9

Magnetic Nanomaterials for Environmental Applications

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9.1

Introduction

9.1.1

The Aim of the Chapter

The aim of this chapter is to provide details of the current state of the art and trends in the development of magnetic nanoparticles for environmental sensing applications, notably for the detection and removal of heavy metals and biological contaminants from complex samples. Recent advances in the use of nanoscale materials for environmental applications have been possible due to tremendous development efforts in the design and synthesis of engineered nanomaterials – that is, materials consisting of nanosized chemical domains and/or materials having extremely high surface areas arising from their nanoscale dimensions [1]. In particular, attention will be focused on the synthesis, functionalization, and application of engineered magnetic nanoparticles (diameter <100 nm in most cases) for the purpose of separating and detecting a wide variety of analytes from complex environmental and biological matrices. Recently, the use of functionalized magnetic nanoparticles in environmentally relevant applications, such as the selective capture and preconcentration of specific analytes from complex samples for sensitive detection, has been described in an increasingly large number of reports [2–18]. In addition, methods to synthesize magnetic nanoparticles with the appropriate attributes for environmental sensing have been exhaustively reviewed in the recent past, and are summarized in Section 9.2 [4, 14, 17].

9.1.2

The Role of Nanomaterials in Environmental Detection

The world's supply of drinking water is contained predominantly in manmade and natural lakes, rivers, and underground aquifers. Unfortunately, these sources often become polluted by a wide range of substances that are deleterious to human

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health, and that may have a substantial impact on the quality of life of those who depend on the polluted aquatic systems. Drinking water has two major classes of contamination, namely biological and chemical [19, 20]. Biological contamination, such as coliform bacteria (e.g., *Escherichia coli*) and viruses, if detected before exposure to human populations, can be remedied by a number of well-established technologies. However, the detection of these analytes in natural environments is a daunting challenge, and much ongoing research is being carried out to improve the current state of the art.

The detection, remediation, and removal of chemical and heavy-metal contamination (e.g., pesticides, radionuclides, and heavy metals such Hg and Pb) are, likewise, difficult challenges [19] (http://www.epa.gov/ogwdw/hfacts.html). The remediation of common organic contaminants such as pesticides, agricultural chemicals, industrial solvents, and fuels can be accomplished using treatments such as UV/ozone, activated-carbon, or plasma technologies [19]. The remediation and/or removal of toxic heavy-metal contaminants (e.g., Hg, Pb, Cd) can be partially addressed by using traditional sorbent materials such as ceramic oxides, although these materials will bind metal ions nonspecifically and can easily be saturated with ubiquitous species (e.g., Ca, Mg, Zn) [19]. Another weakness of traditional ceramic oxide sorbent materials is that metal ion sorption to the surface is a reversible process. Therefore, a functionalized sorbent material with a high chemical specificity that is capable of permanently sequestering the target analytes from the contaminated water system is needed [19, 20]. An ideal sorbent material candidate should have rapid kinetics for sorption of the analyte, while the interaction between the sorbent and analyte should be effectively irreversible in all but specific applications where analyte release is desirable. In addition, sorbent materials that enable a more sensitive detection for a wide variety of analytical methods through separation and preconcentration prior to analysis are needed [6]. These types of materials would allow the analysis of complex samples containing small amounts of analyte, without the high background signals typically associated with environmental samples.

Magnetic nanoparticles have the potential to meet many of the above-mentioned needs for the preconcentration, removal, and detection of both environmental and biological contaminants. These materials have a unique property–namely, superparamagnetism–that arises from their nanoscale single magnetic domain structures [17]. Superparamagnetic behavior manifests itself in nanoparticles that are smaller than the critical diameter, which is both material- and temperature-dependent. Throughout this chapter, the predominant topic of discussion will be iron oxide nanoparticles with diameters ranging from ~5 to 20 nm, which falls within the established critical diameter for this material (~15–20 nm) [17]. From a practical standpoint, a superparamagnetic nanoparticle has little to no remnant magnetization after exposure to a magnetic field, and low to no coercivity (the field required to bring the magnetization to zero); this means that such nanoparticles will not agglomerate magnetically at room temperature [17]. This is a significant factor for sensing applications, where it is desirable for the nanoparticles to be well dispersed in the sample matrix and easily manipulable by an applied external magnetic field. By exploiting not only the ability to remove magnetic nanoparticles from solution with an external field, but also the ability to tailor the surface functionality of the nanoparticles through synthetic means, it is possible to both separate and detect–with great sensitivity–a wide range of analytes. In this chapter, attention will be focused on the attachment of small molecules, polymers, and biomolecules (e.g., nucleic acids and proteins) for the purposes not only of separating the target analyte from complex samples containing interferents, but also of detecting them when the separation is complete. Some selected examples will also be presented of the application of functionalized magnetic nanoparticles for sensing and detection. Thus, the aim is to demonstrate the efficacy and future potential of magnetic nanomaterials for the effective preconcentration and sensing of environmentally relevant analytes from complex matrices such as river, ground, and ocean water.

9.2
Synthesis and Functionalization of Magnetic Nanoparticles

9.2.1
Synthetic Strategies for Magnetic Metal Oxide Nanoparticles

For the majority of sensing applications described in this chapter, the selection of a magnetic nanomaterial containing specific attributes to enable the best sensing performance is vital. Variations in nanoparticle core size, shape, and surface functionality may often have dramatic effects on the performance of the material in sensing applications. A wide range of synthetic methods is available to produce nanoparticles with properties desirable for use in separation and preconcentration applications [4, 5, 14, 16, 17, 21–24]. Such properties include:

- An ability to specifically functionalize the nanoparticle with small molecules or biological molecules so that they have a chemical affinity toward the analyte of interest.
- A high magnetic susceptibility, so that they might be easily captured or manipulated after being placed in contact with the sample of interest.
- A high dispersibility in the sample of interest (typically aqueous systems).
- Paramagnetic or superparamagnetic characteristics to prevent any irreversible magnetic agglomeration of the nanoparticles in solution, while still enabling magnetic recovery and manipulation.

Iron oxide nanoparticles (Fe_3O_4 and γ-Fe_2O_3) have shown the most promise as potential environmental magnetic sensing materials, as the synthesis, tuning of physical properties, and surface functionalization of these materials have been so well established. With this in mind, details of the more common methods of iron oxide nanomaterials synthesis have been summarized here, with a special emphasis placed on those methods that allow for the most versatility in tuning the characteristics of the prepared nanomaterials, particularly for sensing applications. The most frequently described methods are summarized in Table 9.1.

9.2.1.1 Coprecipitation

The synthesis of iron oxide nanoparticles using the coprecipitation method first described by Massart [25], is the simplest and most readily scaled synthetic approach. The precipitation of Fe_3O_4 (magnetite) nanoparticles is achieved by the addition of NaOH or NH_4OH to an aqueous solution of Fe^{3+} and Fe^{2+}, typically in a 2 : 1 ratio of the iron salts, to form Fe_3O_4 nanoparticles as described in Equation 9.1:

Table 9.1 Some common methods for preparing iron oxide nanoparticles.

Synthesis method	Chemical precursors	Benefits/Drawbacks	Reference(s)
Coprecipitation	Iron salts, base	↑ Rapid synthesis with high yield ↓ Unprotected magnetite vulnerable to oxidation/ aggregation	[14, 25, 26]
Hydrothermal	Iron salt, surfactant, high-b.p. reducing agent	↑ Narrow size distribution and good shape control ↑ Scalable ↓ Long reaction times	[27, 28]
High-temperature decomposition	Iron–organic complex, surfactant, 1,2-diol	↑ Good control of size and shape with high yields ↑ Ability to easily make different mixed metal oxide nanoparticles ↓ Further steps required to make water-soluble	[29–31]
Microemulsion	Oil/water/surfactant	↑ Control over particle size ↑ *In situ* stabilization possible ↓ Poor yield and large amounts of solvent required	[32–34]

$$2Fe^{3+} + Fe^{2+} \xrightarrow{8\,OH^-} Fe_3O_4 + 4H_2O \tag{9.1}$$

Adjustment of the ratios of Fe^{3+} to Fe^{2+}, the iron salt source (chlorides, sulfates, nitrates), the solution pH, and the presence of an organic stabilizing ligand will all have an effect on the final size, shape, dispersion, and stability of the Fe_3O_4 nanoparticles formed [14]. As unprotected Fe_3O_4 nanoparticles are vulnerable to oxidation, a controlled oxidation can be purposely carried out to form γ-Fe_2O_3 (maghemite) nanoparticles by dispersion in an acidic medium and heating in the presence of iron(III) nitrate. The γ-Fe_2O_3 nanoparticles obtained in this manner are more stable over a broader pH range and are more resistant to aggregation, although with a lower saturation magnetization than the Fe_3O_4 nanoparticles.

Preparations of iron oxide nanoparticles using this technique can generate superparamagnetic nanoparticles which range from 2 to 17 nm in diameter, simply by adjusting the various synthetic conditions [14]. The typical measured saturation magnetization of unfunctionalized Fe_3O_4 nanoparticles depends strongly on the overall size, and also appears to depend on the preparation temperature [26], although reported values are typically between 30 and 70 emu g^{-1}, slightly lower than the experimental value of 82 emu g^{-1} obtained for bulk Fe_3O_4. The specific surface area of nanoparticles of ~ 7 nm diameter is up to 124 $m^2\,g^{-1}$, with higher values being obtained from smaller nanoparticles, albeit with the trade-off of lowered saturation magnetization values. Nanoparticles prepared using this method can be functionalized with a sensing moiety of interest either *in situ* or immediately following synthesis, and are described in more detail in Section 9.2.2.

