Chapter 10
Removal of Heavy Metal Ions Using Magnetic Materials

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Contents

Abstract Heavy metal ions contaminate water environment through point sources and nonpoint sources. Heavy metal ions are categorized as inorganic contaminants by both the WHO and the USEPA. The heavy metal ions are increasingly being introduced into the environment as pollutants and contaminants resulting from human activities.

Magnetic particles for water treatment applications have received considerable attention from researchers due to high separation efficiency. The magnetic particles behave similar to or even better than various commercial adsorbents. The magnetic

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particles also exhibit high selectivity for the target pollutants from the environment besides enabling ease of operation for reducing the particle separation steps from the flowing stream. A comprehensive and systematic understanding of synthesis and surface modifications of magnetic particles is significant to enhance their practicability in environmental technology. Although high removal performance and reactivity can be achieved by smaller particle size, the stability, toxicity, and recovery of the particles magnetically could be challenging.

In contrast, the active surface of magnetic particles may be forfeited, while surface modifications stabilize and reduce the toxicity of the particles. Reliable surface modifications are necessarily needed for the increment of the number of active sites to remove the heavy metals. For successful environmental applications of the magnetic particles, modification on the magnetic particles is principally crucial to balance the effects on their reactivity, capacity, and reusability.

Keywords Heavy metal ions · Magnetic particles · Contaminants · Heavy metal · Adsorbent · Pollution · Removal · Separation · Magnetic sorption technology

Nomenclature

$\gamma\text{-}Fe_2O_3$	Maghemite
Ag	Silver
BH_{max}	Highest energy product
B_r	Remanence
Ca	Calcium
Cd^{2+}	Cadmium cation
CdS	Cadmium sulfide
CdSe	Cadmium selenide
Cu	Copper
Cu^{2+}	Copper cation
Co	Cobalt
Cr^{4+}	Chromium cation (4+)
Fe	Iron
FeO^-	Negative charge iron oxide
Fe_3O_4	Magnetite
Fe_3S_4	Greigite
Gd	Gadolinium
Hc	Coercive force
Hg^{2+}	Mercuric cation
HGMS	High-gradient magnetic separation
Mg	Magnesium
MIEX	Magnetic ion exchange resin
Mn	Manganese
$MnFe_2O_4$	Manganese iron oxide
MnO	Manganese(II) oxide
Mn-Zn	Manganese-zinc

Nd	Neodymium
Nd-Fe-B	Neodymium, iron, and boron
Na^+	Sodium cation
Ni	Nickel
Ni^{2+}	Nickel cation
$NiFe_2O_4$	Nickel iron oxide/nickel ferrite
nZVI	Nano zerovalent iron
Pb^{2+}	Lead cation
Si	Silicon
Sm-Co	Samarium-cobalt
SPIONs	Superparamagnetic iron oxide nanoparticles
T_c	Curie temperature
USA	United States of America
USEPA	US Environmental Protection Agency
WHO	World Health Organization
Zn	Zinc
$ZnFe_2O_4$	Zinc ferrite

1 Introduction

The conventional adsorbents, including activated carbon, silica gel, zeolite, and clay minerals, which have been widely used to remove heavy metals suffer from high generation costs. The attention was then shifted to the use of adsorbent derived from agricultural waste such as sawdust, orange peel, ground coffee, and almond shell for the heavy metal removal due to their low cost and high abundance. Although these adsorbents were reported to be very useful for water purification, separation of these powdered adsorbents from wastewater in a continuous flow system tends to be very challenging. In recent years, magnetic sorption technology has become one of the emerging technologies in solving environmental problems. Exploration of magnetic materials permits the tendency of applications in water treatment extensively. After the usage, the magnetic particles which act as adsorbent are separated from the solution by magnetic force. Thus, it receives considerable attention due to ease in separation after usage.

