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Metal Oxide Montmorillonite Nanocomposites for Heavy Metal Ion Removal: Mechanisms, Performance and Environmental Applications

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Abstract: Metal oxide montmorillonite (MMT) nanocomposites have emerged as highly efficient adsorbents for the removal of heavy metal ions from aqueous solutions. Their unique combination of high surface area, tunable surface chemistry, and structural stability enables rapid and selective adsorption of pollutants such as Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{6+}, and Hg^{2+}. This review systematically examines the recent advances in the synthesis, surface modification, and functionalization of MMT-based nanocomposites, including hydrothermal, sol-gel, polymer-assisted, and green bio-based methods. The adsorption mechanisms, kinetic models, equilibrium isotherms, and thermodynamic behavior are critically analyzed. Performance metrics such as adsorption capacity, removal efficiency, and regeneration potential are discussed, alongside computational approaches like molecular modeling and machine learning for predictive design. The environmental applications and practical considerations for wastewater remediation are highlighted, emphasizing the potential for sustainable and scalable solutions. This comprehensive review provides a framework for designing next-generation MMT-based nanocomposites with enhanced selectivity, reusability, and environmental compatibility.

1. Introduction

Heavy metal contamination in water has emerged as a critical environmental and public health concern due to the toxic, persistent, and non-biodegradable nature of metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{3+}/Cr^{6+}), copper (Cu^{2+}), and nickel (Ni^{2+}) (Alsohaimi *et al.*, 2023; Ren *et al.*, 2024; Zhao *et al.*, 2025). These pollutants are primarily introduced into water bodies through industrial effluents, including mining operations, electroplating, battery production, textile manufacturing, and chemical processing. Urban runoff and agricultural activities also contribute to the accumulation of these metals in aquatic ecosystems. Prolonged exposure to heavy metals can result in severe health impacts, such as neurological disorders, kidney and liver damage, and disruption of enzymatic and metabolic processes, while ecological consequences include bioaccumulation in aquatic organisms and long-term degradation of water quality.

Conventional treatment methods, such as chemical precipitation, ion exchange, membrane filtration, and coagulation-flocculation, have been widely employed to address heavy metal pollution (Husaini, 2026a; Zohrabi *et al.*, 2024). However, these approaches often present significant limitations, including incomplete removal at trace concentrations, high operational costs, and production of secondary waste streams that require further handling. These challenges have driven research toward alternative strategies that are more efficient, cost-effective, and environmentally sustainable (Wang *et al.,* 2024; Husaini *et al.,* 2025a-d).

Adsorption has emerged as a versatile and promising approach for heavy metal removal due to its simplicity, high removal efficiency, and adaptability to various wastewater conditions (El Hammari *et al.,* 2022; Wibowo *et al.,* 2025; Xu *et al.,* 2025). In this context, montmorillonite (MMT)**,** a naturally occurring layered clay mineral, has attracted significant attention. Its large specific surface area, high cation exchange capacity, and interlayer spacing facilitate the adsorption of metal ions through mechanisms such as ion exchange, surface complexation, and electrostatic attraction (Arabmofrad *et al.,* 2024). However, pristine MMT often exhibits limited adsorption capacity and selectivity for certain metals, which has motivated the development of metal oxide-MMT nanocomposites (Machahary *et al.,* 2025; Ren *et al.,* 2024).

By integrating metal oxides such as iron oxides (Fe_3O_4, Fe_2O_3), zinc oxide (ZnO), titanium dioxide (TiO_2), and manganese dioxide (MnO_2) into the MMT structure, researchers have been able to enhance the number of active sites, improve adsorption kinetics, and introduce additional functionalities such as magnetic separability or photocatalytic activity (Jiang *et al.,* 2024; Machahary *et al.,* 2025). These hybrid materials demonstrate synergistic properties, combining the structural and ion-exchange advantages of MMT with the chemical reactivity and stability of metal oxides, resulting in superior heavy metal removal performance compared to their individual components (Alsohaimi *et al.,* 2023; Zhao *et al.,* 2025).

This review aims to provide a comprehensive overview of the current research on metal oxide-MMT nanocomposites for heavy metal remediation. It focuses on the synthesis strategies, underlying adsorption mechanisms, performance metrics, and environmental applications of these materials (Wang *et al.,* 2024; Zohrabi *et al.,* 2024; Azzaoui *et al.,* 2025). By critically analyzing recent advancements, the review highlights the potential of these nanocomposites as practical solutions for water and soil remediation and identifies key areas for future research to overcome existing challenges and optimize their environmental performance (Arabmofrad *et al.,* 2024).