9.2.1.2 Thermal Decomposition

The synthesis of magnetic nanoparticles using a thermal decomposition method offers the most versatility, as the technique allows for the greatest degree of control over the particle size, shape, size distribution, and crystallinity. An enhanced control over particle saturation magnetization and susceptibility is also possible, and has great importance for many sensing applications. The preparation of monodisperse Fe_3O_4 and γ-Fe_2O_3 by the high-temperature decomposition of an organic iron complex has been reported [29–31], where an iron precursor [e.g., Fe(III) acetylacetonate, Fe(II) oleate, $Fe(CO)_5$] is dispersed in a high-boiling solvent (e.g., benzyl, octyl, or phenyl ether) in the presence of a stabilizing surfactant (e.g., oleic or lauric acid) in an inert atmosphere. Sun *et al.* described the decomposition of Fe(III) acetylacetonate in the presence of oleic acid, oleylamine, and 1,2-hexadecandiol in either phenyl or benzyl ether. Under varying conditions of heating ramp rate and reflux times, nanoparticles of various sizes with a very narrow size dispersity were produced. This method of preparing nanoparticles can also be scaled up, with no effect on the quality of material produced. If larger particle sizes are desired, the smaller (4–6 nm-diameter) nanoparticles may be used as seeds in the synthesis of nanoparticles of up to 20 nm diameter.

Methods using an iron-oleate precursor have provided the ability to tune the particle size and shape by adjusting the ratios and chain length of the stabilizing surfactant to a synthesized iron-oleate complex [30, 35]. Particles obtained in this manner can range from 5 to 50 nm and may be spherical, cubic, or prismatic, depending on the conditions used, and with very narrow size dispersity, as shown in Figure 9.1. Typical reaction conditions yield ~40 g of material, and can be scaled up to produce even larger quantities.

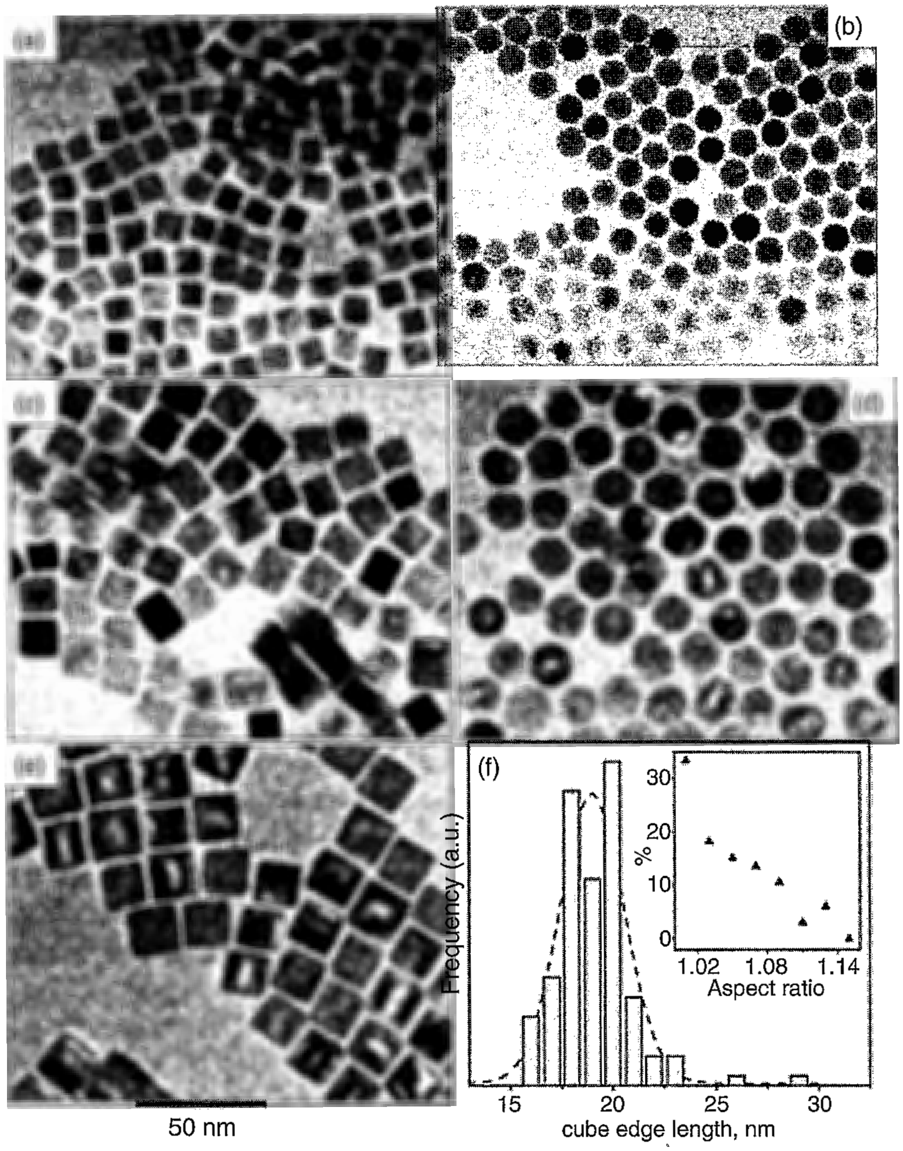


Figure 9.1 Transmission electron microscopy (TEM) images of monodisperse cubic (a,c,e) and spherical (b,d) iron oxide nanoparticles, and size histogram of cubic nanoparticles (f) using the iron-oleate precursor method. Reprinted with permission from Ref. [35]; © The American Chemical Society.

The stabilizing surfactants typically used for each of the described methods are fatty acids of at least six carbon atoms. Oleic acid is the most widely reported, as it is believed that the unsaturated bonds in the chain contribute to the particle's stabilization. Although other surfactants have often been reported, all of the nanoparticles generated using a high-temperature decomposition method typically yield nanoparticles with hydrophobic ligand shells. Regardless of the stabilizing ligand used, a water-soluble moiety is frequently desired, and modification of the as-prepared nanoparticles by thermal decomposition can be carried out in a number of ways (for more detail, see Section 9.2.2).

9.2.1.3 **Other Synthetic Methods**

As noted in Table 9.1, several other methods are available that generate superparamagnetic iron oxide nanoparticles. Although some of their drawbacks make them less desirable techniques, these routes are often preferred for *in situ* modifications over the multistepped, post-synthetic modification approach.

The *microemulsion technique* utilizes a ternary system of water, oil, and surfactant that allows for the formation of uniform-sized droplets in which the surfactant-stabilized nanoparticles are formed. The most commonly used method for synthesizing nanoparticles in this manner is that of *reverse microemulsion* (water in oil, w/o), where the hydrophilic acid head group is solubilized in the water droplet with the long-chain fatty acids dispersed in the oil phase. The size of the nanoparticles can be tuned by varying the water/oil/surfactant ratios. Under optimal conditions, the dispersity of these nanoparticles is narrow. Whilst the preparation of bare particles using this technique is less practical, either polymer or inorganic shells can be incorporated *in situ* using this technique (see Section 9.2.2). Again, the most significant drawbacks are the low material yield and the large volume of solvents required.

The *hydrothermal method* also has some benefits, particularly when tailoring the surface coatings of the nanoparticles. Here, nanoparticles are formed by placing all of the reactants (e.g., iron salt, 1,2-diol, stabilizing surfactant) into an autoclave and heating for a defined period of time, depending on the desired final nanoparticle size. Although this method is still fairly new, and very few reports of synthetic modifications have been made, it shows much promise for the formation of carbon-encased iron oxide (as described in more detail in Section 9.2.2).

9.2.2
Functionalization of Magnetic Nanoparticles

For most sensing applications, the nanoparticle's utility lies in both its magnetic character and its surface functionality. Although the preparation of iron oxide cores of various sizes, shapes, and magnetic susceptibility is relatively straightforward (see Section 9.2.1), further modifications are generally necessary to add the required affinity ligand to the particle surface for sensing applications. Surface modification can have a mild to dramatic effect on the core magnetic character; consequently, the selection of an appropriate surface coating must take these

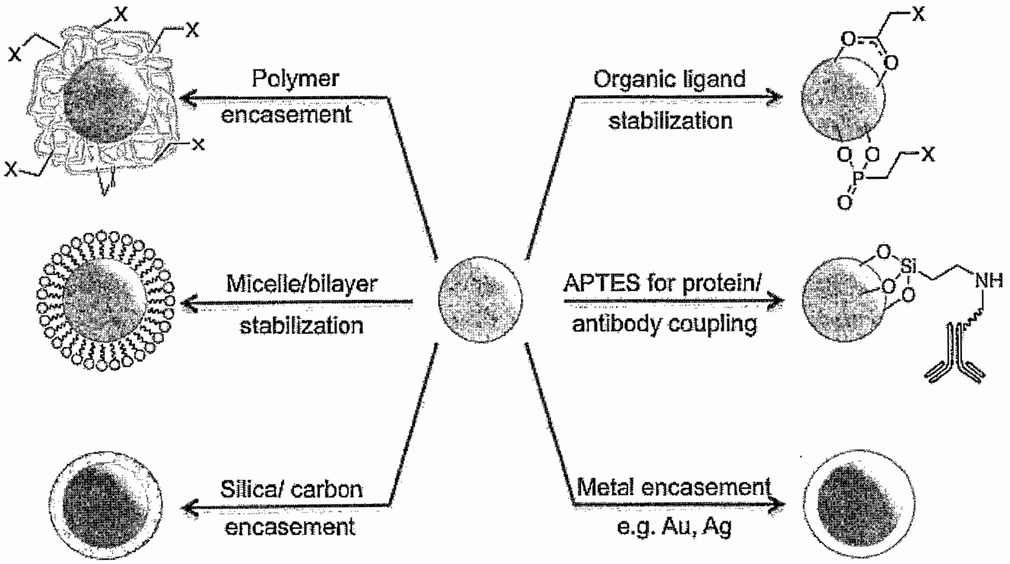


Figure 9.2 Some of the more commonly used methods for coating iron oxide nanoparticles for sensing applications.

requirements into account. Some of the more common methods of surface passivation are described in the following subsections and shown schematically in Figure 9.2.

