Recent progresses of magnetically-controlled adsorption materials in the detection of environmental pollutants

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Abstract: Environmental pollutants, such as heavy metals, textile dyes, and emerging contaminants, pose significant risks to ecosystems and human health, necessitating the development of effective detection and remediation strategies. Traditional methods often lack sensitivity, stability, and operational efficiency. This review highlights recent advancements in magnetically-controlled adsorption materials, including magnetic carbon materials, magnetic metal-organic frameworks (MOFs), and magnetic composites. These materials leverage magnetic responsiveness and advanced adsorption capabilities for efficient separation and high selectivity, even at trace concentrations. Key aspects, including synthesis strategies, structural features, and application in pollutant adsorption, are comprehensively examined. While challenges such as scalability and long-term stability persist, emerging innovations in green synthesis, functionalization, and hybrid material development offer promising solutions. By combining advanced functionalities with sustainable practices, magnetically-controlled adsorption materials present transformative potential for environmental monitoring and remediation, paving the way for sustainable pollutant management.

1. Introduction

With rapid agricultural and industrial development come emerging concerns about environmental pollution, particularly regarding the harmful effects of diverse pollutants on human health. These environmental pollutants, though present in trace concentration in different environments, can still cause significant health and ecological impacts. Residues of pollutants such as heavy metal, pharmaceutical compounds, and pesticides in food and water environment are of particular interest due to their high risk of entering human body even at trace concentration. Thus, it is necessary to advance methods to improve detection sensitivity for trace-level environmental pollutants, which is essential to safeguarding public health and environmental safety.

In recent years, environmental pollutants like heavy metals, organic pollutants, and emerging contaminants have received increasing attention due to their persistence in the environment and toxicity. Heavy metals like lead (Pb) pose serious health risks, affecting the respiratory, cardiovascular, and nervous systems even at low concentrations [1-2]. Organic pollutants, particularly textile dyes, are non-biodegradable and carcinogenic, contaminating water sources critical for life [3-5]. Emerging contaminants, including pharmaceuticals and pesticides, accumulate in wastewater and can lead to cytotoxicity, neurotoxicity, and endocrine disorders [6-7]. These pollutants present challenges for trace-level detection, highlighting the need for effective monitoring methods.

Traditional methods of detection of environmental pollutants such as Ultraviolet-Visible (UV-Vis) Spectroscopy, Enzyme-Linked Immunosorbent Assay (ELISA), Capillary Electrophoresis (CE) and X-ray Fluorescence (XRF) face significant limitations, including low adsorption capacity, potential for secondary pollution, stability issues, and most notably, limited sensitivity for detecting ultra-low concentration pollutants at trace level. Magnetically-controlled adsorption materials, on the other hand, are high-efficiency adsorbents activated by an external magnetic field. These materials feature the ability to rapidly adsorb and separate specific hazardous pollutants. These materials offer high adsorption capacity, enabling them to capture significant amounts of pollutants even at low concentrations, along with easy separation using external magnetic fields, which is critical for minimizing sample contamination and reducing handling times. Additionally, they provide enhanced detection sensitivity for low trace-level contaminants, making them highly effective for environmental monitoring and water treatment applications.

Herein, this review systematically summarizes the progress in detecting typical environmental pollutants in the past three years. This review aims to identify and classify several popular magnetically-controlled adsorption materials, focusing on the trends in synthesis of novel functional material and applications in major environmental pollutant detection. Magnetic carbon materials, magnetic metal organic frameworks, and magnetic composites are thoroughly examined for their potential and application. The applications of these

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*Corresponding author's email: zjack429@gmail.com materials are categorized based on their effectiveness in detecting a range of different environmental pollutants. We firmly believe this review provides meaningful references and inspire broader insights for future research.

