carbon nanostructures. Such as Ni^{+2}-exchanged clinoptilolite with carbon black (CB) modified glassy carbon electrodes (NiZCB-GCE) for the voltammetric determination of vitamin B_6 (VB_6) is a recent one. Structural analysis demonstrated the presence of clinoptilolite as the main phase, with CB-doping resulting in a significant increase in surface area ($S_{BET} \approx 1133$ m^2 g^{-1} *versus* $\approx$ 15.7 m^2 g^{-1} for zeolite).[199] These interferences resulted in a stable baseline, lower background noise and an increased redox signal intensity.

Experimental parameters were optimized and the VB_6 oxidized at +0.72 V *vs.* Ag/AgCl in 0.1 mol L^{-1} phosphate buffer solution (pH 6.6) with a linearity range from 0.050 to 1.0 mg L^{-1} (0.5–5 μg mL^{-1}) and LOD of, 15 μg mL^{-1} (0.9 μmol L^{-1}). The short term repeatability for 0.5 mg L^{-1} VB_6 determination was found to be excellent (RSD of the 2.5–5.4%), and accurate aspects were achieved in real samples, such as multivitamin formulations, energy drinks and spiked surface water or wastewater (intrinsic recoveries generally ranging from 99–103%).[200] The practical fabrication process was implemented by an easy-to-use drop-casting of a Ni-zeolite/CB-polystyrene suspension, which allowed scaling up and use. The enhancement of the analytical figures was attributed to synergetic contributions from (i) ion-exchanged zeolite domains supplying molecular sieving and preconcentration, and (ii) conductive CB framework boosting electron transfer whilst stifling capacitive currents.[201]

These case studies have revealed some important design principles for NP-zeolite environmental sensors in general. The retention of zeolite crystalinity and pore accessibilty during modification is a pre-requisite for predictable analyte partitioning. Second, the selection of extra-framework cations and nanoparticles can be adjusted to acid–base or redox properties of the target analyte, *e.g.*, Fe(II) for thiol compounds or Ni^{2+} for phenolic vitamins. Third, the inclusion of conductive scaffolds like carbon black, graphene or ordered mesoporous carbons can significantly reduce the charge transfer resistance with no loss in selectivity resulting from zeolite frameworks. An additional step of SEM and EIS analysis in order to confirm film uniformity and stability should be necessary prior to field application in real environmental matrices.[202]

Collectively, these advances prove that the synergetic catalysis of zeolite frameworks and loaded NPs-typically supported by conductive carbon additives-allows for remarkable improvements in environmental sensing. These systems show lower overpotentials, better selectivity against interferences and detection limits in the nano- and sub-nanomolar range. NP–zeolite composites can be applicable to screen-printed or micro-electrode formats, as scalable synthetic routes such as ion-exchange, impregnation and drop-casting are available. Such characteristics make NP–zeolites promising for the development of next-generation environmental sensors for detection of toxic gases, trace organics and pharmaceutical pollutants in air

