Review Article

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Applications of Magneto-responsive Smart Materials in Environmental Nanotechnology: Opportunities and Challenges

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ABSTRACT

There is a growing interest in magneto-responsive innovative materials for environmental nanotechnology applications owing to their unique ability to respond to external magnetic fields. These materials, typically nanoparticles, have unique properties and are great candidates for diverse environmental applications such as safe water and air treatments, pollutants reclamation, soil remediation, and renewable energy. This paper discusses the broad application areas where magneto-responsive materials can help to solve significant environmental challenges and demonstrates their potential to offer an efficient, economical, and sustainable route to address these challenges. At the same time, the paper addresses the possibilities and difficulties they imply (e.g., material stability, environmental safety, scalability, etc.). It also presents future directions in developing biodegradable and eco-friendly materials, integration with the Internet of Things (IoT) for real-time monitoring, and the need for interdisciplinary collaborations. Utilizing the multi-functionalities delivered through magneto-responsive transient materials could play a role in environmental remediation and sustainability, heralding a potential era of cleaner, greener future.

Keywords: Magneto-responsive materials; Water treatment; Pollutant removal; Smart materials.

1. INTRODUCTION

There is a growing interest in magneto-responsive innovative materials for environmental nanotechnology applications owing to their unique ability to respond to external magnetic fields. These materials, typically nanoparticles, have unique properties and are great candidates for diverse environmental applications such as safe water and air treatments, pollutants reclamation, soil remediation, and renewable energy. This paper discusses the broad application areas where magneto-responsive materials can help to solve significant environmental challenges and demonstrates their potential to offer an efficient, economical, and sustainable route to address these challenges.

1.1 Overview of Magneto-responsive Smart Materials

Magneto-responsive innovative materials such as magnetorheological (MR) fluids, elastomers, and ferrofluids drastically change their physical properties in magnetic fields with/without deformation (Ahamed *et al.* 2018). These materials are formed from magnetic particles embedded in carrier matrices, allowing for fast and reversible tuning of rheology. Applications are varied, from automotive and construction sectors to targeted drug delivery. MR materials are within a larger umbrella of stimuli-responsive smart materials that respond to external stimuli like pH, temperature, and light (Municoy *et al.* 2020). These composites have potential applications in tissue engineering and drug delivery systems by controlling the release of drugs at specific locations and over time (Municoy *et al.* 2020). Ongoing studies focus on further improving material features and investigating new use cases, including self-sustainable wireless sensor networks, vibration energy harvesting and more.

Magneto-responsive materials are versatile tools for many environmental applications due to tunable properties and adaptiveness. This composite material with incorporated ferromagnetic nanoparticles can be functionalized to endow it with properties (e.g., increased viscosity, increased adsorption capacity or catalytic activity, etc.) tunable by external stimuli (e.g., magnetic field). They possess trade-exceptional assets that imply they may be used for the complete spectrum of drug ambivalence washing and remediation, from pouring poisonous substances from water and air. Offering numerous combinations of methods reachable, including drug delivery, tissue engineering and environmental applications, magneto-responsive hydrogels and nanocomposites have gained huge attention (Omidian *et al.* 2024). Magnetic nanoparticles were combined with films, capsules and gels amongst other things to generate intelligent environmental nanomaterials that could respond to environmental stimuli (Singh *et al.* 2010). Such materials can provide enhanced filtration, oil/water emulsion separation, and air purification (Kim *et al.* 2021). Magneto-responsive materials have a wide range, are small in size, and are highly efficient, making them helpful in solving complex problems related to the environment.

1.2 Importance of Environmental Nanotechnology

Inventions can be utilized to solve environmental problems with advanced nanomaterial. Such materials, e.g. metal oxides, carbon nanomaterials, and metallic nanoparticles, exhibit enhanced adsorptive and catalytic activity toward the environmental decontamination processes (Yadav *et al.* 2021). Due to their very high surface area-to-volume ratio and reactivity, nanomaterials have also proved helpful for soil, water, and air remediation (Taran *et al*. 2020). They are particularly good at eliminating some types of pollutants, such as heavy metals, dyes, pesticides and volatile organic compounds. Nanotechnologies can also prevent pollution, monitor the environment for pollutants, and generate sustainable energy. Nevertheless, risks from engineered nanomaterials' toxicity and environmental persistence suggest more research and development to optimise the safe and responsible application of this class of materials in an extensive range of products and industries. The environmental applications of nanotechnology account for a large part that can help tackle environmental issues like pollution, harmful waste, clean energy, and water purification.

Magneto-responsive nanomaterials are ideal materials with easy recovery to use for environmental remediation (Rasheed, 2022). These materials can effectively clean up water and wastewater from heavy metals, dyes, and organic compounds. Nanotechnology can also be used for air pollution control, soil remediation and energy storage systems. They possess high surface area, biocompatibility, and easy separation techniques (Rasheed, 2022). Magneto-responsive adsorbents are smart materials with excellent desorption and regeneration properties without extra solvents. Nanomaterials are green technology, leading to sustainable development in environmental applications (Beni, 2022). However, more research is needed to address possible risks and have effective regulatory policies for nanomaterial management.