2. Typical Magnetically-Controlled Adsorption Materials

Magnetically-controlled adsorption materials represent a versatile class of adsorbents designed to tackle environmental pollution challenges through their exceptional combination of high efficiency, recyclability, and selectivity. These materials capitalize on the magnetic responsiveness of embedded nanoparticles, allowing for rapid separation and recovery under external magnetic fields, which significantly reduces the operational complexity and cost compared to conventional adsorption techniques. Their ability to function across diverse environmental conditions, coupled with tailored surface functionalities, ensures precise interactions with a wide range of pollutants, from heavy metals to emerging contaminants. Moreover, the scalability and adaptability of these materials make them ideal candidates for addressing the growing demand for sustainable and cost-effective pollutant remediation technologies. By integrating high adsorption capacities with advanced recovery mechanisms, magnetically-controlled adsorption materials have the potential to revolutionize the field of environmental cleanup, offering a robust solution to some of the most pressing global challenges.

This section explores the typical materials, focusing on their synthesis and structural characteristics, highlighting their potential to mitigate environmental pollution effectively.

The subsequent subsections mainly focusing on following typical materials, such as magnetic carbon materials, magnetic MOFs, and magnetic composites, which provides a comprehensive understanding of their development and role in pollutant adsorption. These materials leverage magnetic nanoparticles, such as Fe_3O_4 or γ-Fe_2O_3, to enable rapid separation and recovery under external magnetic fields, minimizing the complexity and cost of operational processes. By embedding magnetic components into various frameworks, such as carbonaceous materials, metal-organic frameworks (MOFs), or composite structures, these materials exhibit tailored functionalities and superior adsorption capabilities.

2.1. Magnetic Carbon Materials

Magnetic carbon materials are a class of advanced adsorbents that combine the high surface area, porosity, and chemical stability of carbon with the magnetic properties of embedded metal or metal oxide nanoparticles. These materials have gained significant attention for environmental applications due to their efficiency in pollutant adsorption, chemical stability, and ease of recovery using external magnetic fields. It is worth noting that the synthesis methods and structural characteristics of magnetic carbon materials significantly influence their performance. For example, the uniform integration of magnetic nanoparticles within the carbon framework determines the material's adsorption capacity, magnetic responsiveness, and surface functionality. The structure is largely dependent on the synthesis method employed, as parameters like precursor type, activation technique, and pyrolysis conditions dictate the final porosity, surface area, and functional group distribution.

The synthesis of magnetic carbon materials involves several methods designed to ensure uniform integration of magnetic components into the carbon framework. Biomass carbonization, for instance, utilizes agricultural and industrial wastes, such as corncob shells and agro-waste, which are converted into carbonaceous materials through pyrolysis in the presence of magnetic precursors. This approach is both cost-effective and sustainable, as it relies on renewable precursors and ensures high porosity [8]. Chemical activation is another widely used method, where precursor materials are treated with activating agents like KOH or H_3PO_4 to enhance porosity and specific surface area while embedding magnetic elements. For instance, Pan et al. (2022) [9] demonstrated that cobalt-seamed nanocapsules activated by KOH exhibited superior adsorption capacities due to their high surface area and uniform magnetic nanoparticle distribution. Controlled pyrolysis of metal-organic frameworks (MOFs) is another advanced approach, yielding structured carbon composites with integrated magnetic properties. This method preserves the high porosity and tunable structure of the original MOFs, allowing for exceptional adsorption and magnetic separation performance [10-11].

Magnetic carbon materials exhibit a hybrid structure that combines the robust framework of carbon with the functional benefits of magnetic components. These materials are characterized by high porosity and surface area, which enhance adsorption kinetics by providing numerous active sites for pollutant capture. For example, magnetic carbon composites derived from MOFs and biomass can exhibit surface areas exceeding 500 m^2/g [12-13]. The presence of oxygen- and nitrogen-containing groups contributes to strong binding interactions with a variety of pollutants, enhancing adsorption selectivity and capacity. Embedded magnetic nanoparticles, such as Fe_3O_4 or γ-Fe_2O_3, enable easy separation and recyclability using external magnetic fields, simplifying operational workflows and reducing secondary pollution risks [14]. These materials show significant potential for a wide range of environmental applications due to their customizable properties and ease of recovery.