2. Synthesis and Surface Modification Methods

The synthesis and surface modification of metal oxide montmorillonite (MMT) nanocomposites is pivotal in determining their adsorption capacity, surface area, porosity, stability, and selectivity. Recent studies have highlighted several advanced strategies for integrating metal oxides and polymers into MMT, resulting in enhanced heavy metal removal performance and multifunctional properties, including magnetic separability and photocatalytic activity (Xie *et al.,* 2025; Yuan *et al.,* 2023).

2.1 Hydrothermal and In-Situ Growth Methods

Hydrothermal synthesis is widely used to grow metal oxide nanoparticles directly on MMT under controlled temperature and pressure. This ensures uniform nanoparticle dispersion**,** strong interfacial bonding, and controlled crystallinity, improving adsorption efficiency. ZnO-MnO_2/Montmorillonite composites prepared hydrothermally displayed significantly enhanced heavy metal adsorption due to uniform nanoparticle distribution and increased active sites (Xie *et al.,* 2025). $LaFeO_3$/Montmorillonite composites synthesized via citric-acid-assisted sol-gel methods demonstrated high homogeneity, porosity, and improved photocatalytic properties (Yuan *et al.*, 2023). Hydrothermal methods allow tuning of particle size, morphology, and interlayer spacing, which influence diffusion rates and adsorption kinetics.

2.2 Polymer-Assisted and Organic-Inorganic Approaches

Polymer integration into MMT matrices effectively increases adsorption sites, selectivity, and material flexibility. Polydopamine-modified MMT/chitosan aerogels (PDA-MMT/CS) achieved superior removal of Pb^{2+} and Cu^{2+} ions due to additional functional groups on the clay surface (Yuan *et al.*, 2023). Carboxyl-functionalized MMT/alginate hydrogels show strong adsorption for dyes and metals, emphasizing polymer incorporation to enhance electrostatic interactions and chelation (He *et al.*, 2025). Gelatin-based MMT composites also increased surface functionality, mechanical stability, and recyclability, demonstrating the potential of bio-polymer integration (Abu Elella *et al.*, 2024). Polymers improve dispersibility of metal oxides, reducing aggregation and increasing active surface area.

2.3 Surface Modification and Green Techniques

Surface functionalization with bio-derived modifiers, surfactants, or natural extracts enhances adsorption while maintaining sustainability. Banana peel ash-modified MMT improved methylene blue and heavy metal uptake, demonstrating eco-friendly, low-cost strategies (Arafa *et al.*, 2025; Husaini, 2023a&b). Sodium alginate hydrogels combined with MMT or organo-clays enhance adsorption due to increased functional group density and structural stability (Ling Felicia *et al.*, 2025). Green modifications allow tailoring of surface charge, hydrophilicity, and interlayer spacing, optimizing adsorption kinetics. These techniques reduce chemical waste and lower production costs, making them attractive for large-scale applications.

2.4 Comparative Performance of Methods

Hydrothermal and sol-gel methods yield well-integrated metal oxide phases, providing high surface areas and structural stability, which are critical for adsorption and catalytic performance (Xie *et al.*, 2025). Polymer-assisted and organic hybrid strategies improve functional group density and selectivity for specific pollutants (He *et al.*, 2025; Abu Elella *et al.*, 2024). Bio-based modifications provide sustainable and environmentally friendly pathways for enhancing MMT properties (Arafa *et al.*, 2025; Ling Felicia *et al.*, 2025). Combining methods can optimize structural integrity, adsorption efficiency, and reusability for practical wastewater treatment.

3. Mechanisms of Heavy Metal Adsorption

Understanding the adsorption mechanisms of heavy metal ions on montmorillonite (MMT)-based nanocomposites is essential for optimizing material design and predicting performance. Adsorption typically involves a combination of surface complexation, ion exchange, electrostatic interactions, and pore-diffusion processes**,** all influenced by pH, ionic strength, and surface charge characteristics of the adsorbent (Raji *et al.*, 2023; Salahat *et al.*, 2023; Han *et al.*, 2024). Knowledge of these mechanisms allows researchers to design targeted modifications that enhance pollutant capture efficiency in environmental applications. Understanding the interplay of these processes also aids in predicting adsorption kinetics, selectivity, and regeneration potential under different wastewater conditions.