2 Magnetic Materials

Magnetic materials are materials that display magnetic response in the presence of a magnetic field. Mitchell [1] claimed that magnetic materials are categorized into two major groups: (1) soft magnetic materials and (2) hard magnetic materials based on their magnetic properties such as remanence (B_r), coercive force (H_c), and Curie

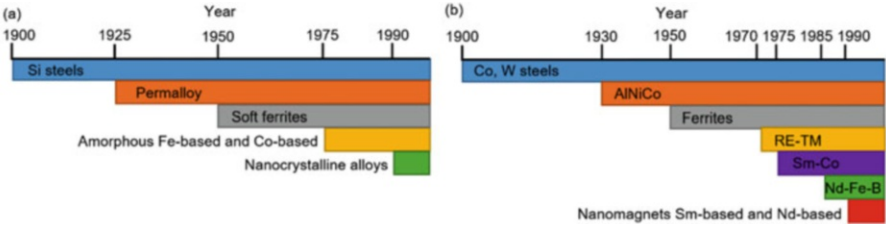


Fig. 10.1 Developments of (**a**) soft magnetic material and (**b**) hard magnetic material. (Source: Dobrzański et al. [7])

temperature (T_c). In other words, magnetic materials are classified as being magnetic or nonmagnetic. A material which is easily magnetized and demagnetized is referred to as soft magnetic material, whereas hard magnetic material is challenging to be demagnetized [2, 3]. The hard magnetic materials remain strongly magnetized after the applied magnetic field is removed and become to be permanent magnets. Iron, steel, and alloy bars are the most common magnetic materials.

Typically, soft magnetic materials denote permeable magnets or electromagnets. Electromagnets (artificial magnets) are constituted of soft-iron cores around which are wound coils of insulated wire [4]. The core becomes magnetized when an electric current flows through the coil; the core loses most of the magnetism when the current ceases to flow. The soft magnetic materials have coercive force less than 1000 A/m and high magnetic permeability. Examples are Si steels, permalloys, Mn-Zn soft ferrites, amorphous Fe-based, and Co-based.

On the other hand, hard magnetic materials denote permanent magnet. Permanent magnets as another type of artificial magnets are hardened steel or certain alloys that have been permanently magnetized. They are distinctive for their excellent magnetic properties such as remanence and coercive force [5, 6]. Examples of this material include Co and W steels, alnico bars, ferrite magnets, magnets from the cobalt alloys with the rare earth group elements, and magnets from the Nd-Fe-B alloys. The evolution of the magnetic material is illustrated in Fig. 10.1. Despite that, some commercially available magnetic materials are tabulated in Table 10.1 with their respective characteristics.

3 Aspect of Magnetism

Magnetism is a remarkable physical property that can be exploited in water treatment by manipulating the physical properties of the pollutants in water. In combination with other processes, it facilitates the efficiency of water purification. The concept of the use of magnetism for water treatment such as anti-scaling technique in boilers, pipelines in factories, coagulation, and biological processes has been extensively reported.

Table 10.1 Comparison of key characteristics of commercially available magnetic materials

Characteristic	Ceramic	Alnico	Bonded Nd-Fe-B	Sm-Co	Nd-Fe-B
Highest energy product, BH_{max} (kJ/m^3)	32	59	79	254	382
Maximum operating temperature (°C)	300	550	150	300	150
Resistance to demagnetization	Moderate	Low	High	Very high	High
Corrosion resistance [uncoated]	Excellent	Excellent	Good	Good	Poor
Mechanical toughness	Moderate	Tough	Moderate	Very brittle	Brittle
Relative cost	Very low	Moderate	High	Very high	High

Source: Hatch and Stelter [8]

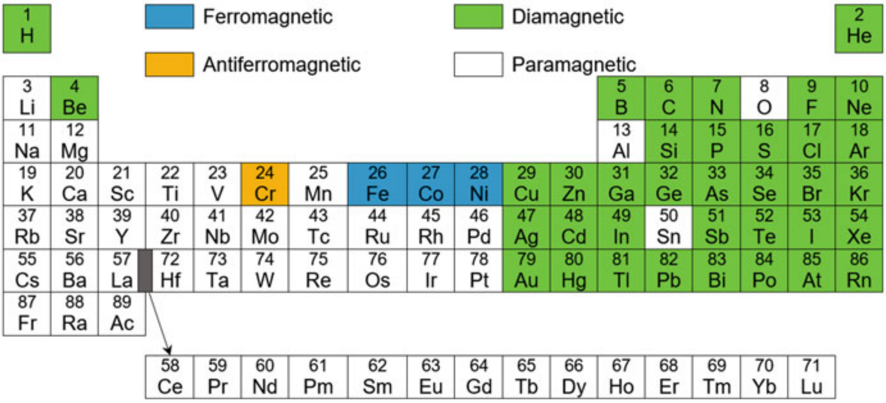
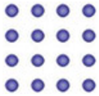
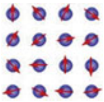
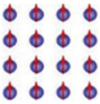
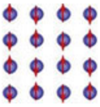
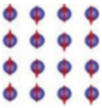