These structural characteristics are reflected through various characterization methods. Techniques like Brunauer-Emmett-Teller surface area analysis quantify porosity and surface area, critical for optimizing adsorption efficiency [10]. Scanning Electron Microscopy and Transmission Electron Microscopy provide insights into morphology and nanoparticle distribution, while X-ray Diffraction confirms crystalline structure and phase purity [8,11]. Vibrating Sample Magnetometry measures magnetic properties, such as saturation magnetization, crucial for ensuring rapid separation under external magnetic fields [9]. Fourier Transform Infrared Spectroscopy and X-ray Photoelectron Spectroscopy identify functional groups and surface chemistry, linking material composition to pollutant adsorption capacity, while Thermogravimetric Analysis evaluates thermal stability under operational conditions [11]. These methods collectively enable comprehensive assessment and optimization of magnetic carbon materials for environmental applications.

Despite their promising features, the broader adoption of magnetic carbon materials faces challenges. Developing cost-effective synthesis methods for large-scale production while maintaining material performance remains difficult. Additionally, ensuring the long-term stability of the magnetic-carbon interface during repeated use is critical to achieving consistent performance. Nonetheless, these materials hold great promise as solutions for addressing environmental pollution challenges due to their high adsorption efficiency, ease of recovery, and sustainable synthesis.

2.2. Magnetic Metal-Organic Frameworks (MOFs)

Magnetic Metal-Organic Frameworks (MOFs) are a class of hybrid materials that combine the high surface area, tunable porosity, and customizable functionalities with the magnetic properties of embedded nanoparticles. This synergy endows them with exceptional potential for diverse environmental applications, including pollutant detection, gas storage, and water treatment. MOFs have become a prominent research focus in recent years due to their versatility, with performance largely determined by structural modification techniques. Methods such as functionalizing organic ligands, doping metal centers, and optimizing pore structures enable the tailoring of MOFs for specific adsorption and catalytic functions [14].

The synthesis of magnetic MOFs typically involves integrating magnetic nanoparticles into the crystalline framework of traditional MOFs. Hydrothermal and solvothermal synthesis are the most commonly employed methods. These techniques utilize high-temperature and high-pressure conditions to drive the self-assembly of metal ions and organic ligands into well-ordered crystalline structures. Hydrothermal synthesis, for example, is widely used to produce Fe_3O_4@UiO-66 composites by incorporating Fe_3O_4 nanoparticles within a UiO-66 framework. This composite leverages the framework's high porosity and the nanoparticles' superparamagnetic properties, making it effective for pollutant removal and separation [15]. Solvothermal synthesis, on the other hand, has been applied to fabricate Cu-BTC-based MOFs with embedded magnetic nanoparticles, resulting in high stability and enhanced adsorption capacities [16]. Beyond these traditional approaches, other advanced synthesis methods have been developed. The post-synthetic modification technique allows for the introduction of magnetic components into pre-formed MOF structures. This method offers precise control over magnetic nanoparticle dispersion and maintains the integrity of the MOF's crystalline framework [14]. Spray-drying has also emerged as an innovative method, enabling the large-scale production of magnetic MOFs with uniform particle sizes and enhanced surface functionalities [17]. These diverse synthetic strategies not only expand the range of achievable material properties but also open new avenues for application-specific design.

Magnetic MOFs are characterized by their high surface area, often exceeding 1000 m²/g, and superparamagnetic properties that allow for easy recovery via an external magnetic field. Fe_3O_4@UiO-66 composites exhibit a surface area of 1200 m²/g, making them highly effective in adsorbing pollutants. The porous structure of MOFs, coupled with tunable metal centers and organic ligands, provides flexibility for designing materials with specific adsorption properties [7]. These features enable magnetic MOFs to address complex environmental challenges by efficiently targeting diverse pollutants and adapting to specific remediation needs.

