Nexus: Jurnal Sains dan Teknologi Vol 01 No 02 (2025) 16–26

Nexus: Jurnal Sains dan Teknologi
Homepage jurnal: https://ojs.polmed.ac.id/index.php/nexus_sains_dan_teknologi

Magnetic Zeolite Composites for Heavy Metal Ions Removal: A Concise Review

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Highlights

- *Magnetic zeolite is porous and magnetically separable*
- *Hydrothermal, coprecipitation, and dry-gel routes yield high surface area*
- *Heavy-metal uptake fits pseudo-second-order and Langmuir models*

ARTICLE INFO

Article History:
Received on 30 Oktober 2025
Revised on 21 November 2025
Accepted on 30 November 2025
Available online on 04 December 2025

Keywords:
carbonisation, biomaterial, ultra high modulus, manufacture.

ABSTRACT

Magnetic zeolite is a composite material that combines the porous characteristics of zeolite with the magnetic separation capability of magnetic nanoparticles. This study discusses the development of magnetic zeolite synthesis using several main methods, including hydrothermal synthesis, coprecipitation, and dry-gel conversion, each offering different levels of control over particle size, surface area, and magnetic strength of the resulting composite. The synthesized materials generally possess a high surface area and strong magnetic response, making them effective for adsorbing heavy metal ions from aqueous solutions. The reported maximum adsorption capacities reach 625 mg g^{-1} for Pb(II), 204 mg g^{-1} for Cd(II), 181 mg g^{-1} for Cu(II), more than 400 mg g^{-1} for Cr(VI), and around 42 mg g^{-1} for Ni(II). According to various studies, the adsorption of heavy metal ions onto magnetic zeolite commonly follows the pseudo-second-order kinetic model and the Langmuir isotherm, indicating that the adsorption process is dominated by a monolayer chemisorption mechanism. In addition to its high adsorption capacity, the main advantage of magnetic zeolite is the ease of separating it from the solution using an external magnetic field, making it an efficient adsorbent that can be easily recovered and reused.

1. Introduction

Advancements in industrialization has prompted environmental concerns due to water contaminations caused by heavy metals, organic pollutants and other emerging contaminants [1]. To treat these contaminants, membrane filtration and ion exchange have been applied for environmental cleanup. However, there are some drawbacks to these techniques such as the relatively expensive cost, efficiency and secondary pollution risks [2]. Among available options, adsorption has been extensively recognized as effective method for its cost-effectiveness and potential regeneration to eliminate various types of pollutants [3].

Zeolites belong to the class of crystalline aluminosilicates commonly utilized as adsorbents attributed to their excellent features possessing considerable active sites, uniform pore size, as well as cation-exchange capacity. Clinoptilolite, chabazite and phillipsite are examples of naturally occurring zeolites [4]. These materials exhibit unique properties such as the capacity to capture and eliminate inorganic and organic pollutants from water, soil and air. However, one common practical limitation is when separating the zeolites from the treated water, which is caused by the fine particle size of conventional zeolites [5]. To overcome this problem, research pertaining to the modification of zeolites have been conducted for efficient and sustainable remediation.

The addition of magnetic nanoparticles to zeolite framework is an intriguing substitute that has been the focus of several investigation since it facilitates both easy separation and recovery [6]. Magnetically modified zeolites have gained considerable attention as multifunctional adsorbents owing to their unique combination properties including large surface area, cation-exchange functionality of zeolites, and the magnetic feature of nanoparticles, which promotes simple separation and reuse [7].

Recent research in magnetic zeolites encompass hydrothermal transformation (including waste-derived pathways using coal-fly ash and red mud), co-precipitation, sol-gel/dry-gel conversion methods, each of these routes offers unique advantages in terms of controlling particle morphology, crystallinity and magnetic behaviour [8-10]. Despite significant advancements have been made, comparative evaluations that apply consistent performance descriptors across studies remain limited, making it difficult to benchmark materials under realistic operating conditions.

Accordingly, this review organizes synthesis and surface-modification strategies for magnetic zeolites and links structure, property relationships to wastewater treatment performance. It then benchmarks adsorption of priority heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{6+}, Zn^{2+}, and Ni^{2+}) using harmonized metrics (capacity in $mg\ g^{-1}$, optimal pH, isotherm/kinetic models), alongside magnetic separability and multi-cycle regeneration efficiency.