Fig. 10.2 The periodic table showing the types of the magnetic behavior of each element at room temperature. (Source: Harris and Willams [2])

Magnetism is defined as a phenomenon associated with magnetic fields. It has the power to attract magnetic materials such as iron, steel, nickel, or cobalt. There are five types of magnetism: diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism, and ferrimagnetism [9, 10]. In magnetic materials, a magnetic field is formed due to the movement of electrons within the material. However, ferromagnetic materials exhibit magnetism on a microscopic scale even without an applied field [11].

Based on Fig. 10.2, diamagnetism and paramagnetism account for the magnetic behavior of most of the elements in the periodic table at room temperature. These elements are indicated as nonmagnetic material. Meanwhile, those elements which are referred to as magnetic are categorized as ferromagnetic. Another type of

Table 10.2 Classification of magnetic material

Type of magnetism	Atomic/magnetic behavior		Susceptibility, χ	Typical materials
Diamagnetism	Atoms have no magnetic moment		Small and negative	Organic materials, superconducting metals, and other metals
Paramagnetism	Atoms have randomly oriented magnetic moments		Small and positive	Alkali and transition metals, rare earth elements
Ferromagnetism	Atoms have parallel aligned magnetic moments		Large and positive, function of applied field, microstructure dependent	Some transition metals (Fe, Ni, Co) and rare earth metals (Gd)
Antiferromagnetism	Atoms have mixed parallel and antiparallel aligned magnetic moments		Small and positive	Salts of transition elements (MnO)
Ferrimagnetism	Atoms have antiparallel aligned magnetic moments		Large and positive, function of applied field, microstructure dependent	Ferrites ($MnFe_2O_4$, $ZnFe_2O_4$) and chromites

Source: Mitchell [1]

magnetism observed in pure elements is antiferromagnetism. Additionally, magnetic materials can also be classified as ferromagnetic. This material is not detected in any pure element but can be found in compounds such as the mixed oxides (ferrites).

The magnetic properties of materials are mostly determined by their structure and the several magnetic interactions between neighboring atoms. There are only 16 elements that have magnetically ordered ground state, and all but oxygen belongs to the 3d or 4f transition series [12]. The magnetic materials are divided into few categories in terms of their magnetic behavior as presented in Table 10.2.

3.1 *Diamagnetism*

Diamagnetism which is usually very weak is a fundamental property of all matter. In a diamagnetic material, the atoms have no net magnetic moment in the absence of applied field [13, 14]. Nevertheless, a negative magnetization is produced in the opposite direction from the applied magnetic field, resulting in negative susceptibility of approximately -10^{-6}. The susceptibility of the diamagnetic materials is temperature independent. These materials are very weakly affected by magnetic fields. Therefore, the contribution of diamagnetism is insignificant unless it is the only magnetism present. Materials such as acetone, alumina, carbon dioxide, copper, lead, quartz, silver, and water are diamagnetic.

3.2 Paramagnetism

Paramagnetism results from the magnetic forces on unpaired electrons. In paramagnetic materials, some of the atoms or ions have a net magnetic moment due to unpaired electrons in partially filled orbitals [15]. Under the influence of an applied field, there is a partial alignment of the atomic magnetic moments parallel to the direction of the field, resulting in a net positive magnetization and positive susceptibility lies between 10^{-3} and 10^{-5}. The net magnetization of the atom is small due to random ordering of moments but more significant than the diamagnetic contribution. Similar to diamagnetism, the magnetization is zero when the field is removed. Materials such as clay, carbonate, silicate, sodium, and platinum are paramagnetic.

3.3 Ferromagnetism

Ferromagnetism occurs when there are exchange interactions among the electrons in the material. In ferromagnetic materials, the atomic magnetic moments align parallel or antiparallel to each other due to an interaction between neighboring moments or mutual reinforcement of the dipoles. Unlike paramagnetic materials, the atomic moments in these materials exhibit powerful exchange forces, equivalent to a field on the order of 1000 Tesla or around 100 million times the strength of the earth's field [16]. The parallel alignment of moments results in large net magnetization even in the absence of a magnetic field, giving high susceptibility approaching 10^6. Above the Curie temperature, ferromagnetic materials exhibit paramagnetic behavior. Iron, nickel, and cobalt and many of their alloys are typical ferromagnetic materials.