While magnetic MOFs offer advantages such as high adsorption capacity and recyclability, their performance can be significantly constrained by factors such as structural instability under harsh conditions and the complexity of large-scale synthesis, necessitating further innovation to unlock their full potential. Despite these limitations, their customizability and efficiency position them as valuable tools for environmental remediation and resource recovery.

2.3. Magnetic Composites

Magnetic composites are hybrid materials that combine magnetic nanoparticles with polymers, carbon-based materials, or other structural components. This integration capitalizes on the superparamagnetic properties of nanoparticles, enabling easy recovery and separation under external magnetic fields, while leveraging the functional versatility of other components to enhance adsorption, catalytic, and sensor applications. Their adaptability across various applications highlights their potential as a solution to complex environmental challenges. Moreover, magnetic composites can be engineered to possess advanced properties, such as hydrophobicity, mechanical flexibility, or elasticity, which distinguish them from other magnetically-controlled materials, offering superior performance in dynamic and harsh conditions [18].

Magnetic composites are typically synthesized by methods such as co-precipitation, sol-gel processes, hydrothermal synthesis, or in situ polymerization, offering unique advantages. Co-precipitation is a straightforward and cost-effective method that ensures homogeneous nanoparticle distribution within the composite matrix [19]. Sol-gel processes enable the precise control of particle size and pore structure, making them suitable for applications requiring high material uniformity. Hydrothermal synthesis facilitates the formation of composites with enhanced crystallinity and stability under high-temperature and high-pressure conditions. For instance, Fe_3O_4-based composites synthesized via hydrothermal techniques exhibit superior surface area and functional versatility [18]. In situ polymerization integrates magnetic nanoparticles into polymer matrices like polystyrene or polyvinyl alcohol, resulting in materials that combine the strength and flexibility of the polymer with the magnetic responsiveness of nanoparticles [20]. These diverse approaches allow the tailoring of magnetic composites for specific environmental applications.

Magnetic composites exhibit structural characteristics and unique properties, such as high surface area, superparamagnetism, and functionalized surfaces. Their mechanical flexibility and hydrophobic properties set them apart from other magnetically-controlled materials, allowing for enhanced durability and operational stability. Beyond these features, magnetic composites offer additional benefits, such as hydrophobicity and elastic behavior in certain formulations, enabling versatility in complex environmental conditions. Graphene oxide-based composites enhance π-π interactions and electrostatic attractions, which are pivotal for removing aromatic pollutants [18,21]. Additionally, the mechanical robustness of polymer-integrated composites ensures durability during repeated use [14]. Fe_3O_4/graphene oxide composites achieve adsorption capacities of up to 160 mg/g for Pb^{2+}, showcasing exceptional efficiency in environmental remediation. Magnetic composites are also increasingly adopted in catalytic and sensor technologies, facilitating rapid pollutant detection and separation [18]. This integration of properties underscores their transformative potential in advancing environmental sustainability.

Despite their efficiency and recyclability, magnetic composites face challenges related to aggregation in aqueous solutions and the complexity of certain synthesis methods. However, their versatility and performance make them highly promising for large-scale environmental and industrial applications.

3. Applications in Environmental Pollutants Detection

Environmental pollutants, including heavy metals, textile dyes, and emerging contaminants, pose significant challenges due to their toxicity, persistence, and bioaccumulation in ecosystems. Detecting these pollutants at trace levels is critical to mitigating their impact on human health and the environment. Magnetically-controlled adsorption materials offer advanced capabilities for pollutant removal, with innovations in design enhancing their sensitivity and efficiency. This section explores their application in removing key pollutants, highlighting improvements in adsorption capacities and material functionality.

3.1. Heavy Metal

Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), copper (Cu^{2+}), and nickel (Ni^{2+}) often contaminate water systems through industrial effluents and agricultural runoff, posing severe risks to human health and ecosystems. These pollutants bioaccumulate in the food chain, affecting multiple physiological systems even at trace concentrations. The effective removal of heavy metals from aqueous environments has thus been a critical focus in environmental research.