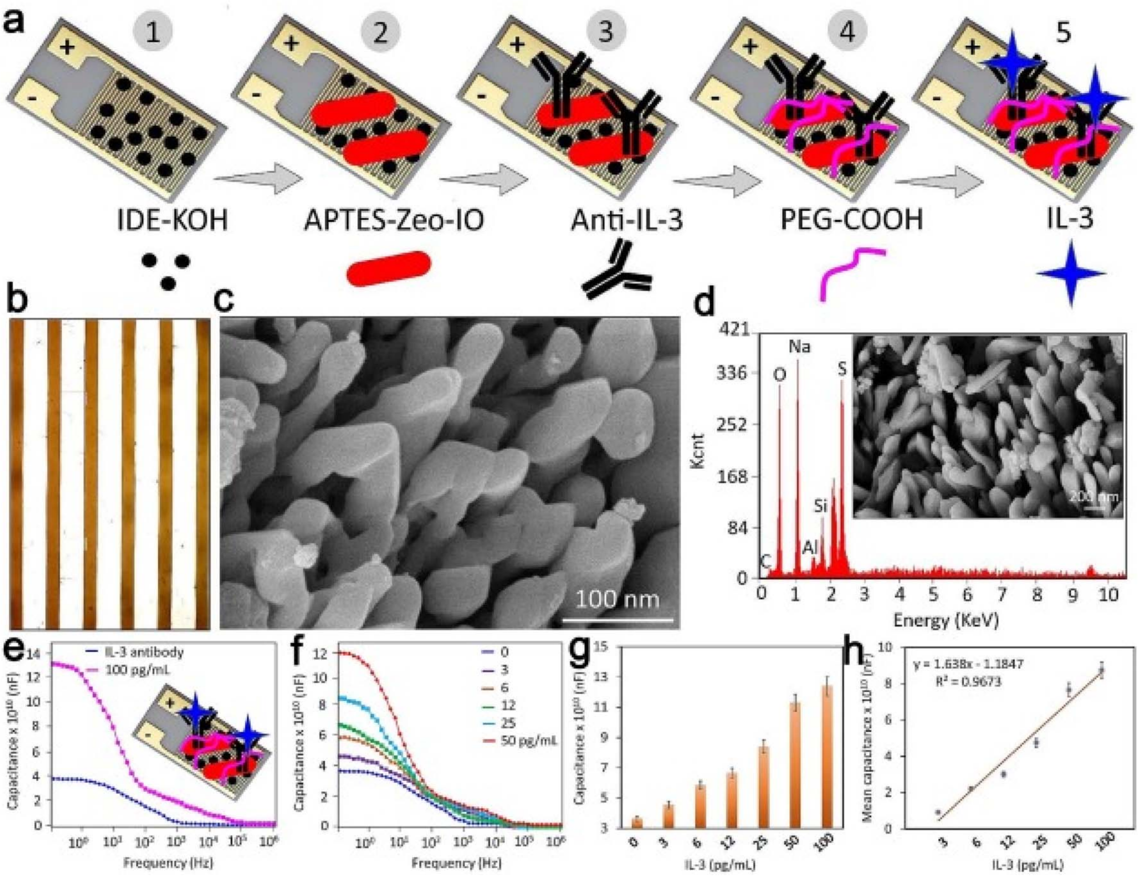


Fig. 12 Fabrication and characterization of the IL-3 immunosensor: (a) schematic steps of fabrication; (b) IDE surface image; (c) FESEM morphology; (d) EDX analysis; (e and f) capacitance response at various IL-3 concentrations; (g) dose-dependent capacitance change; and (h) calibration curve demonstrating linear IL-3 detection with high sensitivity, reproduced from ref. 210 with permission from Elsevier, copyright 2025.

and water to combat urgent public health problems by robust, low-cost and sustainable means (Table 4).

4.7 Biomedical coatings

The incorporation of nanoparticle modified zeolites as a potential method to reinforce biomedical coatings is emerging to be attractive, based on the nanoporous structure,[13] biocompatibility,[204] ion-exchanging capability and strength of these materials.[205] These properties render zeolites good candidates to enhance surface modifications of biomaterials. While regulated drug release patterns show these materials' potential for long-term and focused therapeutic delivery, cytocompatibility criteria, such as cell viability percentages, validate their safe interaction with biological systems. For example, *in situ* grown zeolite coatings on porous titanium implants have shown much enhanced biocompatibility. In fact, these coatings are not just activating the osteogenic gene expression but also can induce new bone formation which has mechanical properties (elastic modulus ~30 GPa) as in natural bone.[206] Additionally, composite coatings of zeolite and bioglass have exhibited improvement in osseo-integration when applied by electrophoretic deposition on to stainless steel bone implants. Such coatings could not only enhance the corrosion resistance but also have potential benefits for controlled expressions of metallic ions. The capacity to promote the formation of hydroxyapatite (HA) in simulated body fluid on stainless steel also compliments their application as bone-related implants, since HA facilitates better growth of the surrounding bone tissue.[207] Antimicrobial activity of zeolite coatings has been notably improved by the addition of nanoparticles. An important example is Ag sulfadiazine loaded NaY zeolite impregnated chitosan films, which finds a significance application in the area of burn wound dressing.[208] These nanocomposite films possess long-term broad-spectrum antimicrobial activities toward pathogens including *S. aureus*, *E. coli.*, *P. aerugionsa* and *C. albicans*. The controlled release of silver ions from its zeolite structure reduces cytotoxic peaks, and ensure good antimicrobial activity.[209] This controlled ion release is particularly important for wound healing purposes, where biocompatibility and long term antimicrobial activity are demanded.