3.1 Surface Complexation and Coordination

Surface complexation occurs when heavy metal ions form coordination bonds with hydroxyl, oxygen, or functional groups present on the nanocomposite surface. In 2D montmorillonite nanosheets, chemisorption dominated adsorption behavior, and pseudo-second-order kinetics confirmed strong binding of Cu^{2+}, Cd^{2+}, Pb^{2+}, and Cr^{3+} ions (Zhao *et al.,* 2025). Functionalization with polymers, amino groups, or metal oxides introduces additional active sites, increasing inner-sphere complex formation and selectivity (Wang *et al.,* 2024). Surface complexation is highly pH-dependent, as protonation of surface groups can either enhance or inhibit binding. This mechanism also improves the long-term stability of adsorbed ions and contributes to the recyclability of MMT composites. It is particularly effective for heavy metals prone to forming stable coordination complexes, such as Pb^{2+} and Cu^{2+}.

3.2 Ion Exchange within the Layered Structure

Montmorillonite exhibits an intrinsic cation exchange capacity (CEC) due to isomorphic substitution in its 2:1 layered structure. Exchangeable cations (Na^{+}, Ca^{2+}, K^{+}) can be replaced by heavy metal ions, which is a major contributor to adsorption capacity (Ren *et al.,* 2024). Modification with metal oxides or polymers increases interlayer spacing, facilitating access to interior sites and enhancing ion exchange efficiency (Alhinqari *et al.,* 2025). The presence of competing cations in solution can influence selectivity, making it critical to consider ionic strength and solution chemistry. This mechanism is reversible, enabling regeneration and reuse of adsorbents. Ion exchange often works in synergy with surface complexation, especially in mixed-metal systems. It also provides a predictable pathway for targeted heavy metal removal in industrial wastewater.

3.3 Electrostatic Attraction and Surface Charge Effects

Electrostatic interactions result from attraction between negatively charged MMT surfaces and positively charged heavy metal ions. Surface charge is highly pH-dependent, with neutral to slightly basic conditions favoring negative charges that enhance adsorption (Han *et al.,* 2024). Functionalization with oxygen-containing groups or carboxyl moieties increases the density of negative sites, promoting stronger binding of Pb^{2+}, Cd^{2+}, and Ni^{2+} ions (Santosh *et al.,* 2024). Electrostatic attraction typically dominates the initial rapid adsorption phase, followed by slower processes such as complexation or pore diffusion. This mechanism can be influenced by ionic strength, as higher concentrations of competing cations reduce adsorption efficiency. Understanding these effects allows for optimization of adsorption conditions for real-world wastewater treatment.

3.4 Pore Diffusion and Physical Adsorption

Physical adsorption occurs when metal ions are trapped in micro- and mesopores of the nanocomposite via van der Waals forces or hydrogen bonding. Composites such as biochar/Montmorillonite exhibit high surface area and well-developed pore networks, enabling multilayer adsorption of heavy metals and organic contaminants (Pylypenko, 2025). Pore diffusion often represents the rate-limiting step during adsorption of larger ions or high-concentration solutions. Optimizing pore size distribution and connectivity enhances diffusion rates and adsorption capacity. Physical adsorption also complements surface complexation and ion exchange, particularly in heterogeneous systems. It provides additional stabilization of ions before stronger chemical interactions occur, increasing the overall efficiency of MMT-based adsorbents.

3.5 Synergistic and Competitive Mechanisms

In practice, adsorption is governed by a synergistic interplay of surface complexation, ion exchange, electrostatic attraction, and physical adsorption (Zhao *et al.,* 2025; Wang *et al.,* 2024). Environmental parameters such as pH, ionic strength, and metal speciation determine which mechanism predominates. Modified MMT composites may also exhibit surface precipitation of metal hydroxides under alkaline conditions, further immobilizing contaminants (Chen *et al.,* 2025; Alhinqari *et al.,* 2025). Understanding these interactions enables tailored design of montmorillonite-based adsorbents for specific heavy metal remediation tasks. Synergistic mechanisms improve adsorption kinetics, total capacity, and adsorbent reusability, making them highly suitable for industrial wastewater treatment applications.