2. Method

The methodology used in this review includes a comprehensive literature search to compile latest developments in the preparation and modification of magnetic zeolite composites and evaluate their effectiveness in adsorbing heavy metals for environmental remediation. Research papers considered relevant are papers published ranging from 2015 to 2025. The papers were chosen from Google Scholar, PubMed and Scopus by applying keywords like “magnetic zeolites”, “synthesis”, “adsorption” and “environmental remediation.” Relevance, publication year, and citation frequency were used as the basis for inclusion criteria. To verify the appropriateness of the studies, the abstracts and conclusions were reviewed. Results from the relevant studies were descriptively summarized as the part of data processing to provide an overview of synthesis methods, modifications, and adsorption efficiencies.

3. Results and Discussions

3.1 Synthesis Methods of Magnetic Zeolite

Recent advancements in the synthesis of magnetic zeolites have utilized various innovative methods with the purpose to increase their functionalities. Here, we summarize some of the promising techniques.

1. Hydrothermal method

Magnetic zeolites are commonly fabricated via hydrothermal synthesis by integrating magnetic nanoparticles, such as Fe_3O_4 into the zeolite framework, often employing industrial by-products (e.g., red mud, fly ash, or low-grade ores) as precursors which will provide the silica and alumina content. The process typically involves an initial alkaline activation (usually using NaOH) to convert raw materials into reactive forms, subsequently subjected to hydrothermal crystallization in a sealed reactor and heated at temperatures around 80-120 °C for several hours, which promotes the crystallization of zeolite structures and the encapsulation or deposition of magnetic particles within or on the zeolite [8, 11].

Significant functional characteristics were shown by the materials such as strong magnetization values ranging approximately from ~12–18 emu g^{-1}, high Brunauer–Emmett–Teller (BET) surface areas approaching 459.8 $m^2\ g^{-1}$, and enhanced sorption capacities for divalent and monovalent heavy metal ions such as Sr(II), Cd(II), Pb(II), and Cs(I). These physicochemical properties demonstrate their use for environmental cleanup, where zeolite framework offers high-capacity and selective ion-exchange performance and magnetic response provides easy solid-liquid separation [11].

2. Co-precipitation method

Magnetic zeolites prepared via co-precipitation started by dispersing natural or synthetic zeolite in deionized water or an alkaline solution in an inert atmosphere to prevent the oxidation of Fe(II), followed by dropwise addition of Fe(II)/Fe(III) salts (1:2) with vigorous stirring near 70 °C, controlled basification typically using NaOH or NH_4OH to precipitate Fe_3O_4 in situ. The resulting black suspension is aged, then cooled, collected thoroughly rinsed with distilled water until the a pH level of neutral is obtained. Subsequently, the magnetic zeolite is dried in an oven at temperatures approximately 60-120 °C and stored for further use. The produced materials generally posses high surface area, superparamagnetism, and strong affinity for diverse pollutans via chemisorption, ion exchange, and complexation, enabling facile magnetic separation from water and demonstrating robust structural stability and reusability suitable for environmental remediation and biocompatible applications [13, 14].

Many studies have been carried out to synthesize magnetic zeolite through co-precipitation. For example, Neolaka and group demonstrated the synthesis of magnetic activated natural zeolite nanocomposites (ANZ-Fe_3O_4) using $FeCl_3.6H_2O$ and $FeSO_4.7H_2O$ as precursors. According to XRD and FTIR results, Fe_3O_4 nanoparticles have effectively been embedded to the zeolite network, leading to 2.850 mg g^{-1} as the maximum uptake capacity for Cr(VI) [14]. Another study was also conducted by Ramos-Guivar and group, where they successfully synthesized magnetic zeolite type 5A using co-precipitation method, in which maghemite nanoparticles were combined with zeolite type 5A, with their content carefully controlled [15].

3. Dry-gel conversion method

To produce magnetic zeolite through dry-gel conversion, the synthesis begins with preparing precursor gel containing the mixture of zeolite materials (such as silica, alumina and structure-directing agents) and well-dispersed magnetic particles (typically Fe_3O_4). The gel is then subsequently crystallized in a sealed autoclave at 140-200 ℃ for several hours to convert the amorphous gel into crystalline zeolite embedding magnetic particles. Subsequently, the materials produced may be optionally calcined at 400-500 ℃ to eliminate organic templates and enhance magnetic performance [16]. Relative to traditional hydrothermal routes, this approach offers several benefits, including faster crystallization, smaller reactor capacity, less by-product generation, and enhanced precision in incorporating magnetic phases [17].

Phouthavong and group reported that magnetic zeolite composite generated by the dry gel conversion method showed excellent methylene blue adsorption, with capacity up to 133 mg g^{-1}. Moreover, SEM images of magnetic and non-magnetic zeolite revealed that there was almost no difference, implying that Fe_3O_4 particles were uniformly embedded by the BEA-type zeolite [18]. All things considered, sol-gel-based dry-gel conversion is a scalable and efficient method for creating high-performance magnetic zeolites that may find use in environmental settings.