Apart from antimicrobial applications, zeolite nanoparticles modified with nanoparticles have also presented exciting prospects in the area of drug delivery. The adjustable surface properties of zeolites make them appropriate for functionalization with different nanoparticles for increased drug load and/

Table 5 Using various zeolite-containing nanoparticles in drug delivery systems *via in vivo* study

Nanoparticles type	Particles size (nm)	Loaded drug-substances	Biological applications	Advantages	Ref.
Cu–X zeolite	N. A.	Cyclophosphamide	Tumor therapy	Continual maintenance concentration of cyclophosphamide *via* oral administration	211
Zeolite Y	2 μm	Fenbendazole	Anti-parasites (intestinal worms)	Efficient slow release	131
Zeolite rock	N. A.	Zn^{+2} erythromycin	Acne treatment	Sustained treatment	212
Magnetic FAU-zeolite	20 to 600 nm	Doxorubicin	Chemotherapy	Simple preparation, avoiding agglomeration of the magnetite nanoparticles to a huge extent	213
Zeolite Y	0.4–0.6 μm	Ibuprofen	Pain, fever, inflammation	Accelerated ibuprofen delivery rate	214
Mixture of zeolite X and zeolite A	4.5 μm	Ketoprofen	Inflammation gastrointestinal pathology	Lower risk of adverse effects related to NSAIDs oral administration	215
Zeolite/polymer composites (chitosan–gelatin–alginate)	∼70–250 μm	Cefalexin and gentamaycin	Homeostatic treatment, antibiotics	Prolonged release	216
Zeolite HY	N. A.	Aspirin	Pain, fever, inflammation	Optimized SiO_2/Al_2O_3 ratio	216
Zeolite-L nanocrystals	60 nm	Peptide nucleic acid (PNA) probes like DAPI	Cancer	Intercellular drug delivery	217
MOR (mordenite), zeolite Y	N. A.	Temozolomide (TMZ)	Glioblastoma brain tumors	Lower systematic toxicity	187
Zinc–clinoptilolite/Graphene oxide (Zn–Clin/GO) hybrid nanostructure	20–30 nm	Doxorubicin	Chemotherapy	Homogeneous and stable nanocomposite	218
Magnetite–zeolite	30 nm	5-Fluorouracil (5-FU)	Gastric cancer	Efficient delivery	219
Zeolite beta (BEA)	N. A.	Nifedipine (NIF)	Hypertension and Angina	Dissolution enhancement for oral bioavailability	220
Microporous zeolites: NaX, ZSM and BEA	2 μm	Indomethacin	Severe osteoarthritis, rheumatoid arthritis, gouty arthritis	Fine-tuned drug release	131
Fine-tuned drug release	41–55 nm	Doxorubicin	Chemotherapy	Excellent biocompatibility noticeable cytotoxic effect	221
Clinoptilolite-rich rock	(805 ± 131) μm	Diclofenac sodium (DS)	Inflammation, gastrointestinal pathology	Satisfactory dosage uniformity, suitable flowability as excipient carrier, meeting pharmacopeia regulations	131

or controlled release. Incorporation of NPs such as gold or silica NPs into zeolite frameworks could increase therapeutic efficiency and specificity, thus overcoming the problem of targeted intracellular delivery in biological system. Also, a diagram as shown in Fig. 12 represents a schematic of zeolite-based sensors and drug delivery systems functionalization.