4. Adsorption Performance and Mathematical Modelling of Metal Oxide montmorillonite Nanocomposites

Evaluating the adsorption performance of metal oxide montmorillonite (MMT) nanocomposites requires a combination of experimental studies and mathematical modeling. Key aspects include adsorption kinetics, equilibrium isotherms, thermodynamics, and performance metrics. Mathematical models allow prediction of adsorption capacity, removal efficiency, and design of treatment systems. Metal oxide-MMT nanocomposites typically show rapid initial adsorption due to abundant active sites, followed by slower equilibrium stages governed by intra-particle diffusion (Chen *et al.,* 2025; Ali *et al.,* 2025). Understanding the adsorption behavior under various environmental conditions, such as pH, temperature, and competing ions, is crucial for practical wastewater treatment applications. These models also provide a basis for scaling laboratory results to pilot or industrial systems while ensuring efficiency, selectivity, and sustainability.

4.1 Adsorption Kinetics

Kinetic studies reveal the rate-limiting steps in adsorption and help optimize contact times for maximum efficiency. Common models include:

Pseudo-first-order:

$$\ln (q_e - q_t) = \ln q_e - k_1 t \qquad \textbf{Eqn. 1}$$

Pseudo-second-order:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \qquad \textbf{Eqn. 2}$$

Intra-particle diffusion (Weber-Morris model):

$$q_t = k_{id} \sqrt{t} + C \qquad \textbf{Eqn. 3}$$

Where q_t is the adsorption capacity at time t (mg/g), q_e is the equilibrium adsorption capacity (mg/g), k_1 and k_2 are rate constants, k_{id} is the intra-particle diffusion constant, and C is the boundary layer effect constant (Kumar *et al.,* 2025). Initial rapid adsorption occurs due to abundant active sites, followed by slower stages controlled by intra-particle diffusion and surface saturation. Kinetic modeling helps distinguish chemisorption from physisorption and guides the selection of operational conditions for maximum metal removal.

4.2 Adsorption Isotherms

Equilibrium isotherms describe how metal ions interact with the adsorbent surface and predict adsorption under different concentrations.

Langmuir isotherm (monolayer adsorption):

$$\frac{1}{q_e} = \frac{1}{q_{max} K_L C_e} + \frac{1}{q_{max}} \qquad \textbf{Eqn. 4}$$

Freundlich isotherm (heterogeneous surfaces):

$$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e \qquad \textbf{Eqn. 5}$$

Temkin isotherm (adsorbate-adsorbent interactions):

$$q_e = \frac{RT}{b_T} \ln (K_T C_e) \qquad \textbf{Eqn. 6}$$

Where q_{max} is maximum adsorption capacity (mg/g), K_L, K_f, K_T are isotherm constants, C_e is equilibrium concentration (mg/L), R is the universal gas constant, T is temperature (K), b_T is a Temkin constant, and n is the heterogeneity factor (Patel *et al.*, 2025; Mehta *et al.*, 2025). Comparing different isotherm models helps identify the surface heterogeneity, adsorption energy distribution, and potential monolayer or multilayer adsorption. These insights are essential for predicting performance in varying wastewater matrices.

4.3 Thermodynamic Analysis

Thermodynamic parameters indicate the feasibility, spontaneity, and nature of adsorption processes.

$$\Delta G = - R \times T \times \ln(K_C) \qquad \textbf{Eqn. 7}$$

$$\ln K_c = \frac{\Delta S}{R} - \frac{\Delta H}{RT} \qquad \textbf{Eqn. 8}$$

Where ΔG is Gibbs free energy (kJ/mol), ΔH is enthalpy (kJ/mol), ΔS is entropy (J/mol·K), K_C is equilibrium constant, R is the gas constant, and T is temperature (K) (Chen *et al.*, 2025). Negative ΔG indicates spontaneous adsorption, while positive ΔH suggests endothermic behavior. Positive ΔS reflects increased randomness at the solid-solution interface during metal ion uptake. Thermodynamic evaluations allow prediction of adsorption performance at different temperatures and help determine energy requirements for practical applications.

4.4 Adsorption Capacity and Removal Efficiency

Performance metrics are critical for comparing different nanocomposites and designing treatment systems.

$$q_e = \frac{(C_0 - C_e) \times v}{m} \qquad \textbf{Eqn. 9}$$

$$R\ (\%) = \frac{C_0 - C_e}{C_0} \times 100 \qquad \textbf{Eqn. 10}$$

Where C_0 and C_e are initial and equilibrium concentrations (mg/L), V is solution volume (L), and m is adsorbent mass (g) (Zhang *et al.,* 2025). Additional metrics include the distribution coefficient (k_d) and regeneration efficiency, which are crucial for evaluating adsorbent reuse and long-term sustainability. High q_e and R (%) values indicate strong adsorption potential, while repeated adsorption-desorption studies ensure reliability under real wastewater conditions. This evaluation also informs the design of pilot-scale or industrial treatment units.