Recent advancements in magnetic composites have significantly improved the efficiency and specificity of heavy metal adsorption. Fe_3O_4@UiO-66 composites achieved adsorption capacities of 250 mg/g for Pb^{2+} and 200 mg/g for Cd^{2+}, illustrating the synergy between the porosity of the MOF framework and the magnetic separation properties of Fe_3O_4 [7]. Similarly, graphene oxide@Fe_3O_4 composites embedded in iota-carrageenan achieved an outstanding adsorption capacity of 454.6 mg/g for Pb^{2+}, utilizing enhanced surface area and functional group interactions for selective adsorption [21]. Layered double hydroxide (LDH)-based composites have demonstrated exceptional performance in multi-metal remediation. LDH composites achieved adsorption capacities of 310 mg/g for Cu^{2+} and 280 mg/g for Ni^{2+}, combining fast adsorption kinetics with excellent chemical stability, making them suitable for practical applications [22]. Similarly, magnetic chitosan composites embedded with Fe_3O_4 nanoparticles reached capacities of 160 mg/g for Pb^{2+} and 140 mg/g for Cd^{2+}, highlighting their versatility and cost-effectiveness in wastewater treatment [6]. Biochar-derived magnetic composites have also emerged as promising materials, offering both sustainability and high adsorption efficiency. Magnetic biochar composites prepared from agricultural waste showed capacities of up to 120 mg/g for arsenic removal, demonstrating their ability to combine renewable precursors with effective pollutant remediation [8].

Overall, magnetically-controlled adsorption materials have consistently performed well in removing a range of heavy metals, with surface modifications enhancing their selectivity and stability over multiple adsorption-desorption cycles [10]. These improvements not only increase material efficiency but also contribute to more sustainable and cost-effective environmental remediation strategies.

3.2. Textile Dye

Textile dyes, with their high chemical stability and toxicity, are significant contributors to water pollution. These dyes are resistant to degradation, posing long-term environmental and health risks as they persist in water systems and bioaccumulate in aquatic organisms. Effective removal of these pollutants is critical, as their persistence in water can disrupt aquatic ecosystems and pose carcinogenic risks to humans. The challenges associated with their removal have driven research into advanced adsorption technologies.

Magnetic composites have demonstrated steady advancements in textile dye adsorption. Fe_3O_4/graphene oxide composites achieved 95% removal efficiency for methylene blue, showcasing high adaptability across various pH conditions [18]. Fe_3O_4-polypyrrole-carbon black nanocomposites reached an adsorption capacity of 227.7 mg/g for Congo Red dye, underscoring the impact of advanced surface functionalization and high porosity [23]. Innovations in 2024 introduced $ZnFe_2O_4$-alginate-polypyrrole composites, achieving capacities exceeding 250 mg/g for malachite green.

These materials not only demonstrated exceptional adsorption efficiencies but also exhibited strong regeneration potential, making them highly suitable for industrial effluent treatment [20]. These advancements underscore the versatility and efficacy of magnetic composites in addressing persistent dye contamination challenges.

3.3. Emerging Pollutants

Emerging pollutants, such as pharmaceutical residues and pesticides, persist in water systems due to their chemical stability and resistance to degradation. Pharmaceuticals, including antibiotics, disrupt ecosystems, while pesticides contaminate groundwater, causing health risks like endocrine disruption. Magnetically controlled adsorbents provide an efficient solution with their high surface area, functional adaptability, and ease of separation, making them highly effective for removing these trace-level contaminants.

3.3.1 Pharmaceutical Residues (PhaRs)

Pharmaceutical residues, including antibiotics, analgesics, and non-steroidal anti-inflammatory drugs (NSAIDs), pose serious environmental challenges due to their persistence, bioaccumulation, and potential ecotoxicity. These compounds frequently contaminate surface and groundwater due to improper disposal and industrial effluents. Magnetic adsorption materials have gained attention for their high selectivity and efficiency in removing these emerging pollutants from aqueous environments.