In this procedure, a number of modifications such as functional groups (PEG-COOH and antibody conjugates) are incorporated into the suggesting connecting technology enable specific binding *e.g.*, the quantitation of IL-3 at nanogram levels. This figure demonstrates the possibility of utilizing nanoparticles-modified zeolites to construct multi-functional nano-platform, which can not only be a biosensor but also achieve real-time detection and monitoring process for target biomolecules.[210] The increased surface area and active sites with nanoparticle modification results in the better perofrmance of these devices for sensitive and reliable biomedical application. These developments have underlined the continuous evolution of NP-functionalized Zs as promising players in the field of advanced bionanocoating and therapeutic systems. The possibility to tailor their properties by choosing the proper type of nanoparticle brings a huge range of opportunities for applications ranging from improving implant performance to providing precision delivery systems for therapeutic drugs (Table 5).

5 Challenges and future perspectives

When compared to conventional zeolites, NPZs-zeolite matrices doped or composite with functional nanoparticles-have become more adaptable materials with improved ion-exchange, catalytic, and adsorption capabilities. These improvements have been shown to outperform unmodified zeolites in contaminant removal and reaction efficiency for environmental remediation, wastewater treatment, and catalysis.[12] However, there are particular difficulties in terms of legislation, market penetration, and scalability when converting these cutting-edge materials from laboratory proofs-of-concept into commercially accepted goods.

5.1 Regulatory landscape and policy challenges

Owing NPZs use designed nanoparticles instead of bulk chemicals or traditional zeolite adsorbents, they are subject to increased regulatory scrutiny because of possible ambiguities about the effects on human health and the environment at the nanoscale. NPZs are currently governed by a variety of current chemical, nanomaterial, and product-specific rules rather than a worldwide unified regulatory framework created especially for NPZs. The U.S. Environmental Protection Agency (EPA) primarily regulates NPZs meant for consumer, industrial, or environmental applications under the Toxic Substances Control Act (TSCA).[222] Composites containing nanoparticles may be categorized as new chemical substances or significant new uses, necessitating pre-manufacture notifications backed by exposure assessments and risk data. The Occupational Safety and Health Administration (OSHA) regulates occupational exposure during NPZ production and handling, and the Safe Drinking Water Act (SDWA) may also apply to applications in water treatment.[223] The Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) framework, which requires thorough physicochemical characterization, toxicological evaluation, and explicit consideration of particle size and surface properties for substances containing nanomaterials, as well as product-specific directives pertinent to consumer or environmental uses, governs NPZs in the European Union. Although they are not legally binding, international organizations like the International Organization for Standardization (ISO TC 229) and the Organization for Economic Co-operation and Development (OECD) Working Party on Manufactured Nanomaterials offer guidelines on terminology, testing procedures, and safety assessment for nanomaterials.[224] These guidelines have a significant impact on national regulatory practices and risk assessment strategies. Despite these efforts, there are still large regulatory gaps because NPZs are usually evaluated as standalone nanoparticles or bulk zeolites rather than as integrated nano-enabled composites. As a result, their combined physicochemical behavior, long-term environmental fate, and full life-cycle impacts are rarely taken into account. Large-scale commercialization and industrial adoption of NPZ-based technologies are severely hampered by this lack of regulatory clarity, which also raises compliance costs and lengthens approval processes.