To guarantee their stability in variable environmental conditions, magneto-responsive materials employ a range of strategies, which span the fields of novel surface modification, composite formation and encapsulation methods. To be well dispersed in different matrices and have high chemical resistance the magnetic nanoparticles can be surface-coated with silica, polymers or surfactants, preventing their agglomeration and oxidation. Moreover, the presence of magnetic nanoparticles in polymer matrices enhances mechanical and thermal stability without compromising responsivity. Recent works have also pinpointed doping with stabilizing agents and tailoring core-shell structures to enhance long-term functionality in diverse pH, temperature and salinity conditions. This broadens the horizons for magneto-responsive materials, which are being used in environment applications in the areas of water treatment devices, contaminant adsorption, and energy storage.

1.3 Objectives and Scope of the Review

This review is focused on summarizing the applications, opportunities, and challenges that must be considered with the development of magneto-responsive smart materials for environmental nanotechnology. The objective of this paper is to examine the essential characteristics and mechanisms of magneto-responsive materials and to elucidate the broad potential for such materials to serve environmental applications, including their contemporary and emerging applications in wastewater treatment, air-mitigation technologies, soil-remediation techniques, and energy systems. It provides real-world case studies demonstrating their application and effect, highlights key challenges and limitations preventing widespread production and adoption, and suggests potential solutions. Moreover, the review discusses future trends and research directions which play a profound role in improving the efficiency and sustainability of these materials. This review aims to fill this gap by discussing future perspectives to bridge material science to environmental engineering, focusing on the more essential objectives of empowering researchers and practitioners on magneto-responsive smart materials for environmental applications.

2. FUNDAMENTAL CONCEPTS OF MAGNETO-RESPONSIVE SMART MATERIALS

2.1 Mechanisms

When applying a magnetic field, smart magneto-sensitive materials can change their physical or chemical properties (Xu *et al*. 2019). Suspensions of these typically consist of metal magnetic grains and carrier matrices and show changes in viscosity, conductivity and strength. The phenomena are based on particle alignment and magnetic dipole interactions. They are also helpful in other applications, such as the construction sector, the automotive industry, and vibration control (Ahamed *et al*. 2018). Furthermore, aiming towards the minimalist nanoscale dimension of the magnetic assembly, the latest study introduced hyper-focusing on nanoscale magnetic assembly to design smart materials with tunable optical properties and shape-morphing functionalities. Among them, the most researched ones are MR fluid, elastomers and foams, which offer fast and reversible to external magnetic field stimuli (Xu *et al*. 2019; Ahamed *et al*. 2018). These materials can potentially develop into more complex sensors, systems that respond to stimuli and adaptive structures.

The magnetic responsive properties of MR materials exhibit switchable dynamic performance via the reconfigurable magnetic field, causing reversible or irreversible changes (Wu *et al*. 2020). These materials introduce magnetic particles into soft polymers, which can change shape rapidly and have programmable properties. These materials are accurately aligned in terms of their composition, particle size, and/or surface modifications to optimize their functions at the material level (Liang *et al.* 2023; Xia *et al.* 2022). Magnetic interaction is introduced to these liquid crystal elastomers by dispersing magnetic inclusions, thus rendering the material as flexible morphable reconfiguration. These advanced materials can be integrated into soft robotics and biomedical devices, in addition to adaptive structures that have remote control, speedy responsiveness, and multifunctional capability.

2.2 Types of Magneto-responsive Materials

2.2.1 Ferrofluids

Ferrofluids are nanofluids that consist of a colloidal suspension of magnetic nanoparticles in a carrier fluid, and they exhibit interesting properties when placed in a magnetic field. Such smart materials can be synthesized via coprecipitation and thermal decomposition (Oehlsen *et al*. 2022). With controllable flow and heat transfer properties, Ferrofluids are useful in innumerable applications. They find applications in environmental sensors, cooling systems, biomedical, and mechanical engineering (Philip, 2022). Ferrofluid behaviour depends on how carrier fluids interact with magnetic properties to achieve desired application performance. In addition, recent studies have improved the synthesis techniques, and better investigated their rheological properties and new applications in optics, drug targeting and water treatment (Oehlsen *et al*. 2022). Ongoing challenges include ensuring stability and controlling properties for specific applications (Philip, 2022).

2.2.2 Magnetorheological (MR) Materials

MR materials are composed of ferrous particles that experience an abrupt transition of rheological behaviours under a magnetic field (Bakr *et al*. 2021). Such materials provide the transition between liquid and solid-like states extremely rapidly, potentially aiding in damping vibrations and inventing systems that take an adaptive approach. MR fluids and elastomers have been widely explored for applications like damping, braking, and seismic hazard mitigation strategies. This effort has been partially met with the development of error correction methods that enhance the stability and performance of MR materials while shrinking the model error (Osial *et al*. 2023). The properties of the MR fluid are influenced by the particle composition, carrier fluid viscosity, additives and the operating temperature (Bakr *et al*. 2021). The MR materials used in geometry sandwiches improve vibration control due to their unique field-dependent behaviour (Sharif *et al*. 2021), which reveals the engineering flexibility of such configuration and a superior potential for advanced engineering applications.