4.5 Advanced Modeling and Predictive Approaches

Emerging techniques integrate computational modeling and machine learning to predict adsorption performance and optimize nanocomposite design. Density Functional Theory (DFT) and molecular dynamics simulations provide atomic-level insights into binding energies, adsorption sites, and electron transfer mechanisms (Sun *et al.,* 2025; Husaini, 2024a). Machine learning models predict adsorption capacity and kinetics using variables like pH, temperature, initial concentration, and material properties (Ali *et al.,* 2025). These methods can simulate multi-ion solutions, dynamic flow conditions, and complex wastewater matrices, bridging lab-scale experiments and field-scale applications. Predictive modeling supports the design of next-generation metal oxide-MMT composites with improved selectivity, higher adsorption capacity, and enhanced recyclability, ensuring practical applicability in real-world wastewater remediation.

5. Adsorption Mechanisms of Metal Oxide montmorillonite Nanocomposites

The adsorption of heavy metals by metal oxide montmorillonite (MMT) nanocomposites is governed by multiple mechanisms, which often act synergistically to enhance efficiency. These mechanisms include electrostatic interactions, ion exchange, surface complexation, and chelation**,** supported by the layered structure of MMT and the high surface reactivity of metal oxide nanoparticles. Understanding these mechanisms is crucial for optimizing adsorption capacity, selectivity, and stability, particularly under complex environmental conditions. Adsorption kinetics often follow pseudo-second-order models, indicating chemisorption as a dominant process, while isotherm studies frequently conform to the Langmuir model, suggesting monolayer coverage on homogeneous surfaces (Wang *et al.,* 2025; Gupta *et al.,* 2024).

5.1 Electrostatic Interactions

Electrostatic interactions occur between charged heavy metal ions and oppositely charged functional groups on the nanocomposite surface. The surface charge of MMT and incorporated metal oxides is highly dependent on pH, influencing adsorption efficiency. At pH values above the point of zero charge (pHpzc), negatively charged surfaces attract cationic metal ions, resulting in rapid initial adsorption (Wang *et al.,* 2025). This mechanism is particularly important for the fast removal stage observed in kinetic studies. Modification with polymers or bio-based materials can introduce additional charged functional groups, enhancing electrostatic attraction and improving selectivity in solutions containing multiple contaminants. Electrostatic interactions often complement other adsorption mechanisms to ensure efficient removal under varying environmental conditions.

5.2 Ion Exchange

Ion exchange is a fundamental mechanism for MMT-based nanocomposites, where exchangeable cations in the clay layers are replaced by heavy metal ions in solution. The layered structure of montmorillonite provides accessible interlayer sites that facilitate cation exchange, while embedded metal oxides can introduce additional exchangeable ions (Gupta *et al.*, 2024). This mechanism is especially effective for divalent and trivalent metals, including Pb^{2+}, Cd^{2+}, and Cr^{3+}. Ion exchange also allows partial regeneration of the adsorbent, as exchanged metal ions can be displaced during desorption, supporting multiple cycles of reuse. Optimizing interlayer accessibility and functional group density is key to maximizing ion exchange efficiency.

5.3 Surface Complexation

Surface complexation occurs when metal ions form coordination bonds with oxygen-containing functional groups such as hydroxyl, carboxyl, or silanol groups on the nanocomposite surface. Metal oxide nanoparticles like Fe_3O_4, TiO_2, and ZnO contribute additional active sites, enhancing complex formation and selectivity (Huang *et al.*, 2025). This mechanism is significant for transition metals such as Cu^{2+}, Ni^{2+}, and Co^{2+}. Environmental parameters, including pH and ionic strength, influence the extent of surface complexation. Strong coordination bonds formed through this process improve the stability of adsorbed ions, minimizing leaching and ensuring long-term effectiveness in wastewater and soil remediation.

5.4 Chelation and Multifunctional Mechanisms

Chelation involves the formation of ring-like structures between metal ions and multiple ligands on the nanocomposite surface. Polymer-functionalized or bio-modified MMT composites can enhance chelation through nitrogen- or oxygen-containing functional groups, increasing selectivity and binding strength (Li *et al.*, 2025). Often, chelation works alongside electrostatic attraction and surface complexation, creating synergistic effects that stabilize metal ions. These multifunctional mechanisms allow the simultaneous removal of heavy metals and organic pollutants. Understanding these interactions is essential for designing high-performance nanocomposites suitable for complex wastewater matrices.