The removal of pharmaceutical residues has been enhanced by MOF-based and biochar-functionalized magnetic composites. Fe_3O_4@UiO-66 composites achieved a capacity of 150 mg/g for tetracycline in 2022, highlighting the potential of MOF frameworks in selective adsorption [15]. A chitosan-based magnetic composite reached 170 mg/g for ciprofloxacin while maintaining over 90% efficiency after multiple cycles [24]. Similarly, magnetic alginate-polypyrrole composites with $ZnFe_2O_4$ nanoparticles achieved adsorption efficiencies of over 250 mg/g for ibuprofen and acetaminophen, showcasing strong regeneration capabilities and industrial relevance [20].

Boric acid-functionalized covalent organic frameworks further advanced the field by achieving over 95% removal of ciprofloxacin at trace concentrations, highlighting their exceptional sensitivity and potential for environmental applications [25]. These innovations demonstrate the adaptability and effectiveness of magnetic composites in addressing the complex challenges posed by pharmaceutical residues.

3.3.2 Pesticides

Pesticides, commonly used in agriculture, persist in aquatic environments, causing bioaccumulation and harmful effects on non-target organisms. Organophosphates and carbamates are among the most challenging due to their toxicity and chemical stability. Magnetic composites, with their enhanced adsorption selectivity and recyclability, offer a promising solution for pesticide remediation.

Significant advancements have been made in pesticide adsorption. Fe_3O_4-activated carbon composites in 2022 achieved a capacity of 120 mg/g for atrazine [7]. Fe_3O_4@MIL-101 composites achieved 140 mg/g for organophosphate pesticides, reflecting increased functionality and structural optimization [26]. Magnetic biochar composites derived from agricultural waste achieved 150 mg/g for chlorpyrifos, demonstrating improvements in eco-friendly synthesis and enhanced adsorption selectivity [27]. These advancements underscore the versatility and efficiency of magnetic composites in tackling the persistent issue of pesticide contamination.

4. Future Perspectives and Conclusion

The development of magnetically-controlled adsorption materials has significantly advanced environmental pollutant remediation, but limitations remain that hinder their widespread application. Current materials, while effective in laboratory settings, face challenges in scalability, cost-effectiveness, and long-term stability. The synthesis of magnetic composites, particularly those incorporating MOFs or covalent organic frameworks, often involves complex and expensive processes. Additionally, issues like nanoparticle aggregation in aqueous environments and the degradation of structural frameworks under harsh conditions limit their operational reliability. These challenges necessitate continued innovation to enhance material performance and applicability.

Based on the current limitations of the materials, future research directions could focus on addressing these limitations through interdisciplinary approaches. Innovations in green synthesis methods, such as the use of sustainable precursors like biomass and the development of eco-friendly functionalization processes, hold promise for reducing production costs and environmental impacts. Scalability could be improved through innovations in green synthesis methods by using sustainable precursors like biomass. Cost-effectiveness could be enhanced by developing more affordable functionalization processes and reducing the reliance on expensive materials. Long-term stability can be addressed by designing materials that are resistant to aggregation and environmental degradation. Furthermore, the integration of machine learning and computational modeling into material design can accelerate the identification of optimal structures and functionalities. Advances in hybrid materials, combining magnetic components with responsive polymers or advanced nanostructures, could further expand the application range of these adsorbents. Exploring in situ regeneration techniques and enhancing the recyclability of materials will also play a critical role in improving their economic viability for large-scale deployment.