9.2.2.1 **Organic Ligand Modification**

The use of organic ligands represents a straightforward method of imparting a specific functionality to the iron oxide surface. In this manner, the nanoparticle's solubility and functionality can be tuned to the application of interest. Ligands can be designed to take advantage of the iron oxide affinity toward carboxylates [6, 7, 36, 37], phosphonates [38–40], sulfonates [36, 41], silanes [42–44], hydroxamic acids [45], and 1,2-diols [46, 47]. The chosen ligand would contain one of these headgroups, as well as an ω-functionality at the periphery of the resulting ligand shell for binding to the analyte of interest. For example, in the sensing of biological materials this ω-functionality would contain an amine, thiol, or carboxylate to facilitate the coupling of antibodies or nucleic acids to the nanoparticle surface. In addition, some of these same functional groups (e.g., thiol) can be used to directly bind and detect environmental contaminants such as heavy metals.

Iron oxide nanoparticles (Fe_3O_4 or γ-Fe_2O_3) prepared using the coprecipitation method can be functionalized either *in situ* or immediately following synthesis. If a water-soluble moiety is desired, the *in situ* modification will require a simple addition of the ligand to the reaction flask (e.g., sodium citrate), followed by heating and subsequent purification of the product. Post-synthetic functionalization will require suspension of the iron oxide nanoparticles in an appropriate solvent and stirring, heating, or sonication [39, 43] in order to achieve attachment of the desired ligand.

If the nanoparticles are prepared by the high-temperature decomposition of an organic iron precursor complex, the as-synthesized nanoparticles can undergo simple ligand-exchange reactions, such that the surface ligand is replaced with the functional molecule of choice. This and similar methods are described elsewhere for an exhaustive number of specific functionalities [4, 14, 15, 17, 42]. More general methods can be selected based on the type of ligand desired. For example, a carboxylate for carboxylate exchange represents one of the more common methods, and allows for an exchange of the surface ligand using either monophasic or biphasic exchange conditions. Ligand-exchange reactions are typically carried out under stirring and/or mild heat, or sonication. Depending on the replacement ligand selected, the ligand exchange will usually occur when using a combination of solvents to promote miscibility of both the starting nanoparticle and the desired incoming ligand. If a solubility change is expected, a successful exchange is evident following purification based solely on the solubility of the resultant nanoparticles. An analysis of the final product, using Fourier-transform infrared (FT-IR) spectroscopy, will confirm successful ligand exchange.

9.2.2.2 **Stabilization with Polymers**

The polymer encasement of iron oxide nanoparticles is sometimes employed in the preparation of nanoparticles for sensing applications, as an appropriate polymer can greatly enhance dispersibility and biological compatibility, as well as prevent agglomeration of the iron oxide [48–50]. In most cases, polymer encasement leads to the formation of larger particles (often >100 nm in diameter) or very large aggregates, but the superparamagnetic character of the starting nanoparticles is retained. Some of the more commonly used polymers include polystyrene [51], poly(*N*-isopropylacrylamide) [51], poly(vinyl alcohol) [52, 53], poly(acrylic acid) [54], dextran [55], and starch [44], to name but a few.

The polymer encasement is carried out either post-synthetically in the case of thermal decomposition and some coprecipitation methods [53, 56], or *in situ* for other coprecipitation [57] and microemulsion [32] methods. Functional groups can be introduced into the polymer backbone itself, or onto the encasing polymer with further modification. This allows the desired functionality to be added, so as to render the particles useful for organic or environmental extraction. It is also possible to encase dyes into the polymer coating for added optical detection capabilities [8]. This typically involves attachment of the dye to the polymer backbone, or inclusion of the dye into the polymer matrix. By constructing these magnetic/optical polymer composite materials, it will be possible to provide sensitive optical detection platforms that seek to utilize the magnetic properties of the core nanoparticle for sample separation and preconcentration.

9.2.2.3 **Inorganic Stabilization with Silica or Carbon**

Stabilization of the magnetic core using an inorganic shell incorporates a variety of benefits not realized with organic stabilization. As organic ligands are only chemisorbed to the iron oxide surface, desorption of the passivating ligand is possible under certain conditions. Thus, it is often beneficial to coat the magnetic sensing material with a chemically inert shell; some of the more commonly described inorganic coatings are listed in Table 9.2 and discussed in more detail in the following subsections.

The coating of magnetic nanoparticles with silica has many advantages, and is by far the most common inorganic coating method, in part due to its synthetic simplicity. Particles formed in this manner contain a high number of surface silanol groups, which allows advantage to be taken of the abundance of functional ligands which contain a siloxane headgroup. As the silica shell is chemically inert, nanoparticles coated and further functionalized in this manner are easily dispersed in solution, and serve as excellent candidates for sensing in low-pH media. Many methods have been reported for producing these core–shell materials [58–75], with the most common – the sol–gel process – typically being a modification of the Stöber method [59], which relies on a silicon alkoxide [e.g., tetraethoxysilane (TEOS)] as the silica source. Varying the concentrations of TEOS, ethanol, and ammonium hydroxide allows the silica shell thickness to be tuned. Many studies have described the effects of varying the concentration of each of these precursors on shell thickness, the degree of aggregation, and the subsequent effect on measured saturation magnetization associated with increased shell thickness. Deng *et al.* demonstrated the dramatic effect of shell thickness on the final saturation magnetization. Here, the size [monitored using transmission electron microscopy (TEM) and vibrating sample magnetometry (VSM)] showed a drop in saturation magnetization, from 55 emu g^{-1} for the uncoated Fe_3O_4, alongside the $Fe_3O_4@SiO_2$ values which decreased from 7.5 to ~1 emu g^{-1} as the shell thickness increased with the greater volumes of TEOS used [60]. Thus, it is the prerogative of the research group to tune the shell thickness to a level which is appropriate for the application, without losing the magnetic characteristic that renders nanoparticles useful in their desired sensing platform.

Despite the loss in magnetic character, one benefit of using an optically transparent material such as silica (as opposed to another inorganic material) is the ability to incorporate dye molecules [58, 76, 77], luminescent inorganic complexes [78, 79], or quantum dots (QDs) [80–82] into the silica matrix, thus adding another dimension to the material for broader detection applications. For example, Yu *et al.* described the encasement of iron oxide nanoparticles in silica, the attachment of a terbium ion, and then further encasement with silica. Although the resultant nanoparticles retained some magnetic character, they also contained a luminescent lanthanide center [78]. The dispersion of these nanoparticles, while retaining magnetic characteristics when exposed to UV and broad-spectrum light, is shown in Figure 9.3; in addition, both scanning electron microscopy (SEM) and TEM images of the materials clearly show the iron oxide core to be surrounded by a uniform silica shell and a luminescent border.

Chih-Wei Lai *et al.* have also reported a microemulsion method for the generation of an iridium complex which was incorporated into the silica shell [79]. The resultant materials were both magnetic and luminescent, with a final core–shell composite diameter of ~80–100 nm.

The carbon-coating of magnetic nanoparticles may have potential in a number of environmental and biological sensing applications, as the carbon shell affords

Table 9.2 Common inorganic coatings for magnetic nanoparticles.

Inorganic coating material	Conditions	Benefits/Drawbacks	Reference(s)
Silica	Sol–gel/ Stöber method, reverse micelle	↑ Good dispersion in aqueous solutions ↑ Surface silanols for easy siloxane modification ↑ Ability to incorporate dyes and QDs ↓ Drastic loss of core magnetic character	[17, 58–61]
Carbon	Hydrothermal, pyrolysis	↑ Biocompatible ↑ High chemical and thermal stability ↓ Few synthetic methods/lack of understanding of formation mechanism	[62–64]
Gold	Microemulsion, solution based reduction	↑ Chemical inertness ↑ Thiol surface ligand modification ↑ Minor loss of core magnetic susceptibility ↑ Surface plasmon peaks for optical detection	[65–68]
Silver	Solution-based reduction	↑ Surface plasmon peaks for optical detection ↓ Difficulty functionalizing the Ag surface	[67, 69, 70]
CdSe or CdS	Solution-based shell growth	↑ Tunable fluorescent shell ↓ Synthetically challenging ↓ Subject to photobleaching ↓ Loss of core magnetic susceptibility	[71–73]