3.4 Antiferromagnetism

Antiferromagnetism occurs when the magnetic moments produced in neighboring atoms line up in opposition to one another in the magnetic field. This magnetic ordering cancels out the magnetic moments, and net magnetization is zero. The magnetic susceptibility is positive and small, approximately 10^{-5} to 10^{-3}. Moreover, these materials exhibit paramagnetic behavior like ferromagnetic materials above a transition temperature, Néel temperature [17]. Cobalt oxide, chromium, manganese chloride, manganese oxide, and nickel oxide are examples of antiferromagnetic materials where chromium is the only element exhibiting antiferromagnetism in the periodic table at room temperature.

3.5 Ferrimagnetism

Ferrimagnetism is observed in more complex crystal structures than pure elements. The magnetic structure is composed of two magnetic sublattices separated by oxygen. In a ferromagnetic material, some atoms are in parallel alignment while others are in antiparallel alignment. The magnetic moments of the sublattices are not equal and result in a net magnetic moment. The magnetic susceptibility is similar to ferromagnetic materials, but ferrimagnetic materials usually have lower saturation magnetizations. The material breaks down into magnetic domains where the diluting effect of those atoms in antiparallel alignment keeps the magnetic strength of this material generally less than that of purely ferromagnetic solids, a relatively low magnitude as only one-eighth of the ions contribute to the magnetization of the material [2]. A well-known ferrimagnetic material is a magnetite, Fe_3O_4.

4 Synthesis of Magnetic Particles

According to Thanh [18], the materials fabricated in the laboratory are mainly composed of magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), greigite (Fe_3S_4), and several types of ferrites ($MeO{\cdot}Fe_2O_3$, where Me = Ni, Co, Mg, Zn, Mn, and others). Iron oxide nanoparticles (Fe_3O_4 and γ-Fe_2O_3) have shown the most promise as potential environmental magnetic sensing materials by way of the synthesis, tuning of physical properties, and surface functionalization [19].

Numerous methods of synthesizing magnetic particles such as coprecipitation, hydrothermal, thermal decomposition, and sol-gel method have been so well established. Some common methods to synthesize magnetic iron oxide nanoparticles for versatility in tuning the characteristics of the nanomaterials are described in Table 10.3. Furthermore, common inorganic coatings for magnetic nanoparticles are presented in Table 10.4.

In order to be successfully exploited in applications, prerequisites such as good dispersibility, nano-sized distribution, highly uniformed superparamagnetic properties, hydrophilic surface with different functional groups, as well as homogenous physical and chemical properties are emphasized for the synthesis of iron oxide nanoparticles [20]. The synthesis of the magnetic particles is divided into two groups: in situ methods and ex situ methods.

Table 10.3 The comparison between various common synthesis methods of magnetic iron oxide nanoparticles

Synthesis methods	Size (nm)	Shape	Benefits	Drawbacks
Coprecipitation	15–200	Spherical/ rhombic	Conventional Low reaction temperature Rapid synthesis with high yield	Not suitable for the preparation of highly pure, accurate stoichiometric phase Unprotected magnetite vulnerable to oxidation or aggregation
Hydrothermal	27	Spherical	Highly crystalline Pure iron oxide nanoparticles Simple and scalable Good morphological control	Hydrothermal slurries are potentially corrosive Harsh reaction conditions Long reaction times
Thermal decomposition	4–20	Spherical	Reasonable control of size and shape with high yields Narrow size distribution Ability to quickly make different mixed metal oxide nanoparticles	Complicated and harsh preparation procedures The surfactant used hinders subsequent surface modification High decomposition temperature
Microemulsion	4–12	Spherical (inverted), cubic, lamellar phases, cylindrical micelles	A simple and versatile method Reproducible Using surfactant limits particle nucleation, growth, and aggregation Better morphological control Homogenous particle size distribution	Low crystallinity of SPIONs on a large scale due to low-temperature usage Complicated purification methods for separation of surfactants Poor yield A large number of solvents required
Sol-gel	20–200	Spherical	Pure amorphous phases Homogeneity and phase purity Low-temperature procedure Moderate morphological control Useful for hybrid nanoparticles’ fabrication	High cost Close monitoring is needed due to the several steps Challenging to obtain monodispersed nanoparticles through hydrolytic sol-gel route Broad size distribution
Sonochemical	5–30	Spherical	Shortened reaction time Uniform particle size Higher surface area Better thermal stability Improved phase purity	Particle agglomeration Not energy efficient Particle size tunability is not readily achievable Use of organometallic precursors causes in vivo toxicity