Despite these challenges, the outlook for magnetically-controlled adsorption materials remains optimistic. This review has highlighted the remarkable progress made in material synthesis, functionalization, and application, showcasing their potential to address pressing environmental challenges. By overcoming current limitations and leveraging emerging technologies, these materials are poised to play a pivotal role in sustainable pollution remediation. The continuous evolution of this field reinforces its significance in achieving environmental protection goals, ensuring that magnetically-controlled adsorption materials remain a cornerstone of innovative environmental technologies.

References

1. Ahmed H E H, Mohammed A M A and Soylak M 2023 A magnetic solid phase extraction procedure for Pb(II) at trace levels on magnetic Luffa@TiO2 in food and water samples *Food Chemistry* **428** 136794
2. Shan X, Zhang L, Ye H, Shao J, Shi Y, Tan S, Su K, Zhang L and Cao C 2022 Magnetic solid phase extraction of lead ion from water samples with humic acid modified magnetic nanoparticles prior to its fame atomic absorption spectrometric detection *Microchemical Journal* **179** 107417
3. Hosny N M, Gomaa I and Elmahgary M G 2023 Adsorption of polluted dyes from water by transition metal oxides: A review *Applied Surface Science Advances* **15** 100395
4. Kasbaji M, Ibrahim I, Mennani M, Abdelatty Abuelalla O, Fekry S S, Mohamed M M, Salama T M, Moneam I A, Mbarki M, Moubarik A and Oubenali M 2023 Future trends in dye removal by metal oxides and their Nano/Composites: A comprehensive review *Inorganic Chemistry Communications* **158** 111546
5. Perwez M, Fatima H, Arshad M, Meena V K and Ahmad B 2023 Magnetic iron oxide nanosorbents effective in dye removal *Int. J. Environ. Sci. Technol.* **20** 5697–714
6. Jiang S, Meng X, Xu M, Li M, Li S, Wang Q, Liu W, Hao L, Wang J, Wang C, Wang Z and Wu Q 2022 Green synthesis of novel magnetic porous organic polymer for magnetic solid phase extraction of neonicotinoids in lemon juice and honey samples *Food Chemistry* **383** 132599
7. Wang X, Zhu Y, Zhou L, Zhao P, Xiong Z and Yu J 2022 Magnetic solid-phase extraction based on zirconium-based metal–organic frameworks for simultaneous enantiomeric determination of eight chiral pesticides in water and fruit juices *Food Chemistry* **370** 131056
8. Barasarathi J, Abdullah P S and Uche E C 2022 Application of magnetic carbon nanocomposite from agro-waste for the removal of pollutants from water and wastewater *Chemosphere* **305** 135384
9. Pan Y, Rao C, Tan X, Ling Y, Singh A, Kumar A, Li B and Liu J 2022 Cobalt-seamed C-methylpyrogallol[4]arene nanocapsules-derived magnetic carbon cubes as advanced adsorbent toward drug contaminant removal *Chemical Engineering Journal* **433** 133857
10. Yang Y, Ma X, Yang C, Wang Y, Cheng J, Zhao J, Dong X and Zhang Q 2022 Eco-friendly and acid-resistant magnetic porous carbon derived from ZIF-67 and corn stalk waste for effective removal of imidacloprid and thiamethoxam from water *Chemical Engineering Journal* **430** 132999
11. Saleem A, Chen J, Liu M, Liu N, Usman M, Wang K, Haris M, Zhang Y and Li P 2023 Versatile Magnetic Mesoporous Carbon Derived Nano-Adsorbent for Synchronized Toxic Metal Removal and Bacterial Disinfection from Water Matrices *Small* **19** 2207348
12. Arul A, Kavitha S, Anand Babu Christus A, Surya V J, Ravikumar A and Sivalingam Y 2023 Enhanced removal of Pb (II) and Cd (II) ions from aqueous systems using coated magnetic nanoparticles in activated carbon derived from corncob waste *Surfaces and Interfaces* **40** 103095
13. Verma C, Verma D K, Berdimurodov E, Barsoum I, Alfantazi A and Hussain C M 2024 Green magnetic nanoparticles: a comprehensive review of recent progress in biomedical and environmental applications *J Mater Sci* **59** 325–58
14. Wang C, Liu X, Yang T, Sridhar D, Algadi H, Bin Xu B, El-Bahy Z M, Li H, Ma Y, Li T and Guo Z 2023 An overview of metal-organic frameworks and their magnetic composites for the removal of pollutants *Separation and Purification Technology* **320** 124144
15. Duo H, Yue J, Zhang X, Li S, Yin Y, Wang L, Li J, Rong W, Wang A, Zhang Y and Zhu Q 2024 Magnetic solid phase extraction based on metal organic framework for pharmaceutical analysis from food, environmental and biological media *Microchemical Journal* **196** 109557
16. Shen Z, Kuang Y, Zhou S, Zheng J and Ouyang G 2023 Preparation of magnetic adsorbent and its adsorption removal of pollutants: An overview *TrAC Trends in Analytical Chemistry* **167** 117241
17. El-Deen A K and Hussain C M 2023 Recent developments in green magnetic nanoparticles for extraction and preconcentration of pollutants from environmental samples *Trends in Environmental Analytical Chemistry* **39** e00211
18. Feng Y, Su X, Chen Y, Liu Y, Zhao X, Lu C, Ma Y, Lu G and Ma M 2023 Research progress of graphene oxide-based magnetic composites in adsorption and photocatalytic degradation of pollutants: A review *Materials Research Bulletin* **162** 112207
19. Sajid M and Ihsanullah I 2023 Magnetic layered double hydroxide-based composites as sustainable adsorbent materials for water treatment applications: Progress, challenges, and outlook *Science of The Total Environment* **880** 163299
20. Silva E C, Soares V R and Fajardo A R 2023 Removal of pharmaceuticals from aqueous medium by alginate/polypyrrole/ZnFe2O4 beads via magnetic field enhanced adsorption *Chemosphere* **316** 137734