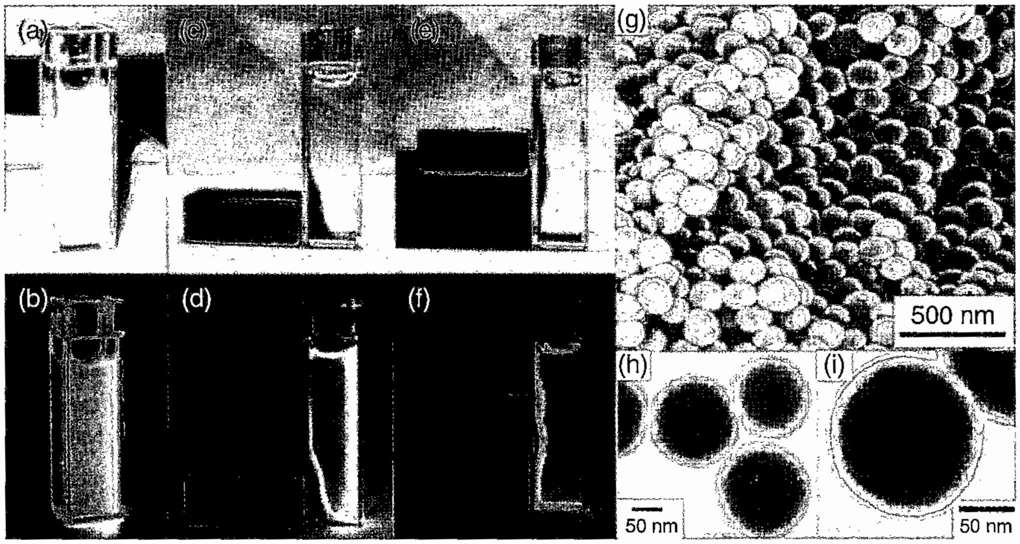


Figure 9.3 Magnetic/luminescent nanoparticles in white light (a,c,e) and ultraviolet (b,d,f) illumination, either dispersed (a,b) or close to a magnetic field (c,e,d,f). Scanning electron microscopy (g) and TEM (h,i) of the $Fe_3O_4@SiO_2$ core–shell materials with the visible luminescent band in (i). Reprinted with permission from Ref. [78]; © The American Chemical Society.

the magnetic material a greater stability in harsh chemical and physical environments (e.g., low- or high-pH waste streams). Although, until recently, the synthesis of these materials has been expensive and required specialized equipment, more recent reports have described the development of synthetic techniques to produce core–shell material, using much less specialized equipment [62, 83]. As an example, Wang *et al.* [63] described a solution-based method that involved the preparation of oleic acid-stabilized iron oxide nanoparticles for incorporation into carbon spheres; this method employed hydrothermal techniques with a carbon source derived from glucose. By carefully controlling the ratio of nanoparticles to glucose, it was possible to create carbon spheres of approximately 100–200 nm diameter, into which iron nanoparticles were embedded. Likewise, Xuan *et al.* [64] described a one-step method using an iron salt, urea, and glucose in an autoclave to generate a 100 nm ferromagnetic magnetite core with a ~30 nm carbon shell, as shown in Figure 9.4. Although the particles exhibited a ferromagnetic behavior, with a saturation magnetization value of ~42 emu g^{-1} (this was less than the bulk material, but a less dramatic loss than seen with silica encasement), their increased stability and ease of functionalization compared to the non-core–shell materials suggested that they might be potentially useful materials for environmental sensing applications.

9.2.2.3.1 **Precious Metal Encapsulation** Encapsulation of the magnetic nanoparticle core with a metal coating can have a variety of benefits, as the loss of magnetic behavior seen with silica coating (and, to a lesser extent, with carbon coating) does

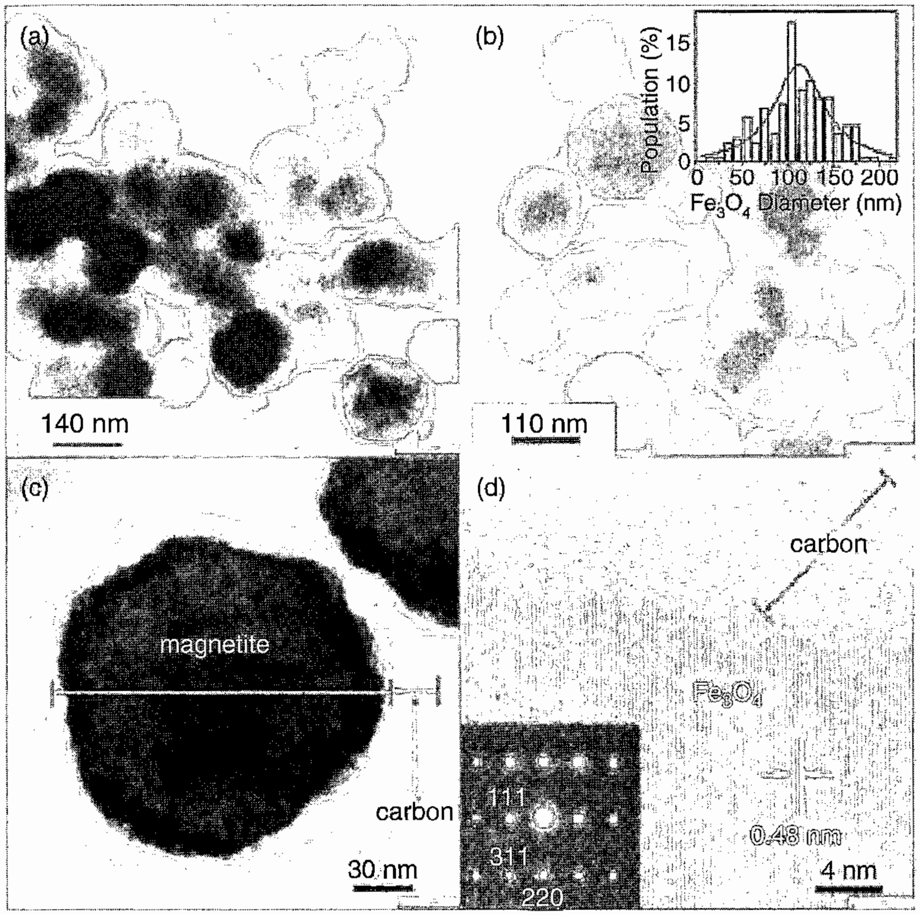


Figure 9.4 Transmission electron microscopy (TEM) images of carbon-coated Fe_3O_4. (a,b) Low magnification; (c) High magnification; (d) High-resolution TEM image of a typical Fe_3O_4@C particle. Reprinted with permission from Ref. [64]; © IOP Publishing.

not always occur when select metals are used. Additionally, the metal itself can aid in the sensing application. For example, when gold or silver is used to coat the Fe_3O_4, small changes in the dielectric environment close to the particle surface can result in wavelength shifts in the surface plasmon peaks, making such particles excellent sensing materials for biological applications.

The coating of iron oxide nanoparticles with gold has the advantage of an increased choice of functional ligands by exploiting the strong gold–thiol interaction, the plasmonic peak at 520 nm, and also the reduced drop in overall saturation magnetization of the core–shell magnetic nanoparticles. Numerous methods have been developed for the preparation of Fe_3O_4@Au core–shell materials using microemulsion techniques [84, 85], citrate reduction [86, 87], the deposition of the noble metal to the Fe_3O_4 surface by heat and/or sonication [69], and the deposition of Au nanoparticle seeds onto the iron oxide nanoparticle surface [65, 66]. Most of these methods allow the gold shell thickness to be tuned simply by adjusting the ratio of the iron precursor and the gold source. For example, Xu *et al.* described the use of $HAuCl_4 \cdot 3H_2O$ [67] to coat oleic acid-stabilized Fe_3O_4 nanoparticles by stirring the gold salt in the presence of the nanoparticles and oleylamine for 20 h at room temperature. The gold shell thickness prepared using this method was ~1 nm, with subsequent gold layers being grown up to 3.5 nm. The resultant nanoparticles could be further functionalized with an organic ligand, or the Ag could be nucleated and grown over the gold. An alternative method describing the growth of a gold shell on an iron oxide core utilizes $Au(OOCCH_3)_3$ [68] as the gold source, with the coating being achieved by heating the reactants at a high temperature for 1.5 h. In this case, the resultant gold shell thickness was ~0.7 nm.

Although less ubiquitous than silica or gold coating, a silver shell on the Fe_3O_4 core also offers the combination of a magnetic core with a surface plasmon resonance at ~400 nm. Several methods have involved silver encasement, including microemulsion [88], sintering [89], and various solution-based growths on iron oxide surfaces [69, 70, 90]. Tang *et al.* proposed the use of core–shell materials for a biosensing application, where the Fe_3O_4@Ag were prepared using the heating and sonication method originally described by Mandal *et al.* to generate core–shell materials with varying shell thicknesses. The nanoparticles prepared in this manner were further functionalized with carcinoembryonic antigen (CEA), a common cancer protein marker, by agitation in the presence of the nanoparticles at 4 °C. The nanoparticles produced showed absorption shifts at different stages of their modification, which simplified their characterization; electrochemical sensing could then be used to detect the specific presence of cancer cells.

9.2.2.4 Less Common Methods of Passivation

More recently, several groups have described the formation of a QD shell grown over a magnetic core seed. Core–shell structures of Co/CdS [71], FePt/CdS [72] and/or FePt/CdSe [91] have each shown potential for generating bifunctional materials for sensing applications. When a Co core was used, there was a complete loss in saturation magnetization, yet the FePt core appeared to retain its magnetic character following coating with CdS or CdSe [72, 91]. Since this method is still in its infancy, there remain many synthetic challenges to creating functional materials of this core–shell composition; however, the promise of a magnetic/fluorescent hybrid material with tunable magnetic and optical properties represents an intriguing topic for many sensing applications.

9.3
Magnetic Nanoparticles for the Separation and Detection of Analytes

9.3.1
Chemical Separations with Functionalized Magnetic Nanoparticles

The subject here is the use of functionalized magnetic nanoparticles as sorbent materials for chemical, biological, and heavy-metal contaminants, that enable sensitive detection among relevant environmental and clinical samples. Whilst the predominant use for these types of functionalized nanomaterials relates to biosensors in the clinical setting, much attention has also been paid to the benefits of using nanomaterial-enhanced biosensor-type systems (i.e., those which use biomolecules as affinity reagents or recognition elements) for the detection of environmentally relevant analytes such as bacteria, pesticides, and viruses [12]. These types of material provide the means to separate analytes from a complex sample and, in cases where a trace sensing of the contaminants is desired, they may also serve as a preconcentration material for sensor enhancement.