3.2 The Application of Magnetic Zeolite as Heavy Metals Adsorbent in Wastewater Treatment

Pb, Cd, Cu, Cr, Zn and Ni are examples of heavy metals which characterized with large atomic mass and density. These heavy metals have potential to harm biological and environmental health [19]. Examples of heavy metals ion such as Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{6+}, Zn^{2+} and Ni^{2+} can lead to numerous chronic health problems, such as like cardiovascular, pulmonary, renal and even cancer [20]. Below we summarize some adsorption studies of those heavy metals using magnetic zeolite adsorbents.

1. Lead(II)

Multiple studies have demonstrated that magnetic zeolite composites exhibit a higher affinity for Pb ions compared to raw zeolites. This enhancement is attributed to synergistic effects between the zeolite framework and Fe-based magnetic modifications. This is because the encapsulation of Fe_3O_4 means adding more active sites, increasing surface area and improving charge distribution besides providing magnetic separability of the adsorbent [29-32]. Various research have discovered that the highest adsorption capacities of Pb(II) exhibited by magnetically modified zeolites ranging from 83 to 625 mg g^{-1} [32, 33].

Literature showed that Pb^{2+} uptake onto magnetic zeolites is well represented by the Langmuir isotherm and pseudo-second-order kinetic model, consistent with monolayer chemisorption on energetically uniform sites and strong sorbate–sorbent affinity. The adsorption is highly pH dependent with optimum pH ranging from 4–6, wherein Pb^{2+} is most available and surface sites are active [32, 33].

2. Cadmium(II)

Magnetic zeolite adsorbents for Cd(II) removal operate through a cooperative mechanism involving cation exchange at zeolitic sites, inner-sphere complexation to Fe–O(H) functionalities within Fe_3O_4/γ-Fe_2O_3 domains, and electrostatic attraction modulated by surface charge, particularly effective at pH 5–7 where deprotonation enhances specific binding while avoiding $Cd(OH)_2$ formation. The equilibrium and kinetic data were consistent with monolayer adsorption mechanism governed by chemisorption, dominated uptake with a rapid approach to equilibrium; maximum capacities range roughly 17.8–204.2 mg g^{-1}, with Fe_3O_4/zeolite composites and polymer/zeolite hybrids often reaching the upper range [9,12].

Operationally, near-neutral conditions optimize selectivity by preserving inner-sphere complexation in the presence of ionic strength and co-ions, while statistically guided optimization identifies precise windows of pH, contact time, and dosage that maximize removal efficiency with strong agreement between model predictions and experiments [25]. Regeneration is typically efficient using dilute mineral acids (≈0.05–0.2 M) or NaOH, achieving high Cd(II) desorption with minimal capacity loss over multiple cycles; composite architectures, including silica-coated magnetic clinoptilolite, polymer–zeolite hybrids, and agro-waste-derived magnetic zeolites, offer tunable micro, mesoporosity and robust magnetization without occluding transport pathways, supporting practical water-treatment deployment and end-of-life stabilization when metal recovery is not pursued [35, 36].

3. Copper(II)

Magnetic zeolites consistently deliver high Cu(II) uptake, with capacities around 16–248 mg g^{-1}, evidencing that magnetization preserves zeolitic ion-exchange while enabling rapid, filtration-free magnetic recovery under external fields [20, 22]. The adsorption behavior is typically described by Langmuir isotherms and pseudo-second-order kinetics, consistent with monolayer chemisorption driven by ion exchange, electrostatic attraction, and surface complexation at zeolitic oxygen sites; uptake is fast (minutes to equilibrium) and optimal near neutral pH (~6–9), aided by hierarchical porosity that enhances mass transfer, while embedded iron-oxide nanophases maintain structural stability across pH without materially compromising capacity [21 ,22]. In terms of sustainability and reusability, magnetic zeolites frequently retain >90% removal over multiple adsorption–desorption cycles [27].

4. Chromium(VI)

Converging evidence across various studies shows that Cr(VI) exhibits strong affinity under acidic conditions, with optimal performance typically observed around pH 1.5–3, where protonated surface sites and Fe-based domains favor electrostatic attraction and interfacial complexation of chromate species [31, 37]. Adsorption equilibrium data from literature mainly showed good correlation with the Langmuir model, which implies the uptake of Cr(VI) occurred in homogenous monolayer on the magnetic zeolite's surface. Further, kinetic evaluation also demonstrated that the pseudo second order rate was the most accurate representation of the Cr(VI) adsorption rate, which also indicates chemisorption is the dominant rate controlling step [15, 37].