2.2.3 Magnetic Nanoparticles

Magnetic nanoparticles (MNPs) have shown great potential for precise environmental cleanup because of their novel features like large surface area, easy synthesis and superparamagnetic (Kim *et al*. 2021; Ghasemi *et al*. 2021). These nanomaterials have been extensively applied to the treatment of many different contaminants in water and sewage, among them heavy-metal ions, organic compounds and pharmaceutical residues. MNPs have some superiority over traditional treatment methods because of their chemical specificity, high clean-up, and lower costs (Yaashikaa and Kumar, 2022). Iron-based nanomaterials are especially sought after for environmental operations because they have a small environmental impact and can be used repeatedly (Ghasemi *et al*. 2021). Recent developments in synthesising functionalized MNPs and magnetic nanocomposites are promising in removing pollutants from water (Rasheed, 2022; Singh *et al*. 2022). MNPs also show promise for nanobiocatalysis in breaking down stubborn contaminants in groundwater.

2.3 Fabrication and Characterization Techniques

2.3.1 Fabrication Techniques

2.3.1.1 Sol-gel Process

The sol-gel method is commonly adopted for synthesizing magneto-responsive smart materials such as magnetic nanoparticles like iron oxide (Fe_3O_4) and cobalt ferrite ($CoFe_2O_4$). The technique consists of preparing a solution containing metal alkoxides or metal salts, which undergoes hydrolysis and results in the formation of a gel. Magnetic nanoparticles should be mixed with the gel matrix before the gel structure is solidified to provide steric mixing of the microparticles and a homogeneous distribution of the magnetic nanoparticles in the material (Shabelskaya *et al*. 2023).

2.3.1.2 Electrospinning

The electrospinning technique can transform nanofibrous materials into magneto-responsiveness. By utilizing a polymer solution that is electrostatically drawn into aligned fibres incorporated with magnetic nanoparticles. Such nanofibers could find applications (such as sensors or actuators) in flexible and lightweight magneto-responsive materials (Blachowicz *et al*. 2020).

2.3.1.3 Polymer Composites

Melt processing, solution casting or in situ polymerisation can incorporate High-quality magnetic nanoparticles into different polymer matrices (thermoplastic, thermoset or elastomers). With added magnetic particles, the material can now respond to magnetic fields. This method has been widely adopted to design resistant and strong magneto-responsive materials for environmental and industrial applications (Mohamed *et al*. 2022).

2.3.1.4 3D Printing

3D printing and other additive manufacturing (AM) technologies have been investigated in the context of magneto-responsive materials fabrication. These 3D structures are developed by merging magnetic particles with photopolymers or thermoplastics and leveraging 3D printers to modulate complex geometries. Advantages of this method include rapid prototyping, and customization to create structures that can respond to a magnetic field (Mazeeva *et al*. 2023).

2.3.2 Characterization Techniques

2.3.2.1 Magnetic Force Microscopy (MFM)

MFM is a scanning probe microscopy used to characterise a material's magnetic properties at the nanoscale. It helps visualize the surface and magnetic interactions between the particles in magneto-responsive materials in detail. It can effectively clarify the dipole array of nanoparticles in composite media (Parker *et al.* 2022).

2.3.2.2 Transmission Electron Microscopy (TEM)

TEM is employed to view a matrix's size, shape, and distribution of magnetic nanoparticles. It further encapsulates the crystallinity and morphology of the material, which play a pivotal role in enabling its magnetic response. TEM is essential to guarantee the uniform dispersion of magnetic particles into the material (Tan, 2020).

2.3.2.3 Vibrating Sample Magnetometry (VSM)

VSM is a technique that involves measuring the magnetization of a sample when placed in an external magnetic field. This is valuable information for the magnetic properties including coercivity, saturation magnetization, and magnetic hysteresis. VSM is a must to assess the strength and reactivity of the magneto-sensitive materials (Phillips *et al*. 2022).

2.3.2.4 X-ray Diffraction (XRD)

XRD is a technique used to characterize the crystalline structure of magnetic nanoparticles in composite material. The crystalline phases in the material affect its overall magnetic responses, which are illustrated in the XRD patterns shown. This approach is instrumental in confirming that the nanoparticles are in the desired phase and contribute appropriately to the material's properties (Fatmawati *et al*. 2024).

2.3.2.5 Dynamic Mechanical Analysis (DMA)

The mechanical properties of magneto-responsive materials are studied dynamically using DMA under various magnetic field strengths. Specifically, by applying magnetic fields to these systems and recording their mechanical deformations (stiffness or modulus changes), DMA will provide insight into the magneto-mechanical coupling of these materials (Patra *et al.* 2020).

These fabrication and characterization approaches facilitate the effective development of high-quality magneto-responsive materials for specific environmental applications. It is essential to understand these techniques to enhance their practical use, deployment and performance in different scenarios.

3. APPLICATIONS IN ENVIRONMENTAL NANOTECHNOLOGY

3.1 Water and Wastewater Treatment

3.1.1 Heavy Metal Ion Removal

Magneto-responsive materials, especially magnetic nanoparticles, are highly efficient for capturing heavy metal ions from wastewater. Their very high surface area and functionalized surfaces allow for selective binding of toxic metals such as lead, cadmium, and arsenic. After the adsorption of the contaminants, the two materials can be easily separated from the water using an external magnetic field, which is efficient and sustainable.

3.1.2 Removal of Organic Pollutants Using Magnetic Adsorbents

Functionalized magnetic adsorbents with different chemical groups have been highly effective in targeting various organic pollutants, including dyes, pesticides, or pharmaceutical residues. As a result, they also respond quickly to magnetic fields for fast recovery and reuse, minimising cost and environmental impact.