A fundamental approach for improving any analytical method is to selectively separate the analyte(s) from the sample matrix and to concentrate them into a smaller volume prior to measurement. The preconcentration of analytes before assay allows improvements to be made to the sensitivity, selectivity, and speed of the analytical process. One approach to improving any analytical method is to separate the analyte(s) from the sample matrix and to concentrate them into a smaller volume prior to measurement. Figure 9.5 illustrates the general analytical process of sample preconcentration (steps 1–3) and detection (step 4) using sorbent materials in a generic sense.

Preconcentration represents an ideal application for functionalized magnetic nanoparticles. Once dispersed in solution, the nanoparticles can rapidly contact high volumes of solution (Stage 1), selectively capture target analytes (Stage 2), and then be magnetically recovered and manipulated by the application of a relatively strong (often >1 T), but easy to generate, magnetic field (Stage 3). The functionalized magnetic nanoparticles may also provide a magnetically controllable sorbent material for solid-phase extraction (SPE). Previously, it has been shown that the

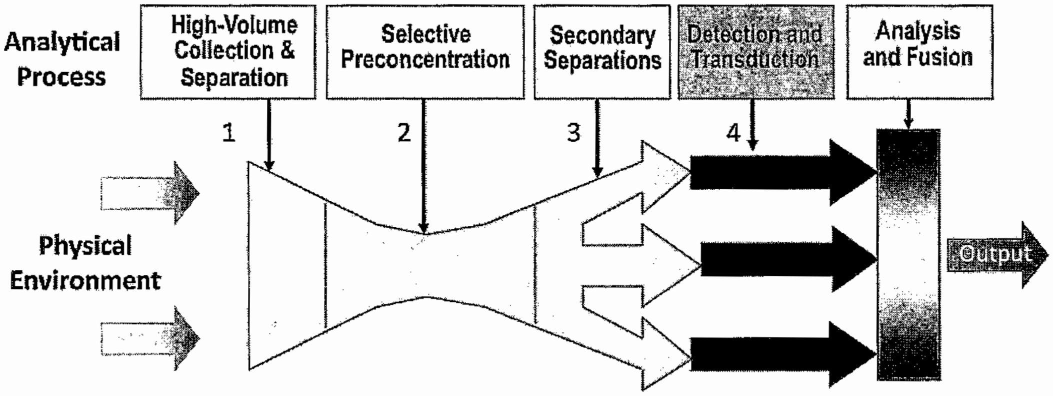


Figure 9.5 Schematic showing the general analytical process used to preconcentrate and detect low levels of analytes in environmental samples. In steps 1–3, the sorbent material (i.e., functionalized magnetic nanoparticles) are used to first bind a target analyte and then, through the application of an external magnetic field, separate it from other constituents of complex samples. In step 4 and beyond, the analyte is measured using the desired analytical method, prior to sending data output that signifies the presence of the intended target in the sample. As can be seen from this schematic, magnetic nanoparticles can play a variety of roles in going from sample to answer using solid-phase extraction and/or preconcentration.

intrinsic high surface area arising from the nanoscale dimensions of these materials, coupled with the ability to impart specific surface functionalization, renders magnetic nanoparticles very effective for SPE [92]. In addition, the magnetic nanoparticles have the advantage that very small quantities of material are required to accomplish an effective preconcentration (Stages 1–3) and detection. Once the preconcentration is complete, the analyte can be stripped from the SPE material for assay as appropriate (e.g., via acid, organic solvent, thermalization, etc). Alternatively, for some applications the SPE material can be assayed directly [92].

The amount of analyte extracted by the SPE material is limited by the magnitude of the partition or distribution coefficient (K_d) of the analyte between the sorbent material and the sample matrix, since at trace levels saturation does not become an issue. The K_d of a sorbent material is simply the mass-weighted partition coefficient between the solid sorbent phase and the liquid supernatant phase, as described in Equation 9.2:

$$K_d = \frac{(C_0 - C_f)}{C_f} \frac{V}{M} \tag{9.2}$$

where C_0 and C_f are the initial and final concentrations in the solution of the target analyte, V is the solution volume (in ml), and M is the mass of the sorbent (in g) [7]. By employing high-surface-area (typically $>100\,\text{m}^2\,\text{g}^{-1}$), dispersible, and specifically functionalized magnetic nanoparticles, it is possible to drive the interaction of the nanoparticle sorbents with the analytes in the sample, thus effectively facilitating both separation and preconcentration. The higher the K_d value, the better the SPE material will function for trace-level assays. Large surface areas (usually $>100\,\text{m}^2\,\text{g}^{-1}$) and high-affinity surface chemistries provide the large K_d values required for effective SPE. The surface chemistry of the SPE material will determine which analytes it will be selective for. An adjustment of the surface chemistry of the SPE material then allows its application to a different class of analytes or functions in different matrices. A summary of the K_d values for a variety of different SPE materials, including functionalized superparamagnetic nanoparticles, in filtered ground water is shown in Table 9.3 [7].

The K_d values of metal ions measured on different sorbent materials containing thiol ligands and capable of binding heavy metals are summarized in Table 9.3. In terms of K_d value, the functionalized magnetic nanoparticles (referred to as DMSA-Fe_3O_4) are significantly superior to commercial GT-73 and activated carbon (Darco KB-B) for capturing Hg, Cd, Ag, Pb, and Tl [7]. The affinity of the functionalized magnetic nanoparticle for As was more modest than for other metals, and similar to that of unfunctionalized magnetic nanoparticles (referred to as Fe_3O_4); this indicates that the thiol ligand shell has very little impact on As capture, which in turn supports the irreversible adsorption of As onto the iron oxide core material previously reported by Yavuz *et al.* [93]. Nevertheless, the massive improvement in K_d values clearly shows the excellent utilization of the ligand shell for improved SPE of the target analytes. When compared to the commercial sorbents tested, the functionalized magnetic nanoparticles proved to be outstanding sor-

Table 9.3 K_d (ml g^{-1}) of metal ions on selected sorbents.

Sorbent[a]	Final pH	Cobalt	Copper	Arsenic	Silver	Cadmium	Mercury	Thallium[b]	Lead
Fe_3O_4-DMSA	6.91	3000	270 000	5400	3 600 000	10 000	92 000	14 000	2 300 000
Bare Fe_3O_4	6.93	1600	7400	5800	13 000	2400	16 000	4000	78 000
SH-SAMMS	6.80	430	1 700 000	950	67 000 000	66 000	1 100 000	15 000	350 000
GT-73	6.76	890	6300	1200	16 000	1500	10 000	2200	41 000
Darco KB-B	6.90	790	26 000	750	27 000	1300	31 000	21	190 000

a The liquid-to-solid ratio (L/S) equals 10 000 ml g^{-1} in 0.45 µm filtered groundwater.

b Thallium added as Tl^{+1}.

bents for Pb, Hg, Cd, Cu, and Ag [7]. In the remainder of this section, we will discuss examples illustrating the use of functionalized magnetic nanoparticles in environmentally relevant detection applications.

9.3.2
High Magnetic Field Gradient Separation and Preconcentration

The concepts of selective capture of a target analyte by a magnetic nanoparticle and subsequent rapid manipulation of the analyte/nanoparticle complex using an applied magnetic field, have been well developed over the past two-plus decades [20]. Most notably, for biological applications magnetic nanoparticles and microparticles (formed primarily from composites of micron-sized polymer beads and nanoparticles) have been used for the better part of the past 20 years for high-gradient magnetic cell-sorting applications, as first reported by Miltenyi *et al.* [94]. Since this seminal report was made, numerous groups have continued development of the use of magnetic nanoparticles for cell sorting within a wide range of molecular biology applications [95–107]. In addition to the more fundamental studies in this field, a commercial line of products that employ biodegradable functionalized superparamagnetic nanoparticles for the separation of cells of all types is marketed under the trade name MACS (http://www.miltenyibiotec.com/en/default.aspx). The concept of high-gradient magnetic cell separation and sorting is shown schematically in Figure 9.6.

As can be seen from Figure 9.6, the magnetic nanoparticle typically plays the role of a tool designed to overcome the mass transport limitations that plague

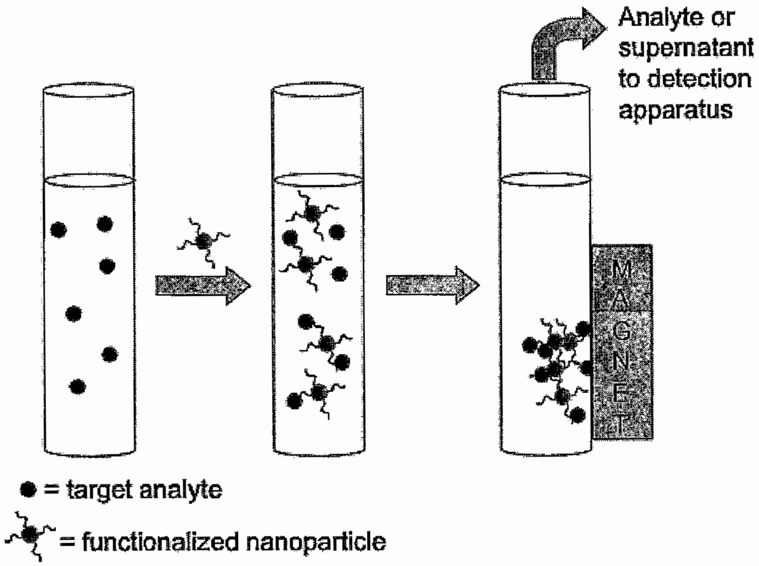


Figure 9.6 Schematic diagram representing the concept of high-field magnetic separation and sorting of analytes. The sample containing the target analyte (left) is exposed to the specifically functionalized magnetic nanoparticle containing an affinity ligand such as a protein, small molecule, or nucleic acid (middle). Then, after a period of incubation, an external magnetic field is applied to separate the nanoparticle/analyte complexes from the sample (right). This effectively enables the selective removal of a target analyte from the sample background, allowing for sensitive detection.

surface-bound sensor systems by attaching to an analyte; this makes the resultant analyte–nanoparticle complex responsive to an applied magnetic field. By using functionalized magnetic nanoparticles and a relatively high-strength magnetic field, it is possible to rapidly pull the bound analytes from solution, independent of any of the other background constituents that might potentially interfere with their processing (e.g., induction and growth of cells) or detection, using a range of techniques.