5.5 Synergistic and Emerging Mechanisms

Recent advances highlight that multiple adsorption mechanisms often act simultaneously to improve efficiency. Electrostatic attraction initially brings ions to the surface, followed by chelation or surface complexation for strong binding (Zhao *et al.*, 2025). Emerging strategies include photo-assisted adsorption**,** where TiO_2 or ZnO nanoparticles generate reactive species under light, enabling simultaneous degradation of organic contaminants and heavy metal adsorption. Magnetic nanoparticles facilitate easy recovery and reuse, while bio-polymer modifications introduce additional functional groups, enabling multi-ion capture in complex effluents (Sun *et al.*, 2025). These synergistic mechanisms are essential for next-generation nanocomposites aimed at comprehensive environmental remediation, combining efficiency, selectivity, and sustainability.

6. Environmental Applications of Metal Oxide montmorillonite Nanocomposites

Metal oxide montmorillonite (MMT) nanocomposites have gained significant attention in environmental remediation due to their high adsorption capacity, large surface area, tunable porosity, and multifunctionality. These nanocomposites are applied in treating industrial effluents, contaminated groundwater, and polluted soils, targeting heavy metals, dyes, and emerging contaminants. The synergistic combination of MMT's layered structure and the functional properties of metal oxides enhances adsorption efficiency. Recent studies report successful removal of Pb^{2+}, Cd^{2+}, Cr^{6+}, Hg^{2+}, and organic pollutants such as dyes and pharmaceutical residues (Patel *et al.*, 2025; Hamza *et al.*, 2025; Khan *et al.*, 2024; Husani, 2024b). Furthermore, the recyclability and regeneration potential of these materials make them promising for sustainable environmental applications.

6.1 Wastewater Treatment

Metal oxide-MMT nanocomposites have been effectively applied for industrial and municipal wastewater treatment. Their ability to remove heavy metals such as Pb^{2+}, Cd^{2+}, and Cr^{6+} is enhanced by electrostatic attraction, ion exchange, and surface complexation mechanisms. Integration of ZnO, Fe_3O_4, or TiO_2 nanoparticles improves adsorption kinetics and overall capacity (Patel *et al.*, 2025). In addition to heavy metals, these composites efficiently remove organic dyes such as methylene blue and methyl orange through π-π interactions and hydrogen bonding (Latifi *et al.*, 2025). Some studies also highlight their potential for removing pharmaceutical residues like antibiotics and analgesics. The versatility and high efficiency of metal oxide-MMT composites make them suitable for treating complex effluents with mixed contaminants, enabling more comprehensive wastewater management.

6.2 Groundwater Remediation

Groundwater contamination with heavy metals and metalloids is a major environmental issue worldwide. Metal oxide-MMT nanocomposites are capable of adsorbing Pb^{2+}, As^{3+}, Cd^{2+}, and Cr^{6+} from contaminated aquifers (Khan *et al.*, 2024). Their layered structure provides slow-release adsorption, maintaining long-term efficiency. Surface functionalization with polymers or bio-based agents improves selectivity toward target ions in the presence of competing cations. Pilot-scale studies indicate that the materials retain high removal efficiency under variable temperature, pH, and ionic strength conditions, demonstrating their suitability for real-world groundwater remediation. Magnetic composites allow easy recovery of the adsorbent, further increasing practical applicability.

6.3 Soil Remediation

Metal oxide-MMT nanocomposites are also used to stabilize or immobilize heavy metals in contaminated soils. Adsorption of Pb^{2+}, Cd^{2+}, and Ni^{2+} reduces bioavailability and prevents leaching into groundwater (Rao *et al.*, 2025). These composites can be applied as soil amendments, improving adsorption capacity while maintaining soil fertility and permeability. Chelation, ion exchange, and electrostatic interactions contribute to heavy metal stabilization. Field studies suggest that the use of nanocomposites in soils minimizes environmental risks and supports sustainable remediation strategies. Their multifunctionality allows simultaneous treatment of metals and organic contaminants, offering a comprehensive approach to soil cleanup.

6.4 Industrial Effluent Treatment

Effluents from mining, electroplating, textiles, and chemical industries often contain high concentrations of heavy metals and dyes (Akartasse *et al.*, 2022; N'diaye *et al.*, 2022; Husaini and Ibrahim, 2025). Metal oxide-MMT composites efficiently remove these contaminants due to their high surface area, porosity, and abundance of functional groups (Mehta *et al.*, 2025). Polymer or bio-based surface modifications enhance adsorption selectivity and regeneration efficiency. Continuous flow systems using these composites have demonstrated rapid pollutant removal, high stability, and low operational costs. Moreover, combining adsorption with photocatalytic degradation allows simultaneous removal of heavy metals and degradation of organic dyes, increasing environmental treatment efficiency.

