Magnetite is the most abundant magnetic iron mineral on the Earth’s surface. Its formation in natural ecosystems is mainly due to microbial activity. Microbially synthesized magnetite, commonly called “biogenic magnetite,” has many beneficial properties for a wide range of environmental and commercial applications. Its high surface reactivity facilitates interactions with (in)organic pollutants in anthropic and natural ecosystems, as well as with reagents in industrial catalysis. Due to its magnetic properties and good biocompatibility, biogenic magnetite is also well suited for biomedical applications such as cancer treatment or drug delivery. Biomineralization of magnetite offers an inexpensive and sustainable method for the production of this highly functional material. Moreover, this biomineralization process results in a biomolecule coating of the magnetite, making it highly amenable to further functionalization. This chapter reviews the application of biogenic magnetite across environmental, medical, and industrial settings. Existing challenges and future opportunities in these applications are also discussed.

**Keywords**: biogenic magnetite; magnetosomes; remediation; biomedicine; catalysis

**BIOMAGNETIC NANOPARTICLES IN EARLY DIAGENESIS, PEDOGENESIS, AND THEIR RESULTING MAGNETIC PROPERTIES**

Magnetite (Fe₃O₄) is an iron oxide mineral commonly found in soils, sediments, and aquifers. Magnetite has a mixed valence (Fe(II)/Fe(III)) with an inverse spinel crystal structure, where the Fe³⁺ ions are located on the tetrahedral A-sites and the octahedral B-sites, and the Fe²⁺ ions are located on the octahedral B-sites. This results in a ferri-magnetic arrangement, thereby providing magnetite with a high magnetic susceptibility. This ferri-magnetic mineral has the largest induced magnetization in the Earth’s field among the common magnetic minerals; its presence is therefore responsible for the magnetic properties of soils and sediments. Moreover, magnetite is the most common magnetic mineral on Earth’s surface and in the shallow crust. Its formation in natural ecosystems is primarily due to microbial activity. For instance, magnetotactic bacteria (MTB) uptake dissolved Fe(II) or Fe(III) from the environment during a biologically controlled biomineralization process to form intracellular biogenic nanomagnetite (Fig. 1) (Fairev and Schüler 2008; Amor et al. 2016). Biogenic magnetite can also form via the anaerobic respiration of various dissimilatory iron-reducing bacteria (DIRB) capable of utilizing Fe(III)-(oxyhydr)oxides such as ferrihydrite (Lovley et al. 1987), lepidocrocite (Ona-Nguema et al. 2002), and maghemite as electron acceptors (Fig. 1). Microbial oxidation of iron, for example, by iron-oxidizing microorganisms that can utilize Fe(II) in green rust as an electron donor, can also result in the formation of biogenic magnetite (Fig. 1). Magnetite can also form via various abiotic processes including through Fe(II)- or thermal-induced alterations of Fe(III)-(oxyhydr)oxides. Due to its mixed iron redox state, magnetite itself can act as an electron donor to Fe(II)-oxidizing microorganisms or as an electron acceptor to Fe(III)-reducing microorganisms, potentially serving as a precursor for the biomineralization of a range of other Fe(II)- or Fe(III)-bearing minerals. Importantly, these anoxic iron oxidation processes may have taken place in banded iron formation (BIF) deposition in ancient environments.

The properties resulting from the biomineralization of magnetite make it highly amenable to a range of environmental, biomedical, and industrial applications (Fig. 1). Apart from the chemical purity and high magnetic susceptibility of magnetite, the biosynthesis process performed by both MTB and certain DIRB results in a biomolecule coating of the nanoparticles that act as capping agents, enhancing nanomaterial stability and reducing aggregation without the need for surfactants (Fairev and Schüler 2008; Kim and Roh 2019). This organic coating also makes the nanomaterials amenable to additional surface functionalization,
such as with catalytically active metals (Coker et al. 2010). The high surface to volume ratio of these nanomaterials also provides a high reactive surface area (e.g., for contaminant remediation or catalysis). The magnetic nature of (biogenic) magnetite not only confers properties useful for a variety of biomedical applications (see “biomedical applications of biogenic magnetite” below), but also enables simple and efficient magnetic recovery of the particles so that they can potentially be recycled and reused (see “application of biogenic magnetite in industrial catalysis” below). Crucially, the microbial synthesis of magnetite offers an inexpensive, environmentally friendly alternative to more traditional methods that require expensive or environmentally damaging approaches (Sun and Zeng 2002), thus making it compatible with a drive toward more sustainable industrial processes.