Studies based on the high-gradient preconcentration and separation methods discussed above have been conducted to target a wide range of analytes that have relevance in both environmental and clinical settings. These include: the separation and sorting of bacteria [102, 105, 107], viruses [104, 108], single cells [96, 97, 99–101, 103, 106], proteins [106, 109, 110], and nucleic acids [111–113]. In most of these cases, the target analytes are bound to the nanoparticles solely for removal from solution, and in order to separate them from background interferents (e.g., proteins, cells, and nucleic acids) common in biological samples. In addition to these examples, a number of studies have shown that magnetic nanoparticles also have potential as analyte preconcentrators for environmental remediation and trace detection sensor systems [20].

In their ongoing studies, the present authors have shown that functionalized superparamagnetic nanoparticles can be effectively dispersed in aqueous environmental samples and sequester a wide variety of analytes, including heavy metals

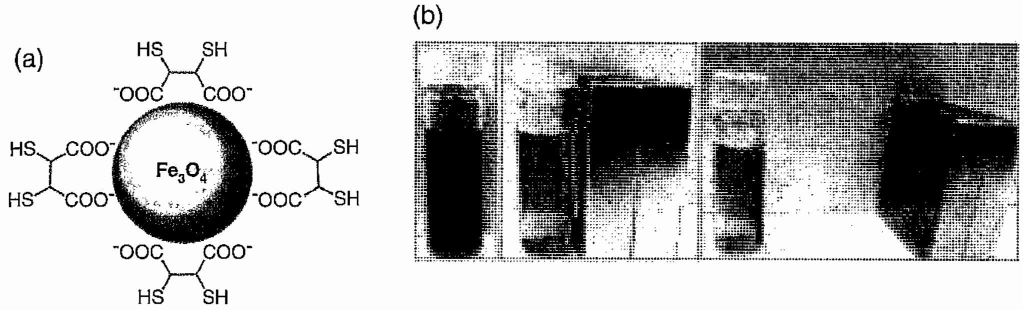


Figure 9.7 (a) Schematic of a DMSA-modified Fe_3O_4 nanoparticle; (b) Removal of the nanoparticles from the liquid phase using NdFeB magnets; initial solution (left panel), after 10 s with the magnet (middle panel), and when the magnet was moved to a distant position (right panel). Reprinted with permission from Ref. [7]; © The American Chemical Society.

[7, 114]. Specifically, thiol-modified Fe_3O_4 nanoparticles that are approximately 6 nm in diameter have been employed to remove Hg, Ag, Pb, Cd, and Tl from natural waters (i.e., river, ground, and ocean water). The scheme is illustrated in Figure 9.7.

The magnetic nanoparticles used in this study had the distinct advantage that they were highly dispersible in aqueous media, but could be removed with relative ease by exposing the sample to a magnetic field. In this case, the field strength used (~1.2 T) was generated by a NdFeB rare earth magnet [7]. By using this set-up, it was shown that the nanoparticles could remove over 99 wt% of 1 mg l^{-1} Pb within 1 min of contact time, and that they have a Hg capacity of over 227 mg g^{-1} (a 30-fold larger capacity than conventional, resin-based sorbents) [7]. In order to determine the efficacy of extraction of heavy metals by the magnetic nanoparticles, a variety of measurements to determine the distribution coefficient (K_d) were made, as summarized in Table 9.3. The data in Figure 9.8 illustrate that, at near-neutral pH in river water, the thiol-modified magnetic nanoparticles proved to be outstanding sorbent materials for soft metals such as Hg, Ag, Pb, Cu, and As ($K_d > 50000$), and also a good sorbent for harder metals such as Cd, Co, and Tl [7]. When the metals were extracted, the trace detection of heavy metal analytes was carried out using inductively coupled plasma-mass spectrometry (ICP-MS) after contact with the magnetic nanoparticles [7].

Studies conducted by other groups have shown similar characteristics of functionalized magnetic nanoparticles and microparticles modified with a wide variety of affinity ligands for the extraction of heavy metals from environmental samples [20, 53]. However, due to the need to fully understand the behavior of the materials when dispersed in the environment (e.g., a tendency towards aggregation and/or decomposition, as well as mobility), this field remains relatively undeveloped with regards to the use of superparamagnetic nanoparticles between 5 and 20 nm in diameter. Although more references are available relating to the use of microparticles (mostly constructed from nanoparticle/polymer composites), these

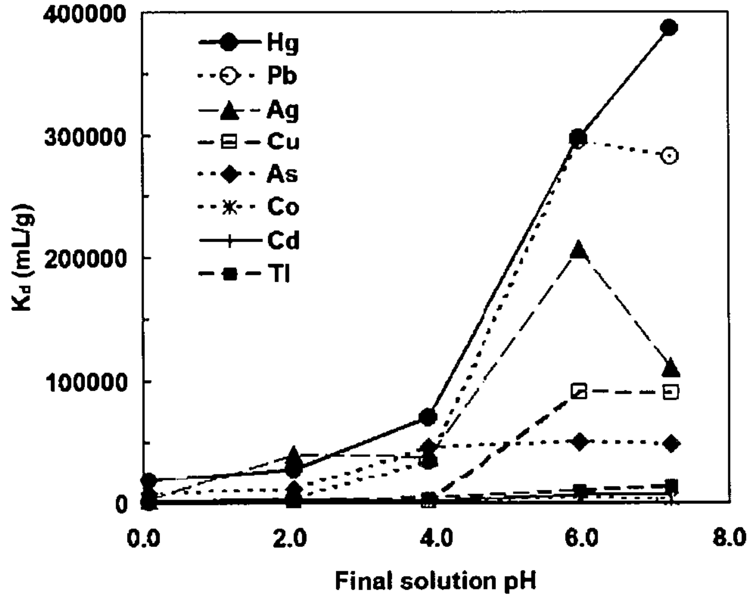


Figure 9.8 Effect of pH on K_d values, measured in HNO_3-spiked unfiltered river water [liquid/solid ratio (L/S) = 10^5]. Reprinted with permission from Ref. [7]; © The American Chemical Society.

materials fall well outside the size range that is traditionally considered a nanomaterial (i.e., their sizes are >100 nm) [20]. In addition to magnetic nanoparticles, a great deal of attention has been paid to nanoporous materials such as silica ceramics (pore sizes ~3–6 nm, but particle size on the order of microns) for the removal and remediation of contaminants from natural waters due to their high surface area and relative ease of functionalization [7, 19, 115–117]. However, although these materials serve as outstanding sorbents for contaminants, they suffer from intrinsic mass transport limitations of moving large volumes of water to the sorbent material. Alternatively, other high-surface-area sorbents that can be surface functionalized and are more readily dispersible in aqueous systems, yet can be easily recovered once bound to the target analyte, offer significant advantages for many applications. Materials such as magnetic nanoparticles [7] and polymer/nanoparticle composites [118–121] offer unique capabilities for magnetically directed separation and sensing processes.

9.3.3
Electrochemical Detection Enhanced by Magnetic Nanomaterials for Preconcentration

Sorbent materials of all types play a role in the binding, separation, and removal of target analytes from complex samples, and may also enable enhancements in the limits of detection for a wide range of sensor systems. Primarily, magnetic nanoparticles have been used in a preconcentration capacity in electrochemical and optical (i.e., fluorescent) detection schemes. Their role is to bind the target analyte in solution and rapidly bring it to the sensor surface, or to separate it from the background interferents upon the application of an external magnetic field. In most cases, an applied magnetic field from either an electromagnet or permanent magnet is typically employed to capture the nanoparticle/analyte complex from solution prior to analysis [6, 13, 122, 123].

The present authors' group has demonstrated the use of both magnetic [6] and nonmagnetic [114] high-surface-area sorbent materials to enhance the electrochemical detection of toxic heavy metals from natural waters. The sorbent materials, which were either functionalized magnetic nanoparticles or mesoporous silica, were modified with a wide range of thiol-containing organic molecules that possesses a high affinity towards heavy metals (e.g., Hg, Pb, Cd), and were placed or collected at an electrode surface (Figure 9.9) [6, 114]. By using these high-surface-area sorbent materials, it has been possible to demonstrate the sensitive electrochemical detection of environmentally relevant heavy metals (e.g., Pb, Hg, Cd) in complex environmental (e.g., river water) and clinical (e.g., urine) samples [6, 114]. Superparamagnetic Fe_3O_4 nanoparticles functionalized with dimercaptosuccinic acid (DMSA) (similar to those discussed above) were used to first bind the heavy-metal contaminants from complex samples, and then subsequently to carry them to the surface of a magnetic electrode (see Figure 9.9) [6].