Source: Wu et al. [19], Ramimoghadam et al. [20]

Table 10.4 Common inorganic coatings for magnetic nanoparticles

Inorganic coating material	Conditions	Benefits	Drawbacks
Silica	Sol-gel/Stöber method, reverse micelle	Good dispersion in aqueous solutions Surface silanols for easy siloxane modification Ability to incorporate dyes and *quantum dots*	Drastic loss of core magnetic character
Carbon	Hydrothermal, pyrolysis	Biocompatible High chemical and thermal stability	Few synthetic methods/lack of understanding of formation mechanism
Gold	Microemulsion, solution-based reduction	Chemical inertness Thiol surface ligand modification Minor loss of core magnetic susceptibility Surface plasmon peaks for optical detection	–
Silver	Solution-based reduction	Surface plasmon peaks for optical detection	Difficult functionalizing with the Ag surface
CdSe or CdS	Solution-based shell growth	Tunable fluorescent shell	–

Source: Kumar [24]

4.1 In Situ Methods

In situ methods refer to the formation of nanostructures from precursor with the presence of another phase material [21, 22]. The most common method for the synthesis of magnetic particles in the literature is the coprecipitation method. In this method, divalent and trivalent iron salts are condensed in the presence of hydroxide bases. This method is relatively simple, cheap, and reproducible and results in high yield besides keeping the surface of particles free for any subsequent functionalization. However, the particles obtained in the first stage might agglomerate due to the neutralization of counter cations such as Na^+ and the negative charge of FeO^- groups on the surface. Moreover, the pH value and the required time to accomplish the transformation of the particle crystal structure are the crucial factors for the synthesis of iron oxides.

Other than that, hydrothermal is another method that has been investigated extensively for the synthesis of magnetic nanoparticles. The hydrothermal method is a process where the iron precursors in aqueous solution are heated at high temperature and pressure followed by crystallization of the dissolved material from the fluid [23]. The water can be replaced by other polar or nonpolar solvents such as benzene. The combination of microwave and hydrothermal method reported for the preparation of superparamagnetic iron oxide nanoparticles is advantageous for scale-up and fabrication of uniform particles.

4.2 *Ex Situ Methods*

Ex situ methods refer to the blending of pre-synthesized nanostructures with polymer using specific techniques such as ball milling, melt blending, and thermal curing. Unlike in situ methods, it is relatively challenging to handle the nanoparticle agglomeration due to the high surface energy of nanoparticle in preparing high-performance magnetic particles.

5 Magnetic Separation for Water Purification

Ideal water purification techniques at a low cost have attracted broad interest to be affordable for developing countries as well. Adsorption technology using an adsorbent satisfies the requirement due to its high performance, ease of operation, and insensitivity to toxic substances [25]. An optimal adsorbent ought to have the following characteristics: (1) high performance, (2) fast kinetics, (3) cost-efficient, (4) environmentally friendly, (5) reusability, and (6) ease of separation to be applied commercially. The most problematic issue for the removal process is the effectiveness of particle separation from aqueous solution. Water purification process has to implicate recyclable materials for successive treatment cycles and evade generation of secondary waste on an industrial scale. Among the adsorbent materials established, the feasibility of magnetic nano-adsorbents that have a high surface-to-volume ratio, tunable morphology, and excellent removal performance besides the magnetism property shows the most promising application for water and wastewater treatment systems. It is anticipated that magnetic separation can emerge to be a more cost-effective and expedient process for separating tiny powdered particles than sophisticated membrane filtration.

In the year 1995, magnetic ion exchange resins (MIEX) with the magnetic beads were introduced for the removal of natural organic matter [26]. Later, the removal of bromide ion was claimed to varying degrees by using MIEX, but the process was highly dependent on the alkalinity of the water and concentrations of the competing ion [27]. The small resin beads with a high surface area allow rapid exchange kinetics of selective ions, enabling a suitable usage in a continuous process. Agglomeration of the magnetic beads leads to flocculation, which allows higher settling velocity than for the single particles or fluidization at higher hydraulic loading rates.