Beyond surface adsorption, electron-donating sites on magnetite or polymeric components within the composite have been shown to promote the simultaneous reduction of harmful Cr(VI) to the less mobile and environmentally benign Cr(III) [33]. The reported maximum adsorptive capacities vary significantly according to the composite's composition and synthesis route, ranging from approximately 25–50 mg g^{-1} for chitosan-based materials to over 400 mg g^{-1} for advanced core–shell or polypyrrole-modified systems [33].

5. Zinc(II)

Mirjavadi and group found that Zn(II) can be removed up to about 96% by using composite such as Fe_3O_4/zeolite/cellulose under optimum conditions, with quick uptake within the first 30 minutes and continue to function well even under the influence of competing ions. These materials particularly favor Zn(II) uptake in neutral pH [34]. Another study by Buzukashvili and group, the adsorption capacity in a single ion system was confirmed as 177 mg g^{-1}. This value demonstrated an excellent adsorption efficiency compared to coal fly ash synthesized zeolite reported in the literature. In addition, adsorption kinetics revealed that Zn(II) ions required approximately 90 hours to achieve the equilibrium at a final concentration of 123 mg L^{-1}. This rather slow equilibrium method raises the possibility that intraparticle diffusion is a key component of the adsorption mechanism. [27].

Zn(II) adsorption performance on the magnetic zeolite composite was optimally described by the Langmuir model, whereas the kinetic data aligned with a second-order rate equation, suggesting that chemisorption leading to monolayer formation regulates the process. Adsorption parameters affecting the performance of the adsorbent including solution pH (typically optimum near ~7 for Zn^{2+}), temperature, and the ionic matrix. In addition, in multi component settings, lanthanum-modified zeolites can increase Zn(II) removal, particularly when phosphate is present. This can be achieved by creating a ternary surface complexes that stabilize co-adsorbed species [35].

6. Nickel(II)

Owing to its toxicity and bioaccumulative nature, nickel becomes a common contaminant in industrial wastewater, particularly from electroplating, stainless steel manufacturing, and battery industries. If these ions are exposed to the environment, it will impact significant risks to both environmental and human health [36, 37]. According to studies, nickel concentrations in industrial wastewater can considerably surpass the legal limits, with reported values ranging from traces to over 120 ppm, depending on the source and treatment efficacy [38]. Even exposure to nickel concentrations as low as 0.5 mg L^{-1} can adversely effect aquatic ecosystems and threaten human health [39].

Al-Gaashani and group reported that doping zeolite with magnetic materials such as MgO, Fe_3O_4 and ZnO can enhance Ni(II) removal up to 96%, with a maximum adsorption capacity of 17.13 mg g^{-1}, surpassing the raw zeolite. In addition, the isotherm behaviour consistently follows Langmuir isotherm and pseudo-second-order kinetic model, which indicates monolayer chemisorption as the predominant pathway, electron interactions between doped-oxide active sites and Ni(II) support quick adsorption and good selectivity [40].

Another research by Kotova and group reported that zeolite with varied content of nanoparticles of cobalt-zinc ferrite enhance nickel extraction by about 1.5 – 1.7x, achieving 70–80% removal with equilibrium reached in about 20 minutes and simple magnetic separation that promotes regeneration. In addition, zeolite made from coal fly ash also demonstrates strong adsorption capacity for Ni(II) in multicomponent ion system, which is up to 42 mg g^{-1}, even though the selectivity is still lower than for Pb(II) and Cu(II), pointing out the significance of compositional adjustment for competitive matrices [27].

4. Conclusion

This review suggests that adsorption using magnetic zeolites represent a promising class of adsorbents that effectively integrate significant surface area, magnetic separability, and robust binding ability with toxic metal species. Recent developments in hydrothermal, coprecipitation, and dry-gel conversion synthesis methods have enhanced their structural uniformity, surface functionality, and magnetic performance. Previous studies show that adsorption behaviour for selected heavy metal ions (lead, cadmium, copper, chromium and zinc) aligns with the Langmuir isotherm and exhibits Ho and McKay pseudo second order kinetic, reflecting a single layer chemical interaction on the adsorbent surface. With stable reusability and simple magnetic recovery, magnetic zeolites demonstrate significant potential as efficient, recyclable materials for practical wastewater treatment applications.

CRediT Authorship Contribution Statement

W. Gracias: Conceptualization, Data curation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **A. N. Dienna** and **D.I. Permatasari:** Writing – review & editing.

Conflicts of Interest

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

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