5.2 Current NPZs available in the market

Given their early stage of industrial maturity and regulatory ambiguity, NPZs are still somewhat limited in mainstream commercial markets as compared to well-established nanoparticle-based products in industries like electronics, cosmetics, or medicine. Wastewater remediation, antimicrobial surface treatments, heterogeneous catalysis, and improved adsorption processes are the main application areas for NPZs, which are currently limited to pilot-scale demonstrations or early commercialization. The delivery of zeolite nanoparticles or nanosized zeolite precursors, which are sold for industrial and research purposes and then functionalized with metal or metal-oxide nanoparticles to create application-specific NPZs, is the main focus of commercial activity. Simultaneously, zeolite composites modified with silver and metal oxide have been investigated for antimicrobial coatings and surface treatments; a number of these materials have advanced to prototype or limited-scale deployment, suggesting a feasible route toward commercial antimicrobial formulations. NPZs with nanoparticles like TiO_2 or ZnO have demonstrated improved performance in environmental engineering for heavy-metal sequestration and organic pollutant degradation, leading to their initial use in industrial wastewater treatment trials and pilot-scale filtering systems. In contrast to conventional zeolite adsorbents, fully commercialized NPZ products with globally recognized branding, standardized specifications, or ISO certification are still rare despite these advancements.[225] This is due to the longer regulatory approval timelines, technical optimization requirements, and market validation processes that are typical of advanced nano-enabled composite materials.

5.3 Market growth projections

The growth trajectory of NPZs can be fairly deduced from established patterns in the worldwide zeolite and advanced adsorbent markets, even if they are not yet listed as a separate market category in the majority of commercial databases. Due to growing demand in adsorption, catalysis, and environmental applications, the broader zeolite market-which includes both natural and synthetic materials-continues to grow steadily. According to recent estimates, the market is valued at more than USD 12.5 billion in 2024 and is expected to reach USD 22 billion by 2032, representing a compound annual growth rate of roughly 7.2%.[226] Modified zeolite composites and nano-enabled adsorbents are becoming more and more popular in this developing field as industry and regulatory agencies put more stringent requirements on resource efficiency, pollution management, and water quality. This change is anticipated to benefit NPZs in particular because of their increased adsorption capacity, better selectivity, and multi-functional performance, which address the drawbacks of traditional zeolites.[227] Adoption of NPZ is expected to accelerate in high-value niche applications such the removal of new pollutants, advanced wastewater treatment, and catalytic processes requiring customized active sites as performance advantages continue to be confirmed under real-world operating conditions. Therefore, convergent growth trends in zeolite composites and nano-adsorbent technologies strongly suggest significant commercialization potential for NPZs, even though NPZ-specific revenue figures are still limited. This is especially true when combined with regulatory compliance, scalable manufacturing strategies, and cost-effective material design.

5.4 Principal challenges ahead

Despite their proven functional benefits, a number of interrelated technological, legal, and socioeconomic issues prevent NPZs from being widely adopted. The scarcity of thorough toxicological and environmental destiny data for particular NPZ formulations is one of the biggest obstacles, which makes risk assessment more difficult and delays regulatory approval procedures. Simultaneously, the lack of globally standardized definitions, testing procedures, and evaluation criteria for nano-enabled composites like NPZs limits cross-border commercialization and introduces ambiguity into regulatory processes. Scalable production of NPZs with consistent performance, controlled pore architecture, and uniform nanoparticle dispersion is still technically challenging from a manufacturing standpoint, and the related production costs may restrict competitiveness in price-sensitive markets unless distinct and long-lasting performance benefits are proven. Furthermore, public and stakeholder acceptance remains a non-technical challenge because nanotechnology-based materials are frequently scrutinized more closely, especially in consumer-facing and environmental applications. To foster trust and promote market uptake, transparent communication, strong safety validation, and life-cycle-based risk assessments are required.