3.2 Air Pollution Control

3.2.1 Magnetic Catalysts for Pollutant Degradation

Air pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NOx) can be broken down using magnetic catalysts. These components are typically magnetic nanoparticles loaded with active species, allowing for high catalytic activity and easy recovery and recycling.

3.2.2 Smart Filters for Particulate Matter Removal

Magneto-responsive smart filters embed magnetic particles into fibrous matrices and capture fine particulate matter (PM2. 5, and PM10). These filters can also be recycled via magnetic field-induced cleaning, making them efficient and suitable for various pollution levels.

3.3 Soil Remediation

3.3.1 Magnetic Nanoparticles for Contamination Removal

The soil's heavy metals, hydrocarbons, and other contaminants are extracted using magnetic nanoparticles. The tiny size permits the sweeping of the soil matrix for effective remediation. Contaminants can be easily separated and removed due to an external magnetic field.

3.3.2 Integration with Biological Agents for Soil Health Improvement

Another path towards sustainability is through magneto-respired materials, which, when mixed with biological agents (microbes/enzymes), can be used to revive the soil. This synergistic process speeds up the decomposition of organic pollutants while retaining soil's inherent fertility and structure.

3.4 Energy Applications

3.4.1 Magneto-responsive Materials in Solar Energy Systems

These materials are used in solar energy systems for enhanced light absorption and energy conversion efficiency. For instance, magnetic nanoparticles can be embedded in photovoltaic devices to increase the mobility of charge carriers and decrease energy losses.

3.4.2 Role in Energy Storage Devices for Environmental Sustainability

Magneto-responsive materials are crucial in advanced energy storage methods like batteries and supercapacitors. This enables better efficiency rates for high energy density, fast cycles for charge-discharge, and long time for stability, therefore ensuring cleaner and greener energy systems.

4. CASE STUDIES

4.1 Magnetic Nanoparticles for Arsenic Removal in Drinking Water

4.1.1 Description of a Real-world Application

Magnetic nanoparticles, especially iron oxide-based nanoparticles, have attracted great interest as potential adsorbents for arsenic removal from contaminated water. For instance, their sorption capacity for As(III) and As(IV) species can be up to 250 mg/g (for $CoFe_2O_4$ nanoparticles) (Morales *et al*. 2021) and even as high as 964 mg/g for Fe2O3 nanoparticles (Deotale *et al*. 2021). Their effectiveness is attributed to large surface areas, mesoporous structures, and functionalization possibilities. The adsorption process is described by either Langmuir or Freundlich models, producing a fast process with complete removal in as little as two minutes (Vicente *et al.* 2023). Magnetic properties make separation and regeneration cheap and environmentally friendly (Jain, 2022). Recent innovations include graphene aerogels decorated with iron oxide nanoparticles and the development of point-of-use water treatment devices, demonstrating the versatility and potential of this technology for addressing global arsenic contamination issues. The process of arsenic removal from wastewater using magnetite nanocomposites can be seen in the Fig. 1

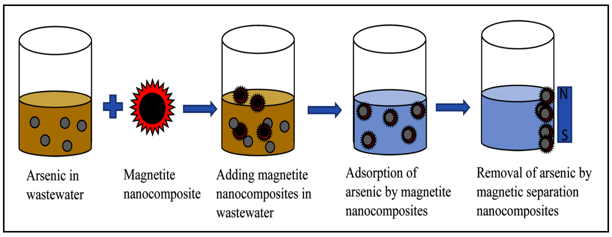

Fig. 1: Arsenic removal from wastewater using magnetite nanocomposites (Jain, 2022)

4.1.2 Outcomes and Impact

With this approach, arsenic levels have shown to be well under acceptable limits. As a result, very little secondary waste is generated by the magnetic separation process, which is environmentally sustainable. Pilot projects have successfully utilized the technology, demonstrating its promise for large-scale projects in rural and urban environments.

4.2 Ferrofluid-based Filters for Industrial Effluent Treatment

4.2.1 Analysis of Implementation in Industries

Magnetic nanoparticles (MNPs) are becoming more promising adsorbents of industrial effluents, heavy metals, and organic pollutants. These contributions may use biotemplates with high surface area, biocompatibility, and magnetic separability (Rasheed, 2022). Ferrofluids are colloidal dispersions of iron oxide nanoparticles with strong magnetic properties that allow them to be manipulated by external magnetic fields (Oehlsen *et al*. 2022). These materials have presented high adsorbent capacities for different pollutants and radionuclides with a removal efficiency of up to 98% in just minutes (Chen *et al*. 2022). Silicates, clay, carbon, polymers, and waste materials used as magnetic nano adsorbents to remove organic pollutants. Iron oxide nanomaterials, including magnetite and maghemite, have effectively removed dyes, heavy metals, and aromatic compounds from wastewater (Saharan *et al*. 2014). Fig. 2 shows the ferrofluid particles attached to the magnet in the filtration process.