On the application of an external magnetic field, the magnetic adsorbents can be rapidly and easily separated from water due to the presence of the metal components which are oxides of metals such as Fe, Co, Ni, and Cu in the adsorbent. Since magnetic particles were modified with polymer, carbon nanotubes deserve due attention to be used commercially for water treatment due to chemical stability, mechanical and thermal stability, and high surface area.

In addition, spinel ferrite magnetic materials with the general structural formula MFe_2O_4 (M = Ca, Co, Cu, Mg, Mn, Ni, Zn) are becoming more popular for remediation of metal ions due to their tunable sizes, diverse structures, high surface areas, excellent chemical and thermal stabilities, ease of separation, high sorption performance, and wide pH ranges [49]. A ferromagnetic $NiFe_2O_4$ which is synthesized by a sol-gel method using egg white shows high adsorption capacity for Cu^{2+}, Cr^{4+}, and Ni^{2+} because its 3D interconnected porous structure was reported to keep high removal efficiency (>97%) during seven reusable cycles [28]. Some other findings on the removal of heavy metals by using magnetic particles are presented with their respective synthesis methods in Table 10.5.

Table 10.5 Magnetic particles for heavy metal removal with their respective synthesis methods

Magnetic particles	Pollutants	Synthesis methods	References
Maghemite nanoparticles	Cr^{6+}	Sol-gel	[29]
Carbon nanotubes-iron oxide magnetic composites	Cu^{2+}, Pb^{2+}	Catalytic pyrolysis	[30]
Magnetic alginate microcapsules containing the extractant Cyanex 272	Ni^{2+}	Coprecipitation	[31]
Alginate encapsulated magnetic sorbent	As(V), organic arsenate, Cu^{2+}	Encapsulation	[32–34]
Zirconium-based magnetic sorbent	As(V)	Coprecipitation	[21]
Thiourea-modified magnetic chitosan microspheres	Cu^{2+}, Hg^{2+}, Ni^{2+}	Coprecipitation and hydrothermal	[35]
Amino-functionalized $Fe_3O_4@SiO_2$ core-shell magnetic nanomaterial	Cu^{2+}, Cd^{2+}, Pb^{2+}	Coprecipitation	[36]
Magnetic chitosan nanoparticles	Cu^{2+}	Coprecipitation and hydrothermal	[37]
Superparamagnetic iron oxide nanoparticles (SPIONs) modified with poly(γ-glutamic acid) (PGA)	Cd^{2+}, Pb^{2+}	Coprecipitation	[38]
Magnetic Fe_3O_4 @ silica-xanthan gum composite	Pb^{2+}	Coprecipitation	[39]
Magnetic chitosan/cellulose hybrid microspheres	Cu^{2+}, Cd^{2+}, Pb^{2+}	Sol-gel	[40]

6 Recovery of Magnetic Particles

Although abundant experimental photographic results were reported for the prospect of separation and recovery of magnetic nanoparticles from water or wastewater, there is no successful industrial application of magnetic particles for water or wastewater treatment that have been published. The discrete magnetic particles which are prone to agglomerate due to the magnetism property were believed to decrease the heavy metal removal capacity. The problem has become a prodigious limitation for recovery and reuse of the magnetic particles. Several conditions are manipulating the applicability of magnetic particles in a sustainable treatment process.

Several studies have indicated that the nanoscale iron oxide, which behaves as superparamagnetic material, can offer high accessibility and reusability for water or wastewater treatment systems [21, 41–43]. Majority of the systems require centrifugation or filtration process to separate solid wastes. Magnetic nanoparticles, however, can be separated and recovered easily with the aid of an external magnetic field due to the inherent characteristic of the nanoparticles, magnetism [44].

Magnetic separation is a technique to collect or separate magnetic substances from flowing streams. High-gradient magnetic separation (HGMS) device comprises of a bed of magnetically susceptible filling placed inside an electromagnet usually practiced in magnetic separations. Scientific literature has indicated that magnetic field-enhanced process with magnetite and HGMS offers substantial improvement for the removal of heavy metals from wastewater [45]. The generation of significant magnetic field gradients, size and magnetic properties of particles, and the area of magnetized surfaces are the crucial factors for effective particle collection. When the particle suspension flows through the separation unit, the magnetic force attracting particles must be on top of the gravitational, fluid drag, buoyancy, inertial, and diffusion forces.