By using an applied magnetic field to remove the target analytes from solution prior to electrochemical analysis, the analytes are effectively isolated from the huge number of potential interferents present in complex sample matrices. In using this system, two of the biggest problems that have prevented the widespread

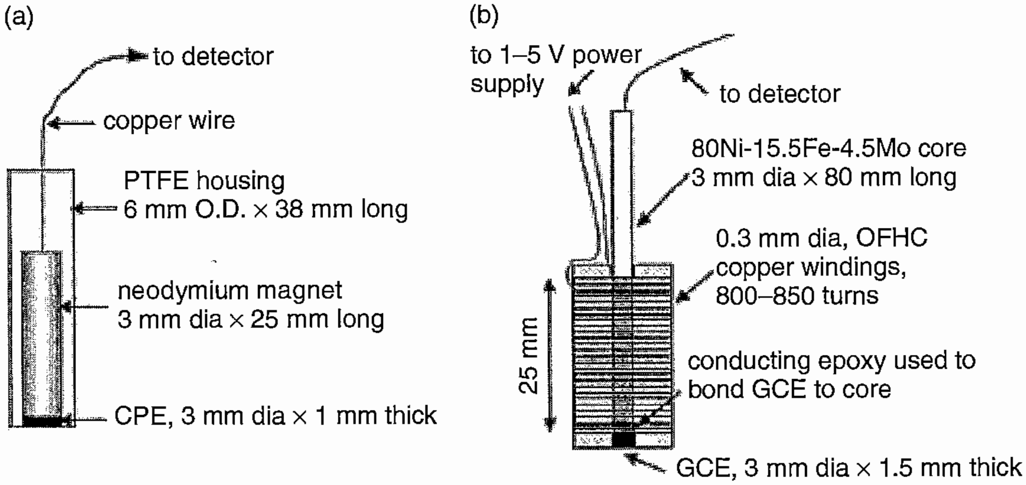


Figure 9.9 Schematics of (a) the magnetic electrode and (b) the electromagnetic electrode which preconcentrate metal ions using superparamagnetic nanoparticles. Reprinted with permission from Ref. [6]; © The Royal Society of Chemistry (RSC).

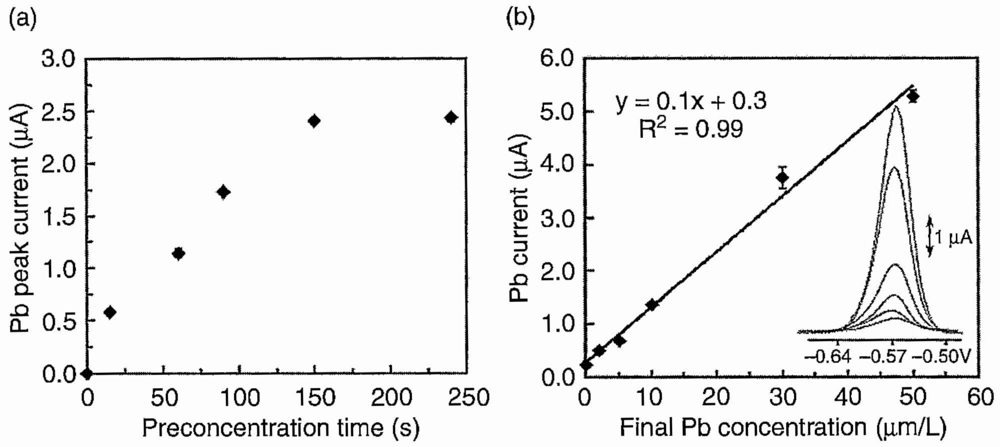
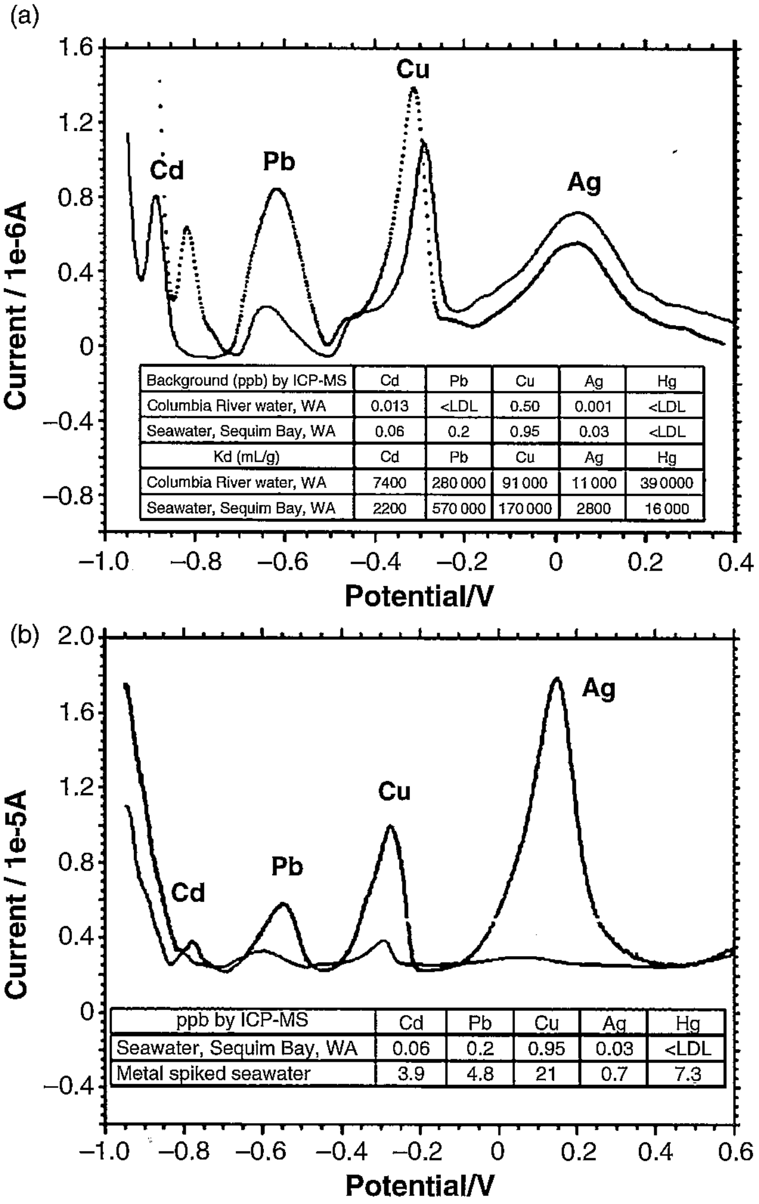


Figure 9.10 (a) Signals of 10 ppb Pb measured at DMSA–Fe_3O_4-magnetic sensors in samples containing 25 vol.% rat urine with varied preconcentration time; (b) Linear Pb calibration curve measured at DMSA–Fe_3O_4-magnetic sensors in Pb-spiked samples containing 25 vol.% rat urine. Reprinted with permission from Ref. [6]; © The Royal Society of Chemistry (RSC).

adoption of electrochemical sensors for the analysis of metal ions in biological samples have been successfully overcome, at least to some extent: (i) binding of the target metals to proteins present in the sample matrix, leading to a lowered signal response; and (ii) electrode fouling caused by proteins. As shown in Figure 9.10, this approach has permitted the successful measurement of Pb concentrations in rat urine samples (25%, v/v) as low as 10 ppb, with as little as 20 s preconcentration (after an optimal 90 s preconcentration period, the detection limit was 2.5 ppb Pb).

Further, the data in Figure 9.11 show that the magnetic nanoparticles are also capable of enabling the detection of multiple heavy metals (i.e., Cd, Pb, Cu, Ag) from a variety of natural waters (river and ocean) with a preconcentration time of only ~2.5 min.

In addition to these studies, several other groups have reported the use of magnetic nanoparticles in the electrochemical analysis of other environmentally relevant targets other than heavy metals, such as proteins and nucleic acids [13, 15, 124]. At this point, the reader is directed to a number of recent reviews on the application of high-surface-area magnetic nanomaterials for the detection of biological analytes [13, 123]. It is important to note here that, even though the bulk of the studies conducted in this area was aimed at clinical applications, the detection of biological species is of paramount importance for environmental sensing, due to the fact that many common environmental contaminants are of biological origin. A recent example in which magnetic nanomaterials were used to detect a protein biomarker to pesticide exposure utilizes a similar magnetic electrode as described above (see also Figure 9.9) [125]. In these studies, the magnetic particles



Background (ppb) by ICP-MS	Cd	Pb	Cu	Ag	Hg
Columbia River water, WA	0.013	<LDL	0.50	0.001	<LDL
Seawater, Sequim Bay, WA	0.06	0.2	0.95	0.03	<LDL
Kd (mL/g)	Cd	Pb	Cu	Ag	Hg
Columbia River water, WA	7400	280 000	91 000	11 000	390000
Seawater, Sequim Bay, WA	2200	570 000	170 000	2800	16 000

ppb by ICP-MS	Cd	Pb	Cu	Ag	Hg
Seawater, Sequim Bay, WA	0.06	0.2	0.95	0.03	<LDL
Metal spiked seawater	3.9	4.8	21	0.7	7.3

Figure 9.11 Sensor measurements of (a) background metal ions in seawater (dashed line) and river water (solid line) and (b) background metal ions (thin line) and metals spiked (thick line) in seawater, after 150 s of preconcentration time. The inset tables show metal concentrations, measured with ICP-MS, and distribution coefficients of multiple metal ions (L/S of 0.01 g l^{-1} DMSA–Fe_3O_4, initial metal concentration 500 ppb each, pH of 7.2 for river water and 7.64 for seawater). Reprinted with permission from Ref. [6]; © The Royal Society of Chemistry (RSC).

were bound with gold nanoparticles to provide an extremely responsive material for the electrochemical analysis [122, 125]. These composite nanomaterials were then used to bind and separate protein biomarker targets from solution, followed by their detection, without the need for any amplification that is typically important in many protein-detection systems [122, 125].

