magnetochemistry

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Editorial

Magnetic Material-Enabled Environmental Remediation Technologies: Current Status and Prospects

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With the acceleration of industrialization and urbanization, heavy metals, organic pollutants, microplastics, and emerging contaminants are continuously entering the environment, posing a serious threat to ecosystems and human health [1,2]. Against this backdrop, innovation in environmental remediation technologies has become an urgent priority. In recent years, magnetic materials, particularly magnetic nanomaterials (MNMs), have demonstrated immense application potential in environmental science due to their unique magnetic responsivity, capacity for functionalization, and excellent capabilities for highly efficient separation and recovery; they are rapidly transitioning from laboratory research to practical engineering applications [3–5].

1. Overview of Recent Research Developments

Currently, the application of magnetic materials in environmental remediation is becoming increasingly diversified and refined. Iron-based magnetic nanoparticles, exemplified by magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), have become the most widely studied functional materials for environmental applications due to their earth-abundant raw materials, favorable biocompatibility, and facile magnetic separability [6–8]. Research has shown that surface functionalization, for instance, via the introduction of functional groups such as amino, carboxyl, and sulphonic acid groups, can significantly enhance the selective adsorption of specific pollutants by magnetic materials [9–11]. For instance, Fe_2O_3 nanoparticles modified with carboxylic acids (e.g., oxalic acid) and deposited onto $MgMn_2O_4$ and α-MnO_2 cathodes can significantly improve battery performance [10].

From a fundamental catalysis perspective, the reactivity of magnetic transition-metal surfaces is increasingly interpreted through the d-band model and spin-dependent electronic structure: the position of the d-band center, together with spin polarization and surface magnetic moments, governs the adsorption strength of reaction intermediates in processes such as oxygen reduction and hydrogen evolution [12]. This indicates that magnetic surfaces are not merely carriers for separation, but can be rationally designed at the electronic-spin level to lower reaction barriers in advanced catalytic remediation.

Significant breakthroughs have been achieved in the degradation of organic pollutants through the integration of magnetic materials with advanced oxidation processes (AOPs). Magnetic nanoparticles can act as heterogeneous catalysts, driving reactions such as photocatalysis, Fenton-like reactions, and persulphate activation, thereby generating reactive oxygen species (ROS) to non-selectively oxidize and degrade organic pollutants [12–14]. Furthermore, composite systems, such as magnetic biochar, magnetized graphene oxide, and magnetized metal–organic frameworks (MOFs), demonstrate excellent performance in

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the treatment of complex wastewater through synergistic adsorption and catalytic mechanisms [13,15]. Magnetic layered double hydroxide (LDH)/Fe_3O_4 composites and Fe_3O_4-based catalysts have been shown to remove heavy metals (Cu, Pb, Cd, Cr) and degrade dyes/pharmaceuticals via combined adsorption–catalysis pathways, while remaining separable under an external field [16].

Notably, the range of applications for magnetic materials is constantly expanding. Spanning traditional water remediation, soil remediation, atmospheric pollutant capture, and even the magnetic separation and recovery of microplastics, magnetic materials are gradually becoming an important tool for multi-media environmental remediation. In the sub-field of bio-based magnetic adsorbents, recent work demonstrates that $CuFe_2O_4$ immobilized on silane-modified rice-husk-derived zeolite can remove 89.35% chlorogenic acid within 1 h and be recovered at 85% mass yield under a magnetic field, simultaneously realizing agricultural-waste valorization and low-toxicity operation [17]. In parallel, magnetic chitosan composites prepared by co-precipitation or cross-linking use $–NH_2$/–OH groups for heavy-metal chelation while enabling rapid magnetic recovery, showing strong performance for Pb, Cr, Cd, Cu and multi-ion systems [18].

2. Emerging Trends and Cutting-Edge Directions

Currently, several notable emerging trends are evident in this field. First, there is a growing focus on green synthesis and sustainable design principles. The preparation of traditional magnetic materials often involves high-temperature sintering, toxic solvents, and energy-intensive processes; researchers are actively developing green preparation methods such as hydrothermal/solvothermal synthesis, bio-templating, and microwave-assisted synthesis, aiming to reduce energy consumption and waste emissions by approximately 30% [19,20].