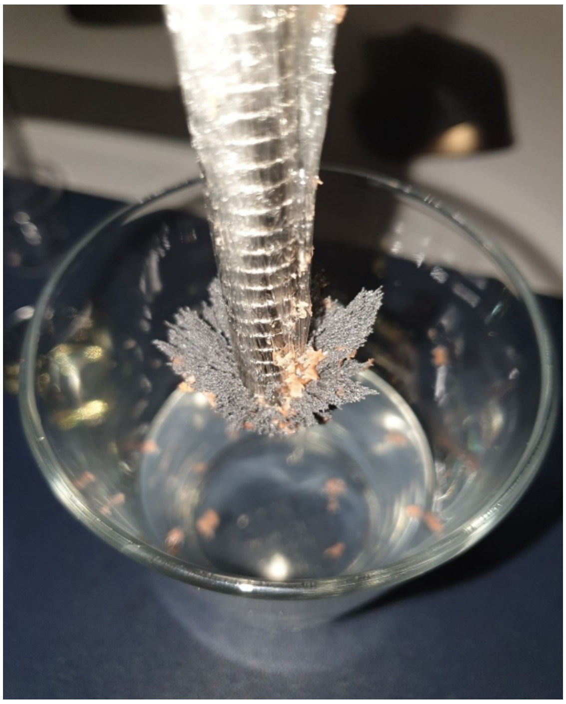

Fig. 2: Ferrofluid is attached to the magnet in the process of filtration (Source: blogs.brighton.ac.uk/applegatetech)

4.2.2 Observed Benefits

The ferrofluid filters have reduced contaminant concentrations, allowing discharge under stringent limits. Also, magnetic field-induced cleaning is used to regenerate the filters, helping to mitigate operative costs and waste generation. Industries have reported increased compliance with environmental regulations and a better public image thanks to the implementation of this technology.

4.3 Magnetic Adsorbents in Oil Spill Cleanup

4.3.1 Efficiency and Deployment

Oil spills are some of the most damaging environmental threats to marine ecosystems. Due to their large surface area and oil affinity, magnetic adsorbents have been circulated as natural candidates for the remediation of oil spills (Singh *et al.* 2020). These materials, such as functionalized superparamagnetic iron oxide nanoparticles and magnetic nanocomposites, can be applied to oil spills for fast adsorption and recovery through magnets (Kim *et al.* 2021). Recent developments must include polyolefin-based magnetic sorbents (Kim *et al.* 2021), buoyant oleophilic magnetic activated carbon nanoparticles (Samia *et al.* 2022) and silica aerogel composites with innate superparamagnetic capability (Renjith *et al.* 2023). These materials exhibit high oil absorption capacity, reusability and efficiency under diverse environmental conditions. These advanced sorbents are a versatile solution for efficient and eco-friendly oil spill containment. Schematic Representation of Oil-Water Separation Using Magnetic Nanoparticles can be seen in Fig. 3.

4.3.2 Limitations

It is a very efficient method in practice for dealing with oil spills at small and moderate scales, but there are still challenges in dealing with major oil spills. Challenges posed by material cost, deployment logistics, and post-treatment of recovered oil and adsorbents must be tackled. However, magnetic adsorbents are one of the potential ways to fight oil spill catastrophes.

4.4 Magnetically Responsive Coatings for Corrosion Prevention

4.4.1 Analysis of Implementation in Infrastructure

In recent years, much study has been devoted to improving metallic anticorrosion performance by designing smart self-heal coatings. These films augment properties by incorporating diverse technologies, such as magnetically active microcapsules (Liu *et al.* 2024), nanofillers (Pengpeng *et al.* 2023) and micro/nanocontainers (Sanyal *et al.* 2024) (see Fig. 4). They react to environmental stimuli such as magnetic fields, a change in pH, and mechanical damage. The coatings required no external cues to relax, shrink or swell to autonomously heal minor damages, enhance corrosion resistance, and extend the longevity of structures (Yimyai *et al.* 2023). Some high-tech coatings integrate active and passive corrosion inhibitors (such as polymeric materials), which can provide long-term protection against corrosion and respond quickly

(Pengpeng *et al*. 2023). Recently, various novel methods such as composite coating or liquid-like magnetic nanofluids have been suggested to enable multifunctional coatings with excellent anticorrosion and self-healing properties (Pengpeng *et al*. 2023). These advancements mark essential progress in corrosion protection technologies for different industrial purposes.

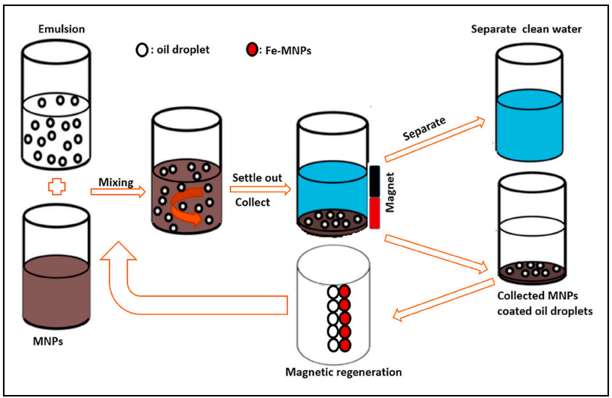

Fig. 3: Schematic representation of oil-water separation using magnetic nanoparticles (Elmobarak *et al.* 2021)

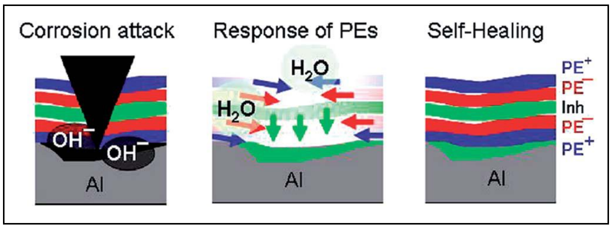

Fig. 4: Schematic illustration of the self-healing action of a "smart" polyelectrolyte anticorrosion coating (Wei *et al.* 2014)

4.4.2 Observed Benefits

It is known that magnetically responsive coating materials have been field tested, and it has been proven that they can significantly reduce corrosion rates. Thus, increasing the durability and lowering maintenance costs. In the oil and gas industries, this technology has been successfully implemented to a great extent, thereby significantly improving the asset lifespan and environmental friendliness.