6.5 Emerging Applications

Beyond conventional remediation, metal oxide-MMT nanocomposites are being explored for photocatalytic degradation of pollutants, antimicrobial water treatment, and removal of pharmaceuticals and personal care products (Sharma *et al.*, 2025; Patel *et al.*, 2025). Metal oxides such as TiO_2 or Fe_3O_4 confer photocatalytic activity, enabling simultaneous adsorption of heavy metals and decomposition of organic pollutants. Magnetic composites allow easy recovery and reuse of adsorbents. These multifunctional applications expand the environmental relevance of nanocomposites, making them suitable for modern wastewater treatment, soil remediation, and safe reuse of water resources. Integration with bio-based polymers enhances sustainability and reduces overall environmental impact.

7. Challenges and Future Perspectives

Despite the promising performance of metal oxide montmorillonite (MMT) nanocomposites in heavy metal removal, several challenges remain before large-scale environmental deployment. Issues such as nanocomposite stability, aggregation, regeneration efficiency, and scalability limit practical applications. Long-term environmental effects, including potential nanoparticle leaching and accumulation in ecosystems, are not fully understood (Husaini, 2026b&c). Optimizing synthesis methods and surface modification strategies can improve structural stability, adsorption capacity, and selectivity. Future research should focus on developing eco-friendly, cost-effective, and multifunctional nanocomposites that maintain high performance under realistic environmental conditions (Zhou *et al.*, 2025; Ali *et al.*, 2024). Integrating computational modeling and pilot-scale studies can guide the translation from lab-scale success to industrial application.

7.1 Stability and Structural Challenges

A major limitation is the stability of metal oxide nanoparticles embedded in the MMT matrix. Nanoparticle aggregation can significantly reduce active surface area and adsorption efficiency. Hydrothermal synthesis, polymer functionalization, or bio-based modification can enhance dispersion and interfacial adhesion (Zhou *et al.*, 2025). Environmental factors such as pH, ionic strength, and temperature fluctuations can affect stability during adsorption, while fouling from organic or inorganic substances can block active sites, reducing efficiency. Engineering the surface properties to resist fouling and maintaining nanoparticle dispersion remain critical challenges for practical environmental applications (Husaini, 2026d).

7.2 Regeneration and Reusability Limitations

Although metal oxide-MMT nanocomposites can be regenerated, repeated use often leads to gradual loss of adsorption capacity. Chemical regeneration using acids or bases may alter or remove functional groups, while thermal regeneration can recover capacity but increase energy consumption (Ali *et al.*, 2024). Developing mild and sustainable regeneration protocols is essential to maintain adsorbent performance without environmental harm. Studies should also evaluate long-term adsorbent stability in real wastewater, where complex mixtures of contaminants can affect adsorption sites and overall efficiency. Ensuring consistent performance over multiple cycles is vital for industrial feasibility.

7.3 Scalability and Economic Considerations

Scaling up nanocomposite production from laboratory to industrial levels presents technical and economic challenges. Low-cost precursors, simplified synthesis methods, and low-energy fabrication are required for commercial adoption (Cheng *et al.*, 2025). Continuous flow systems need optimization for flow rate, contact time, and sorbent packing to achieve consistent removal efficiency. Integrating these nanocomposites into existing wastewater treatment infrastructure may reduce costs and facilitate practical implementation. Conducting life cycle assessments and techno-economic analyses ensures that scale-up strategies are both environmentally and economically sustainable.

7.4 Future Perspectives

Future research should focus on developing multi-functional nanocomposites capable of removing multiple contaminants simultaneously. Incorporating magnetic nanoparticles, bio-polymers, and green synthesis techniques can improve selectivity, recyclability, and ease of separation. Advanced computational modeling, artificial intelligence, and machine learning approaches can predict adsorption performance, guide optimal design, and reduce experimental trials. Field-scale studies and pilot projects are critical to validate laboratory results in realistic environments (Husaini *et al.*, 2024c). Interdisciplinary collaboration between scientists, engineers, and policymakers will accelerate the translation of these materials into practical, sustainable solutions for environmental remediation.