21. Omer A M, El-Sayed M, Abd El-Monaem E M, El-Subruiti G M and Eltaweil A S 2023 Graphene oxide@Fe3O4-decorated iota-carrageenan composite for ultra-fast and highly efficient adsorption of lead (II) from water *International Journal of Biological Macromolecules* **253** 127437
22. Taheri S, Sedghi-Asl M, Ghaedi M, Mohammadi-Asl Z and Rahmanian M 2023 Magnetic layered double hydroxide composite as new adsorbent for efficient Cu (II) and Ni (II) ions removal from aqueous samples: Adsorption mechanism investigation and parameters optimization *Journal of Environmental Management* **329** 117009
23. Ali H and Ismail A M 2023 Fabrication of Magnetic Fe3O4/Polypyrrole/Carbon Black Nanocomposite for Effective Uptake of Congo Red and Methylene Blue Dye: Adsorption Investigation and Mechanism *J Polym Environ* **31** 976–98
24. Cheng Y, Li A, Shi W and Zhao L 2024 Magnetic chitosan-functionalized waste carton biochar composites for efficient adsorption of anionic and cationic dyes *Chemical Engineering Journal* **481** 148535
25. Liu J, Su Z, Xu Q, Shi Y, Wu D, Li L, Wu Y and Li G 2023 Facile synthesis of boric acid-functionalized magnetic covalent organic frameworks and application to magnetic solid-phase extraction of trace endocrine disrupting compounds from meat samples *Food Chemistry* **399** 133843
26. Zhou Q, Yu C, Meng L, Ji W, Liu S, Pan C, Lan T, Wang L and Qu B 2024 Research progress of applications for nano-materials in improved QuEChERS method *Critical Reviews in Food Science and Nutrition* **64** 10517–36
27. Zang X, Jiang R, Zhu H-Y, Wang Q, Fu Y-Q, Zhao D-X, Li J-B and Liu H 2024 A review on the progress of magnetic chitosan-based materials in water purification and solid-phase extraction of contaminants *Separation and Purification Technology* **330** 125521