4.5 Magnetic Nanoparticles for Agricultural Soil Remediation

4.5.1 Efficiency and Deployment

Heavy metal soil pollution significantly threatens agricultural products and food security. Research has shown the potential of functionalized magnetic nanoparticles for soil remediation. Such particles as $Fe_3O4@SiO_2$ follow chelation by their preparation with specific chelating agents (e.g., iminodiacetic acid, diethylenetriaminepentaacetic acid (DTPA)) and exhibit the capacity to bind with and eliminate heavy metals from polluted soils (Hughes *et al.* 2018). High removal efficiencies of metals (cadmium, lead, and copper) were observed in complex soil leachates (Huang and Keller, 2020). Nanoremediation was more cost-effective and eco-friendly than the conventional method (Mathur *et al.* 2022). Hybrid nanoparticles combine various components, which have the potential for both metal remediation and nutrient supplementation (Umair *et al.* 2024). Although phytoremediation is an effective process, magnetic biochar has shown to be an efficient, reusable alternative to extracting heavy metals (Lin *et al.* 2022). Magnetic nanoparticles have been used to remove contaminants from water by coating them with compounds such as natural chitosan (Mboyi *et al.* 2017). Magnetic nanoparticle methods for eliminating contaminants can be seen in the fig. 5.

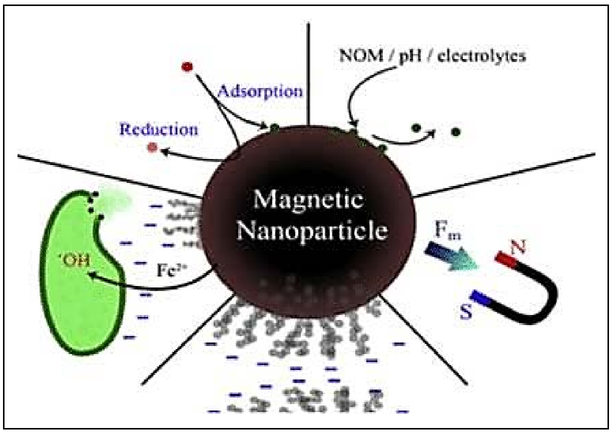

Fig. 5: Magnetic nanoparticle methods for eliminating contaminants (Maggy *et al.* 2017)

4.5.2 Limitations and Future Prospects

Although this method works well in removing the heavy metals found in soil, it has not yet been scaled up to work in big agricultural fields. Active research continues to develop more efficient magnetic particles and cheaper ways to deploy them. Despite these challenges, this technique has proved effective in pilot studies that increase soil health and agricultural productivity.

Although introducing magneto-responsive materials in existing water treatment and soil remediation infrastructure offers opportunities and challenges. Many water treatment plants can take advantage of its high efficiency and simple magnetic separation for agents, resulting in sludge minimization and operational costs reduction. But widespread deployment hits barriers such as optimizing the stability of the materials, increasing regeneration efficiency, and preventing secondary contamination. In the soil remediation, using the magnetic nanoparticles to extract heavy metals has proven effective, but scaling this up becomes complicated in practice due to varying soil composition in the field, field conditions and economical issues in technique. Advances in material engineering, combined with policy support and pilot-scale demonstrations in the future, are the key to surmount these challenges and broaden the thighs of use.

4.6 Magnetic Catalysts in Wastewater Treatment

4.6.1 Description of a Real-world Application

Advanced Oxidation Processes (AOPs) represent a promising strategy to mineralize aqueous organic contaminants via reactive oxygen species (Pandis *et al*. 2022). These processes include UV/H2O2, Fenton reactions, ozonation, photocatalysis and sonolysis (Atalay and Ersöz, 2016). Nanocatalysts, especially encapsulated transition-metal nanoparticles, have been demonstrated to be excellent catalysts for optimizing AOPs owing to their unique physicochemical properties (Yu *et al.* 2023). The use of magnetic nanoparticles (e.g., Fe_3O_4@PDA/Ag) also allows for easy removal and reutilization, thereby increasing efficiency and reducing waste (Jin *et al*. 2022). It should be noted that other catalysts, such as rare earth elements and copper-based nanocatalysis, have demonstrated high catalytic activity in AOPs (Saviano *et al.* 2023; Li *et al.* 2023). Nanomaterials combined with AOPs enhanced degradation of different pollutants such as pharmaceuticals, dyes and other organic compounds (Cardoso *et al*. 2021). Pollutants typically present in textile effluents can be eliminated with the help of these catalysts, which offer removal efficiencies as high as 99% (Mahadevan *et al*. 2023). The schematic representation of the water purification using MNS can be seen in Fig. 6.