Table 1: Reviewed Literature

Nanocomposite Type / Modification	Target Pollutants	Method Used	Reference
ZnO-MnO_2 / Montmorillonite	Pb^{2+}, Cu^{2+}	Hydrothermal growth	Xie *et al.*, 2025
$LaFeO_3$ / Montmorillonite	Pb^{2+}, Cd^{2+}	Sol-gel, citric acid assisted	Yuan *et al.*, 2023
Carboxyl-functionalized MMT / Alginate	Cu^{2+}, Pb^{2+}	Polymer-assisted hydrogel formation	He *et al.*, 2025
Gelatin-modified MMT	Pb^{2+}, Cd^{2+}	Bio-polymer integration	Abu Elella *et al.*, 2024
Banana peel ash-MMT	Methylene Blue, Pb^{2+}	Surface functionalization	Arafa *et al.*, 2025
Sodium alginate-MMT	Pb^{2+}, dyes	Hydrogel / surface functionalization	Ling Felicia *et al.*, 2025
Metal oxide-MMT composites	Pb^{2+}, Cu^{2+}	Batch adsorption	Li *et al.*, 2025
Metal oxide-MMT	Pb^{2+}, Cd^{2+}	Batch adsorption	Zhang *et al.*, 2025
MMT-TiO_2 / Metal oxide	Pb^{2+}, Hg^{2+}	DFT / molecular modeling	Chen *et al.*, 2025
Metal oxide-MMT	Pb^{2+}, Cu^{2+}	Machine learning prediction	Ali *et al.*, 2025
MMT-ZnO / Metal oxide	Pb^{2+}, Cd^{2+}	Kinetic modeling	Kumar *et al.*, 2025
Fe_2O_3-MMT	Pb^{2+}, Cu^{2+}	Isotherm studies	Patel *et al.*, 2025

MMT-CuO	Pb^{2+}, Zn^{2+}	Isotherm evaluation	Mehta *et al.*, 2025
MMT-Mixed metal oxides	Pb^{2+}, Cr^{6+}	Molecular dynamics / simulation	Sun *et al.*, 2025
Fe_3O_4-MMT	Pb^{2+}, Cd^{2+}	Thermodynamic evaluation	Zhang *et al.*, 2025
TiO_2-MMT	Pb^{2+}, Ni^{2+}	Sol-gel synthesis	Wang *et al.*, 2024
ZnO-MMT	Cu^{2+}, Cd^{2+}	Co-precipitation method	Singh *et al.*, 2024
MgO-MMT	Pb^{2+}, Cr^{6+}	Hydrothermal-assisted calcination	Liu *et al.*, 2024
Fe_3O_4-MMT / Chitosan	Pb^{2+}, Hg^{2+}	Surface functionalization	Sharma *et al.*, 2024
CuO-MMT	Cd^{2+}, Ni^{2+}	Sol-gel-assisted polymer integration	Gupta *et al.*, 2024
NiO-MMT	Pb^{2+}, Cu^{2+}	Hydrothermal synthesis	Zhao *et al.*, 2024
Co_3O_4-MMT	Cr^{6+}, Pb^{2+}	Co-precipitation	Patel *et al.*, 2024
MnO_2-MMT	Cu^{2+}, Zn^{2+}	Surface modification	Ramesh *et al.*, 2024
TiO_2-Fe_3O_4-MMT	Pb^{2+}, Cd^{2+}	Magnetic nanocomposite synthesis	Lee *et al.*, 2024
ZnO-Al_2O_3-MMT	Pb^{2+}, Hg^{2+}	Hydrothermal co-precipitation	Kim *et al.*, 2024

Conclusion

Metal oxide-montmorillonite nanocomposites represent a versatile and effective class of adsorbents for heavy metal removal from wastewater. The combination of metal oxides with montmorillonite enhances surface area, functional group density, and structural stability, resulting in high adsorption capacities and rapid kinetics. Various synthesis and surface modification techniques; including hydrothermal, sol-gel, polymer-assisted, and bio-based green methods play a pivotal role in tuning the adsorption performance. Adsorption studies, including kinetics, isotherms, and thermodynamics, demonstrate that these nanocomposites can achieve efficient and selective removal of heavy metals under varying environmental conditions. Advanced computational tools, such as molecular dynamics and machine learning, provide predictive insights that bridge laboratory findings with practical applications. Overall, metal oxide-MMT nanocomposites offer a promising, sustainable solution for industrial and municipal wastewater treatment, with potential for scale-up, regeneration, and multi-pollutant remediation.

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