9.3.4

Analyte Detection Using Magnetic Nanoparticles through Nonelectrochemical Methods

The use of magnetic nanoparticles in optical detection scenarios has also received much recent attention, with the reviews of Corr *et al.* and Katz *et al.* examining at great depth the formation of nanomaterial composites for biological detection and biomedical applications [8, 15]. However, it is important to note that the bulk of reported detection schemes center on the use of magnetic nanoparticles in electrochemical assays. This is because, even when all of the potential benefits associated with using a fluorescent nanomaterial that also is magnetic (e.g., ability to separate bound analyte from a sample and monitor the process optically) are considered, it is possible still for many complications to arise. Primarily, the use of materials such as magnetic nanoparticles in an optical detection platform can scatter, absorb, or even quench, the optical signal from the fluorescent reporter, which in turn will lead to a decrease in signal output [8]. To that end, many different types of magnetic/fluorescent nanomaterial composite have been constructed, as shown in Figure 9.12.

Each of these nanomaterial composites has unique features that overcome some of the potential limitations, and perhaps make them useful for select environmen-

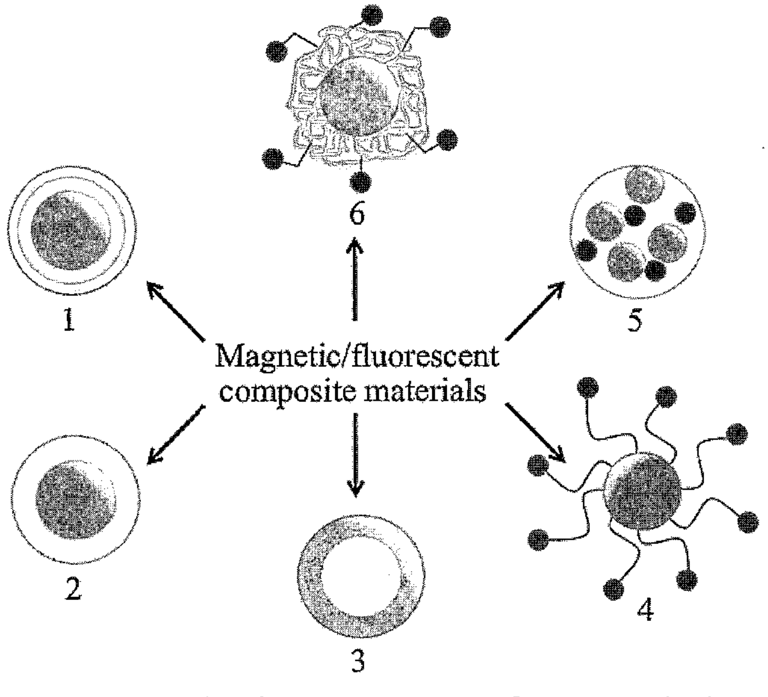


Figure 9.12 Examples of some composite magnetic/fluorescent nanoparticles for optical sensing applications. 1, $Fe_3O_4@SiO_2$ coated with a silica or polymer shell containing fluorescent molecules; 2, $Fe_3O_4@CdS$; 3, $CdS@Fe_3O_4$ core–shell nanoparticles; 4, fluorescent molecules attached to the Fe_3O_4 core using organic ligands; 5, Fe_3O_4 and fluorescent molecules or quantum dots encased in a silica or polymer matrix; 6, fluorescent molecules attached to polymer-encased Fe_3O_4.

tal sensing applications. In addition, Figure 9.12 demonstrates that, by using the synthetic methods discussed in Section 9.2, and which are typical for the production of magnetic nanomaterials (e.g., polymer and silica encasement and core–shell structure formation), it is possible to construct a wide range of useful nanomaterial composites that should enable a variety of applications [8]. These types of material have shown great promise in environmental sensing, mainly because they allow a target analyte to be separated/preconcentrated from a complex sample prior to analysis, thus preventing unwanted optical noise from background interferents. Yet, at the same time, they allow the optical labeling of a target analyte upon binding, such that a rapid sample analysis using traditional optical methods with exquisite sensitivity can be conducted when the separation is complete. It is believed that, as materials production methods continue to mature and more magnetic/fluorescent composite nanomaterials become available, there will be an explosion in the use of these types of material in environmental sensing applications.

The use of magnetic nanoparticles in sensor systems designed to take advantage of the intrinsic properties (e.g., magnetoresistance) of individual nanoparticles has grown tremendously during recent years, especially in the field of biosensors. While this type of sensor has not found great favor among the environmental sensing community, it is nonetheless an important sensing application of magnetic nanoparticles of all types, as biological targets are of major interest in this area. At this point, we will review some of the most common sensing scenarios that utilize the intrinsic properties of magnetic nanoparticles, and also provide some insight into the future of this type of sensor for the detection of environmentally relevant analytes. Most of the examples here focus on the detection of target analytes that are predominantly relevant in a biological laboratory or clinical setting, but they also provide context and performance metrics for a wide range of promising sensors. In addition, the examples provide a proof-of-concept and lay the foundations for the eventual widespread adoption of these types of sensors in the environmental sensing community.

The intrinsic properties of nanoparticles, which are typically exploited for the types of sensors discussed here, include magnetoresistance, giant magnetoresistance (GMR), and spin-valve GMR [3, 126–128]. While these properties have been exploited at length in the production of magnetic storage media (e.g., hard-disk drives) since their discovery in 1988 (which led to the Nobel Prize in Physics in 2007 for its discoverers, Fert and Grunberg), they are only now (within the past five to seven years) beginning to gain wide acceptance as viable methods of signal transduction in sensor systems [128]. First, a broad definition of these properties is provided, within the context of how they can be used for sensitive biodetection assays.

In their most basic implementations, sensors that seek to utilize the intrinsic GMR properties of the magnetic nanoparticles measure a change in sensor resistance in response to the concentration or binding of nanoparticles onto a functionalized magnetic transducer surface, after binding a target analyte [126]. The magnetoresistive effect arises from the change in resistance of the magnetic materials as the overall magnetization of the sample changes from parallel with respect to current flow to perpendicular or transverse [3, 126]. (For a detailed explanation of the construction and driving principles behind GMR sensors, the reader should refer to recent reviews, as the explanation falls beyond the scope of this chapter [126, 128–131].) By using this configuration, it is possible to sensitively detect the fringe magnetic field of nanoscale magnetic particles once they have been brought, through specific interactions, to the engineered surface. Typically, the nanoparticles are on the order of 10–20 nm in diameter, and display either paramagnetic or superparamagnetic character with little to no remnant magnetization in order to prevent magnetic agglomeration in solution prior to binding the target analyte [128].

A typical biodetection reaction is carried out by either labeling the target analyte in solution with a magnetic nanoparticle prior to binding the nanoparticle–analyte complex to a substrate with a complementary probe molecule bound to the engineered surface, or by capturing the analyte on the surface and labeling with a magnetic particle in a second step [126]. A change in the sensor resistance at a fixed sense current signifies the presence of the magnetic nanoparticle, and subsequently the analyte. Any analyte that is not specifically bound to the sensor surface through the complementary probes or the nanoparticle can then be washed away to reveal a signal that is derived only from the desired target analyte [126, 128]. One type of sensor that utilizes magnetic nanoparticles as intrinsic labels exploits the magnetoresistance of the nanoparticle to signal molecular affinity interactions in bioassays [3]. In order to measure changes in magnetoresistance, arrays of specialized magnetic transducers are employed to measure the binding events between an affinity ligand (e.g., antibody or nucleic acid) and an analyte of interest (e.g., cell, organism, or protein). One manifestation of this type of assay comes in the form of a magnetoimmunoassay, in which primary and secondary antibodies are used to first capture an analyte from a sample, and second to label the captured analyte with an antibody that has been coupled to a magnetic nanoparticle [3]. Based on the current state of the art, magnetoresistive sensors have the potential to play a large role in the detection of biological analytes that have environmental relevance such as protein toxins, bacteria, and viruses [20, 126].

9.4
Summary and Future Perspective

Functionalized magnetic nanoparticles synthesized using the methods described in the chapter provide a number of unique and interesting opportunities for the improvement of environmentally relevant sensing applications. We have highlighted the myriad possibilities that exist for the synthesis and functionalization of magnetic nanoparticles that display the attributes that are most desirable for sensing applications, namely dispersbility, high surface area ($>100\,m^2\,g^{-1}$), flexible surface chemistry, and superparamagnetism. These characteristics make the magnetic nanoparticles ideal for applications where it is necessary to first bind and separate an analyte from a complex sample matrix prior to analysis, by using a variety of methods which range from electrochemical detection to optical and magnetoresistive sensing platforms. In addition, the functionalized nanoparticles continue to show enormous promise as renewable surface sensors, since it is possible simply to bring new materials into contact with the sample of interest to regenerate both the sorbent material and the sensor surface. Ultimately, this will allow their use in samples that would cause other types of sorbent material to be fouled irreversibly. Further, functionalized magnetic nanoparticles have promise in the separation and sensing of analytes, ranging from heavy metals and biological species to chemical and radiological contaminants. This flexibility is limited only by the availability of the appropriate affinity ligand or surface coating. For bench-scale applications where cost is a greater consideration, the functionalized magnetic nanoparticles have the potential to be inexpensive and, as only small amounts are required for preconcentration and detection, the materials costs will remain very low. In situations requiring the large-scale environmental release of these materials, additional investigations must be completed before the systems can be claimed as cost effective. Nonetheless, the current state of the art shows great promise for these nanomaterials in the above-described applications, as evidenced by the many reports which have been made recently in the biological realm. In addition, a large rise should also be expected in the number of occasions where these materials are applied within the environmental sensing arena.

Acknowledgments

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