**ENVIRONMENTAL REMEDIATION: REACTIVITY OF (BIO)MAGNETIC NANOMATERIALS WITH (IN)ORGANIC CONTAMINANTS**

The fate of (in)organic chemical elements in environmental systems is heavily influenced by their complex interactions with geological nanomaterials. In this context, magnetite nanoparticles play an important role in controlling the fate of (in)organic contaminants because of their high reactive surface area and dynamic redox properties. Interactions of (in)organic pollutants with magnetite can occur through processes including surface adsorption, surface catalyzed redox transformations, or incorporation into the mineral structure (Fig. 2). Contaminant transformation can occur via Fe(II)-mediated Fenton-like reactions (i.e., reactions which, like the Fenton reaction, lead to the formation of hydroxyl radicals and other highly oxidizing species, but unlike a true Fenton reaction, they do not do so using Fe(II) and H$_2$O$_2$ at pH values of 1–3) using reactive oxygen species or other free radicals, such as ferryl species produced in the presence of strong oxidant (e.g., H$_2$O$_2$) or soft oxidant (e.g., O$_2$) or via Fe(II)-facilitated reduction of the contaminant. For example, Fenton-like reactions at the magnetite surface during As(III) adsorption in the presence of dioxygen, were shown to convert As(III) to As(V) (Ona-Nguema et al. 2010). The mechanism of this reaction involves the oxidation of Fe(II) in magnetite by dioxygen resulting in the production of free radicals that oxidize As(III) to As(V) (Fig. 2). The role of Fe(II) in such a reaction has been demonstrated by adding aqueous Fe(II) solution to ferricyanhtride suspensions during As(III) adsorption experiments under both oxic and anoxic conditions. The investigation of the redox state of arsenic after its interaction with Fe(III)-oxyhydroxide revealed that the oxidation of As(III) at ferricyanhtride surfaces by Fe(II) occurred only in the presence of oxygen, as observed for Fe(II)/Fe(III)-containing green rust and magnetite (Ona-Nguema et al. 2010). This result is of interest as it underlines the importance of the anoxic chain to preserve the oxidation state of redox-sensitive elements when collecting samples from natural environments. In contrast to Fe(II)-mediated oxidative transformation of (in)organic contaminants, electron

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**Figure 1** Illustration of the microbial synthesis and potential applications of biogenic magnetite. Microbial synthesis of biomagnetite can be facilitated by magnetotactic bacteria (MTB), dissimilatory iron-reducing bacteria (DIRB), and iron-oxidizing bacteria. In environmental remediation, in situ synthesis or direct injection of biogenic magnetite relies on the transport of reactants from the synthesis or injection point to the area requiring remediation. Alternatively, a permeable reactive barrier containing immobilized biogenic magnetite could be placed in the subsurface to treat a plume of contaminated groundwater. In biomedicine, the magnetic nature of magnetite nanoparticles enables them to be directed to specific target sites in the body for imaging, therapeutic, or drug delivery applications. This magnetism also enables the simple magnetic recovery of magnetite catalysts or magnetite-supported catalysts for their subsequent reuse in various industrial processes.