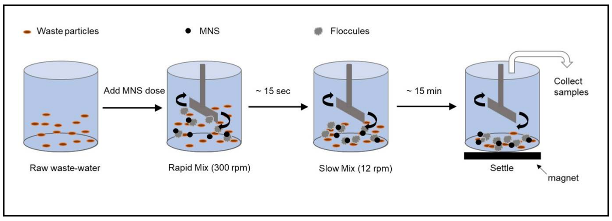

Fig. 6: Water purification system using magnetic nanoparticles (Chhetri *et al.* 2022)

4.6.2 Outcomes and Impact

Magnetic catalysts have been reported to exhibit much higher degradation rates for contemporary persistent pollutants (e.g., dyes, pharmaceuticals) in wastewater. Increased availability of these catalysts for reuse has lowered operational costs for the process, allowing it to become economically feasible. Pilot tests of this technology have been conducted on wastewater treatment plants at a pilot scale.

Although magneto-responsive materials have many advantages for tackles environmental applications, potential risks are posed by their degradation and interaction with pollutants. Thus, magnetic nanoparticles can oxidize or leach over time causing their release into the environment with possible side effects. Moreover, functionalized magnetic materials can release secondary pollutants under extreme environments, such as high acid, high salinity and UV light. Studies have demonstrated that surface coatings (e.g., silica, polymeric shells, and bio-degradable encapsulation) can help overcome these risks by improving materials' stability and reducing their leaching. Additionally, research is still continuing to understand the long-term behavior of these materials in aquatic and soil environments for minimal ecological consequences (Namdeti *et al.* 2024). An important challenge for widespread deployment is developing sustainable recovery and recycling processes for spent magneto-responsive materials.

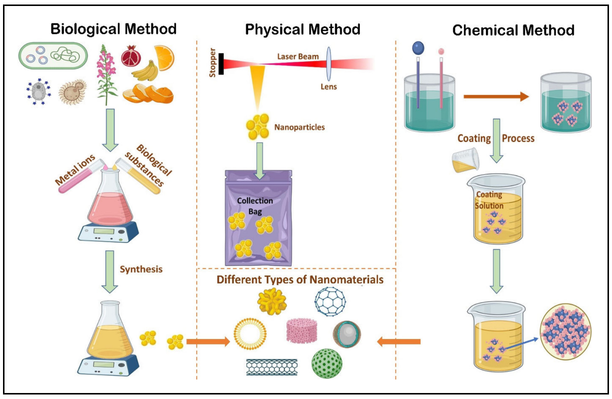

Fig. 7: Physical, chemical and biological methods for synthesising different types of MNPs (Shukla *et al.* 2021)

4.7 Magnetic Responsive Drug Delivery Systems for Wastewater Bioremediation

4.7.1 Efficiency and Deployment

Over the last two decades, magnetic nanoparticles (MNPs) have been recognized as a novel technology for environmental cleaning and targeted drug delivery. Due to their high specific surface area and unique characteristics, MNPs are widely applied in wastewater treatment for the removal of different pollutants such as heavy metals, organic contaminants, and microbes (Shukla *et al*. 2021) (see Fig. 7). Such nanoparticles can eliminate most pollutants with 100 per cent efficiency within few minutes (Shukla *et al*. 2021). Other approaches are also adapted for bioremediation using microorganisms for decontamination to an extent using MNPs (Saeed *et al*. 2021). MNPs are known as effective carriers for drugs in medical applications due to their biocompatibility, superparamagnetic properties, and their capability to target specific tissue using an external magnetic field (Mou *et al*. 2015). MNPs play an essential role in environmental and medical applications, as the particles can be functionalized with various coatings to optimize performance and limit potential toxicity (Gupta *et al*. 2017).

4.7.2 Limitations and Observed Benefits

This method suits localized wastewater treatment with high organic loads. However, the challenges are the cost of manufacturing and ensuring that the agents are distributed evenly. Field studies have shown that the approach is feasible, enhancing wastewater quality and better compliance with discharge standards.

5. CHALLENGES AND LIMITATIONS

5.1 Stability and Reusability of Magneto-responsive Materials

Although magneto-responsive materials have many applications, their stability and effectiveness during multiple use cycles pose challenges. If these materials are exposed to harsh environmental conditions for extended periods (for example, changing pH values, temperature, or high salinity), the performance of the materials can be reduced. Moreover, the magnetic responsiveness of certain materials diminishes after repeated use, demanding novel approaches to improve robustness. While the research on coating techniques, doping with stabilizing agents, and hybrid materials have the potential to resolve these difficulties, this topic must be addressed further to apply the technology in practice.

5.2 Environmental and Health Concerns of Nanomaterials

While their advantages are numerous, the underlying porous magneto-responsive materials and the incorporated nanomaterials can create significant environmental and toxicological issues. They are small enough to scatter into ecosystems, where they may concentrate and react in biological systems in novel ways. Toxicity shows potential risk to marine organisms, soil organisms, and humans; this possibility highlights the necessity for critical risk assessment. Moreover, the long-lasting impact of these materials on the environment is still not fully understood, underlining the need for biodegradable and environmentally friendly alternatives.

5.3 Cost-effectiveness of Large-scale Applications

The high price limits the widespread application of magneto-responsive materials for large-scale environmental remediation. Developing highly pure nanomaterials and modern engineered fabrication technologies may be expensive. The challenge is scaling these technologies for industrialisation without sacrificing performance or quality. This limitation can be tackled with the partnerships between academic institutions and industries in synergy with the technological evolvement of low-cost manufacturing processes to allow the scalable application of these novel materials.