Separation of magnetic nanoparticles with a low-gradient magnetic field or a handheld permanent magnet (usually made of Fe and Nd) from solution has been regularly conveyed [46]. However, a higher magnetic force for a superconducting magnet in HGMS instead of an electromagnet is required when the particle size is reduced to the nanoscale. Complementary to this, aggregation due to strong magnetic dipole-dipole interactions between particles can either be coated with a surfactant to provide steric stability or particle surfaces be modified to produce a repulsive electrostatic force [47, 48]. In short, an optimum particle size, synthesis methods of magnetic nanoparticles, and fluid properties are the aspects needed to be considered to design an effective recovery and high removal performance system.

7 Environmental Application of Magnetic Particles

Magnetic particles such as nano zerovalent iron, magnetite, and maghemite and composite magnetic nanoparticles have been extensively utilized in environmental applications. These particles demonstrated favorable performance for eradicating pollutants from waterway systems. These promising findings have laced an alternative solution for the removal of heavy metal ions from contaminated water using magnetic adsorption technology [50].

Remediation of heavy metal pollution is possible by immobilizing them in a non-bioavailable form or re-speciating them into fewer toxic forms with nano zerovalent iron (nZVI). Several practical experiences of site remediation using nZVI have been established in the USA, and this remediation technique is expected to phase out in the coming decades. In Europe, many pilot test projects with the application of nZVI for different pollutants through three full-scale applications were merely conveyed. The pilot studies of 7 kg nZVI were reported to treat 1–5 g/L of Cr (VI) at Permon, Czechia [51]. Furthermore, macroscale zerovalent iron has been documented as a suitable electron donor in aquatic environments.

Economic constraints and the precautionary attitude in Europe raise concerns regarding the feasibility of nZVI as a cost-effective technique for aquifer remediation. Nontechnical aspects, including the probability of negative repercussions and the novelty of the technology for consultancy, governments, as well as the public, tend to be significant challenges for the commercialization of nZVI.

Glossary

Adsorbent	A material which will allow a liquid, gas, or dissolved solid to adhere to its surface
Adsorption	A process by which a solid holds molecules of a gas or liquid or solute as a thin film
Carbon nanotubes	Cylindrical molecules that consist of rolled-up sheets of single-layer carbon atoms (graphene)
Chemical stability	Resistance of a chemical to change in a chemical reaction
Coprecipitation	Simultaneous precipitation of more than one compound from a solution
Curie temperature	Temperature at which certain magnetic materials undergo a sharp change in their magnetic properties
Heavy metal ions	Metallic cation and anion that have relatively high density and are toxic or poisonous at low concentrations
Hydrothermal	A chemical reaction in water at both high temperature and pressure in a sealed pressure vessel
Ion exchange	A reversible chemical reaction where dissolved ions are removed from the solution and replaced with other ions of the same or similar electrical charge
Ion exchange resin	A resin that acts as a medium for ion exchange
Magnetic force	

	Attractive or repulsive force that is exerted between the poles of a magnet and electrically charged moving particles
Magnetic field	A vector field that describes the magnetic influence of electric charges in relative motion and magnetized materials
Magnetic sorption technology	A process by which a magnetic solid holds molecules of a gas or liquid or solute as a thin film
Mechanical stability	The quality of being free from change or variation
Microemulsion	A thermodynamically stable, isotropic emulsion with a droplet size of 1–100 nm
Nanoparticle	A microscopic particle with at least one dimension less than 100 nm
Permanent magnet	Material with the magnetic field that is generated by the internal structure of the material itself
Pyrolysis	Decomposition brought about by high temperatures
Reverse micelle	Aqueous-phase droplet in organic solvent that is stabilized by surfactant
Sol-gel	A wet chemical process involving the formation of an inorganic colloidal suspension (sol) and gelation of the sol in a continuous liquid phase (gel) to form a three-dimensional network structure
Stöber method	A chemical process for preparation of silica (SiO_2) particles of controllable and uniform size
Sonochemical	Application of ultrasound to chemical reactions and processes
Thermal decomposition	Some compounds breaking down when heated, forming two or more products from one reactant
Thermal stability	The ability of the material to resist the action of heat and to maintain its properties
Toxic substances	Substances that can be poisonous or cause health effects
Water purification	The process of removing undesirable chemicals, biological contaminants, suspended solids, and gases from water

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