Second, biohybrid systems are emerging. Combining enzymes, microorganisms, or biodegradable polymers with magnetic nanostructures to construct multistage responsive platforms that integrate adsorption, catalysis, and biotransformation functions has become a highly promising area of research. This biomimetic design not only enhances pollutant removal efficiency but also endows the materials with improved environmental adaptability and biocompatibility [21].

Third, recyclability and life cycle assessment (LCA) are receiving increasing attention. The core advantage of magnetic materials lies in their ability to facilitate rapid separation and recycling via an external magnetic field, which significantly reduces material loss and the risk of secondary pollution [22,23]. However, issues such as long-term operational stability, surface oxidation, and the decline in magnetic properties still require attention. Incorporating circular economy principles and LCA methods into the design and evaluation of magnetic materials has become a key pathway for promoting sustainable development in this field.

Beyond remediation, magnetic-field-assisted synthesis is opening a new frontier in functional magnetic materials. A high magnetic field can modulate the reduction pathway, crystallite size, and π–π stacking of radical-based organic magnets, demonstrating that external fields themselves can be used to tune structure–property relationships in magnetic semiconductors [24]. This "field-engineering" concept may later be transferred to the controllable fabrication of smart environmental magnetic materials.

3. Key Areas for Future Research

Although remarkable progress has been made in the application of magnetic materials in environmental science, the transition from laboratory-scale studies to engineering

applications still faces numerous challenges. We believe that future research should focus on the following areas:

First, the mechanisms of environmental behavior and long-term risk assessment in complex environmental media require systematic investigation. Existing research has largely concentrated on the removal performance of single pollutants in ideal aqueous solutions, whereas real-world environmental systems are characterized by high salinity, extreme pH levels, the coexistence of multiple pollutants, and interference from complex matrices. Systematic research is still required with regard to the stability, agglomeration behavior, coating degradation, and potential environmental mobility of magnetic nanoparticles under these conditions. In particular, there is an urgent need to establish a standardized assessment framework for the ecotoxicological effects following the release of these materials, including their impact on microbial communities, aquatic organisms, and soil ecosystems.

Second, intelligent and responsive magnetic materials should be designed. Future environmental remediation materials should not merely possess passive adsorption or catalytic functions, but should be capable of responding intelligently to external stimuli (such as pH, temperature, light, magnetic fields, or specific pollutant concentrations) to achieve selective recognition of pollutants, controlled release, and self-repair functions. The development of magnetically responsive smart materials with on–off switching properties will provide a novel strategy for precision environmental remediation.

Third, large-scale preparation and engineering application demonstrations must be prioritized. At present, most research remains confined to gram-scale synthesis and batch experiments, and a significant gap remains before practical engineering applications can be realized. In the future, it will be necessary to develop continuous, low-cost, large-scale preparation technologies and to establish long-term operational demonstration projects for magnetic materials at real-world contaminated sites (such as industrial wastewater treatment plants, contaminated farmland, and leachate treatment systems). By accumulating operational data and optimizing process parameters, these efforts will provide a scientific basis for the formulation of technical standards and the improvement of policies and regulations.

The application of magnetic materials in environmental science is currently at a critical stage of rapid development and profound transformation. From fundamental materials design to composite functionalization, and from laboratory research to engineering practice, this field is demonstrating unprecedented vitality and potential. However, we must also clearly recognize that any technological progress must be grounded in environmental safety and sustainability. Only by building on a thorough understanding of the environmental behavior of materials, adhering to the principles of green design, and promoting interdisciplinary collaborative innovation can we truly achieve the large-scale, long-term, and safe application of magnetic materials in environmental remediation, thereby harnessing the power of materials science to create a clean and beautiful world. We look forward to more researchers joining this field, which is full of opportunities, to collectively advance the field of magnetic environmental materials.

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