Development of established safety protocols and regulatory guidelines is also necessary for the safe deployment of these kinds of magneto-responsive smart materials in environmental applications. Regulatory bodies across various countries, including the Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA), acknowledge that risk assessment frameworks need to be developed specifically for engineered nanomaterials. Critical factors include their fate in the environment, bioaccumulation potential, and potential toxicity under various conditions. Research into sustainable substitutes, like eco-friendly coatings and functionalized nanoparticles with diminished leaching, can lower risks. To open the door for industrial adaptation, the corresponding regulatory compliance should be as smooth as possible, to ensure safety for both people and the environment. Regulation in the future needs to be based on standardized testing methodologies, life cycle assessments, and real-world case studies that will inform safety frameworks for translating proposals to the wider world.

6. FUTURE TRENDS AND RESEARCH DIRECTIONS

6.1 Advances in Biodegradable and Eco-friendly Magneto-responsive Materials

The design of biodegradable and green magneto-responsive materials is a key direction for future research. Promising approaches include using natural polymers, such as cellulose and chitosan, as matrices to embed magnetic nanoparticles. Such eco-friendly materials not only mitigate environmental concerns but also improve biocompatibility. Developing hybrid systems incorporating magneto-responsiveness and a natural degradation process will significantly facilitate the preparation of sustainably applicable environmental nanotechnology.

6.2 Integration with IoT for Smart Environmental Monitoring

The integration of magneto-responsive materials and IoT offers excellent promises for environmental monitoring. Wearables and smart sensors equipped with these materials can report pollution levels, detect contaminants in water, and monitor air quality. Using wireless communication systems, data can be sent to centralized systems for analysis and quick response to environmental hazards. Together, nanotechnology and

IoT serve as a great line of defence to help monitor the environment in real-time.

Overall, diverse IoT technologies can be utilized for monitoring magneto-responsive materials in environmental applications. For this reason, wireless sensor networks (WSNs) based on magneto-responsive nanomaterials can offer real-time data regarding water, air, and soil contaminants. The environmental data generated from these sensors can be efficiently processed and analyzed when paired with cloud computing platforms like AWS IoT or Microsoft Azure IoT. This also requires deploying edge devices like a Raspberry Pi or NVIDIA Jetson to process data near the source and reduce latency. In addition, the utilization of LoRaWAN and 5G communication networks in smart environmental monitoring systems up-scales the interconnectivity and coverage of these systems. Even more advanced AI predictive maintenance systems can improve the long-term performance of magneto-responsive materials in environmental applications.

6.3 Potential for Multidisciplinary Research Collaborations

The challenges related to environmental nanotechnology are complex and need interdisciplinary attention to overcome the issues. Chemists, materials scientists, environmental engineers, and data scientists are invited to collaborate in investigating new magneto-responsive materials. Such collaborations could lead to advancements in novel sustainable synthetic methods, large-scale implementation strategies, and computational modelling. Only through interdisciplinary partnerships can these materials be realized to address global environmental challenges.

7. CONCLUSION

Magneto-responsive smart materials enable environmental nanotechnology with diverse functions and potential applications. These materials are essential in air and water purification, energy sustainability, and soil remediation. While they hold great potential, challenges related to the needed materials' stability, environmental safety, and cost-effectiveness remain significant obstacles to widespread use.

The hurdles in this area can be overcome by designing more biodegradable and eco-friendly materials, incorporating IOT for warehouse smart monitoring, and carrying out substantial multidisciplinary studies. Research efforts will continue to expand and improve the functionality of these materials and facilitate sustainable environmental solutions. With advancements in the field, magneto-responsive smart materials are set to revolutionize the trajectory toward a cleaner, greener, and more sustainable future.

Several successful case studies and partnerships have demonstrated the practical implementation of magneto-responsive materials in environmental remediation. For example, the use of magnetic nanoparticles for arsenic removal has been implemented in real-world scenarios, reducing arsenic levels in drinking water to safe limits and minimizing secondary waste generation. Additionauid-based filters have been deployed in industrial effluent treatment, achieving high contaminant removal efficiency while enabling cost-effective regeneration. In the oil and gas inetic adsorbents have been successfully used for rapid oil spill cleanup, offering an efficient and reusable solution for mitigating environmental damage. Furthermore, collaborative rese between academic institutions and industries are accelerating the commercialization of these technologies, ensuring that magneto-responsive materials transition from laboratory research to large-scale implementation. These case studies highlight the transformative potential of these materials and emphasize the need for continued innovation and policy support to maximize their impact on environmental sustainability.

In addition to ongoing research, emerging materials and novel technologies have the potential to further enhance the functionalities of magneto-responsive materials in environmental remediation. Hybrid nanomaterials, such as graphene-magnetic composites and bio-inspired magneto-responsive structures, offer improved adsorption capacity, selectivity, and mechanical stability. The development of magnetically tunable hydrogels and aerogels also provides promising avenues for applications in water purification and oil spill cleanup. Furthermore, the integration of artificial intelligence (AI) and machine learning algorithms with magneto-responsive materials is expected to optimize their efficiency in environmental monitoring and adaptive responses. These advancements, coupled with interdisciplinary collaborations, will drive the next generation of smart environmental nanotechnology solutions.

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CONFLICT OF INTEREST

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