5.5 Future perspectives

Future NPZ development and commercialization will be contingent upon the coordinated advancement of legislative frameworks, market preparedness, and ongoing technological innovation. To establish suitable physicochemical characterization parameters, safety data requirements, and acceptable exposure thresholds that reflect the composite nature of NPZs rather than treating them as traditional zeolites or standalone nanoparticles, early and ongoing engagement with regulatory authorities will be crucial. Simultaneously, active participation in global standardization projects, like those headed by ISO Technical Committee 229, can speed up regulatory acceptability and cross-jurisdictional market access by facilitating the development of uniform quality benchmarks and testing procedures. Demonstration-scale validation in specific industries, like heterogeneous catalysis and industrial wastewater treatment, where cost-effectiveness, operational stability, and performance improvements can be directly compared to current technologies, will be necessary for the shift from laboratory research to commercial deployment. Incorporating thorough life-cycle assessment methods, from the procurement of raw materials to end-of-life management, will also be essential for measuring the effects on society and the environment and coordinating NPZ development with new sustainability and circular economy regulations. All things considered, NPZs have a great deal of potential for next-generation adsorption, catalytic, and remediation applications. Nevertheless, their successful transition to widespread commercial use will ultimately depend on resolving regulatory uncertainty, attaining scalable and financially feasible manufacturing, and continuously exhibiting distinct performance advantages within clearly defined application niches.

6 Techno–economic perspectives on application potential

Both significant promise and urgent issues that will impact their industrial adoption are reflected in NPZs. The catalytic, magnetic, and antimicrobial properties of nanoparticles are combined with the porous, thermally stable structure of zeolites to create NPZs, which provide multipurpose solutions for the biomedical, water treatment, energy, sensing, and catalysis industries. However, synthesis costs, scalability, and market competitiveness must be critically assessed as they move from lab research to large-scale commercialization. The synthesis of NPZs is a significant obstacle. Traditional methods like sol–gel, hydrothermal, solvothermal, and ion-exchange routes are time-consuming, energy-intensive, and frequently depend on expensive organic templates or noble metals like Pt, Pd, and Au. Although these composites perform better catalytically or antibacterially, scalability is hampered by high material and processing costs. Therefore, cost-effective techniques like dry-gel conversion, template-free procedures, and mechanochemical synthesis are crucial for cutting production costs. Similarly, although there are still difficulties in maximizing stability and activity, the use of less expensive substitutes like Ni, Fe, Cu, or TiO_2-based systems provides a route toward wider commercialization. Several important factors should be taken into account in a thorough techno–economic assessment of NPZs in order to guarantee both sustainability and industrial viability. Precursor costs, synthesis complexity, and post-processing requirements must all be taken into consideration when calculating the cost-*per*-ton of material production. Energy consumption, particularly in hydrothermal or solvothermal processes, is a significant operational expense. Another crucial element is raw material availability, which emphasizes the utilization of biogenic, waste-derived, or earth-abundant precursors to ensure long-term supply. Practical implementation also requires scalability measures, such as yield consistency, batch-to-batch reproducibility, and compatibility with continuous or large-volume manufacturing. Further information about the material's industrial application is provided by process efficiency indicators such nanoparticle usage, lifespan stability, recyclability, and performance retention under actual working settings.

One of the most promising markets is environmental remediation. NPZs can reduce treatment steps and operating costs by combining disinfection, catalysis, and adsorption into a single material. For instance, magnetic zeolite composites are cost-effective for treating wastewater because they make recovery and reuse simple. However, NPZ systems need to show better cost-*per*-unit performance in large-scale applications in order to compete with activated carbon, polymer membranes, or bio-adsorbents. For industrial validation, lifecycle cost analyses and pilot studies will be essential. Green chemistry, biomass conversion, and petrochemical processing are all made possible by NPZs in catalysis. By stabilizing nanoparticles inside zeolite frameworks, they can increase selectivity and extend catalyst lifetimes, which lowers operating costs. However, new reactor designs or catalyst systems may have high initial capital costs, necessitating the adoption of supportive policies or incentives. NPZs could also improve energy storage, CO_2 reduction, and hydrogen production in renewable energy. Achieving high efficiency at competitive energy inputs, in line with declining renewable energy costs and more stringent carbon regulations, will be crucial to their techno–economic viability. Despite significant economic and regulatory obstacles, biomedical applications-such as drug delivery and antimicrobial coatings-show great promise. It is expensive to produce medical-grade NPZs, and approval requires thorough toxicity and biocompatibility studies. As a result, NPZs may start out in high-value markets like implant coatings or targeted cancer treatments before moving into more general healthcare uses as prices come down.

By facilitating regenerable, multipurpose systems, NPZs support the objectives of the circular economy from a sustainability standpoint. However, lifecycle assessments are necessary to address issues with nanoparticle leaching, long-term stability, and safe disposal. Cost savings and predictive material design may be further accelerated by developments in scalable, environmentally friendly synthesis and integration with digital tools like machine learning. Finally, NPZs have a bright techno–economic future, but it depends on resolving issues with stability, scalability, safety, and synthesis costs. In the upcoming decades, NPZs may develop into technologically and economically advantageous materials that revolutionize the environmental, energy, and biomedical sectors with sustained innovation, encouraging regulations, and demand driven by sustainability.

7 Conclusions

NPZs are a quickly developing class of materials that hold great promise for a variety of uses in energy conversion, environmental remediation, biomedical applications, and catalysis. NPZs offer multipurpose platforms that can tackle urgent global issues by fusing the special functions of nanoparticles with the inherent qualities of zeolites, such as ion-exchange capacity, high thermal stability, and tunable pore size. Improvements in selectivity, catalytic activity, and adsorption capacity have been made possible by advances in synthesis and structural modification, exhibiting distinct advantages over traditional materials. In spite of these successes, a number of obstacles need to be removed before NPZs are widely used in industry. Costs associated with synthesis, dispersion of nanoparticles, stability over time, scalability, and possible toxicity are still major obstacles. It will be essential to address these problems by utilizing low-cost or earth-abundant nanoparticles, hierarchical structuring, and green and energy-efficient synthesis. Furthermore, in order to guarantee both economic viability and environmental sustainability, thorough techno–economic evaluations and life-cycle analyses are required. Future prospects for next-generation technologies are exciting due to the creation of multifunctional NPZ systems that combine sensing, catalysis, and adsorption. The rational design of NPZs will be accelerated by interdisciplinary collaboration aided by developments in machine learning, *in situ* characterization, and computational modeling. In the future, combining machine learning-assisted synthesis design with AI-based predictive modeling provides a potent technique to quicken NPZ development. In order to guide optimal material design and minimize experimental trial-and-error, data-driven techniques can facilitate the quick correlation of synthesis parameters, structural descriptors, and functional performance. Machine learning may greatly improve the logical design, scalability, and application-specific optimization of NPZ systems when paired with computational modeling and *in situ* characterisation methods. The real-world impact of NPZs will ultimately depend on how well laboratory-scale ideas are translated into reliable, commercially viable solutions. The true impact of these materials will ultimately depend on how well laboratory-scale innovations are translated into workable, large-scale solutions. This review highlights that NPZs have the potential to become transformative materials that propel sustainable advancements in healthcare, energy, and the environment with further research and techno–economic optimization.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors. As a review manuscript, it synthesizes existing research and does not involve new data collection requiring ethical approval.

Author contributions

Fatema Jesmin, Jannatul Ferdous Mitu: writing original draft; Ahmed B.M. Ibrahim: resources; Al Amin Mia Anik, Khalid I. Anojaidi, Waleed A. Al-Suwaylih, Md. Kamrul Hasan: writing, proof reading and editing; Tasmina Khandaker, Muhammad Sarwar Hossain: writing original draft, methodology, validation, and supervision.

Conflicts of interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this paper.

Data availability

No primary research data, software, or code were generated, analyzed, or reported in this review article. All information discussed is drawn from previously published literature and appropriately cited within the manuscript.

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