**Figure 2** Schematic displaying mechanisms of contaminant remediation by magnetite nanoparticles. The left side shows Fe(II)-facilitated reduction of contaminants with potential incorporation of the reduced product into the magnetite crystal structure. The right side displays Fe(II)-mediated free-radical generation, facilitating oxidation of contaminants. Abbreviations: ads = adsorption; inc = incorporation; C = organic carbon compounds.
transfer from Fe(II) on the magnetite surface can result in direct reductive transformation of various (in)organic contaminants (Cutting et al. 2010). Reduction of contaminants, coupled to oxidation of Fe(II) in magnetite, can result in immobilization of contaminants that are less mobile in their reduced form. This process has been extensively explored in the remediation of toxic chromium, where the more toxic and mobile Cr(VI) is initially adsorbed at magnetite surfaces, followed by Fe(II)-facilitated reduction to the relatively less toxic and less mobile Cr(III). In addition, the reduced Cr(III) can then be incorporated into the magnetite structure, further limiting the spread of this contaminant (Fig. 2).

During the last 15 years, many field and laboratory studies have investigated the interactions of magnetite and maghemite with inorganic pollutants and have shown that these (bio)magnetic nanomaterials play important roles in the scavenging of a wide range of heavy metals and metalloids in natural systems, including As(III) and As(V) (Morin et al. 2008), Zn(II), Cu(II), Hg(II), and other trace metals (e.g., Ni(II), Co(I)). Considerable work has also demonstrated the potential for biogenic magnetite to immobilize priority radionuclides such as U(VI), Sr(II), Eu(II), Eu(III), Cs(I) (Husnain et al. 2018), Pu (Kirsch et al. 2011), Se(VI) (Poulain et al. 2022), and other radionuclides (e.g., Tc(IV)) through adsorption and/or Fe(II)-catalyzed redox transformations. Understanding these interactions, particularly in environmental systems, is critical to the development and optimization of (bio)remediation processes utilizing biogenic magnetite to limit the spread and dispersion of a range of pollutants (Fig. 1).

**BIOMEDICAL APPLICATIONS OF BIOGENIC MAGNETITE**

On the way to personalized medicine, magnetic nanoparticles are essential to achieve more targeted and effective treatments. In this scenario, a specific type of biogenic magnetite nanoparticle is widely studied for several biomedical applications, namely, magnetosomes biosynthesized by MTB. These aquatic microorganisms are able to passively align parallel to the Earth’s magnetic field lines while actively swimming in search for nutrients and optimal oxygen conditions. This behavior, known as magnetotaxis, is due to the presence of one or more chains of magnetosomes (Fig. 3A; Faivre and Schüler 2008). Magnetosomes are intracellular organelles composed of a core of a magnetic iron biomineral, typically magnetite (Fe₃O₄) or greigite (Fe₃S₄), enclosed by a proteolipidic membrane (Fig. 3B). Magnetosome size and morphology differ among bacterial species, but are consistent within a single species that synthesizes magnetosomes with a characteristic morphology and narrow size distribution. Due to their uniform shape and size, chemical purity, magnetic properties, and biocompatibility conferred by the surrounding proteolipidic membrane, magnetosomes are actively being studied in the context of several biomedical applications, mostly related to the treatment and diagnosis of cancer (Fig. 4). More recently, the use of the whole bacteria as a biomedical agent is also being investigated because they have intrinsic characteristics that make them advantageous for various applications, as discussed below (Fdez-Gubieda et al. 2020).

**Magnetic Hyperthermia**

Magnetic hyperthermia is a cancer treatment based on the conversion of magnetic energy to heat. Magnetic nanoparticles injected intratumorally can work as agents for heat generation as a response to an alternating magnetic field. The local temperature increases to a “therapeutic window” typically between 42 and 44 °C, causing death or damage to cancer cells without affecting healthy tissue. This is possible because cancer cells have been shown to be more susceptible to heating than healthy cells. Compared with conventional chemotherapy and radiotherapy, magnetic hyperthermia has the advantage of being a localized treat-
ment and therefore having fewer side-effects. However, magnetic hyperthermia is mostly used as an adjunct therapy with other conventional cancer therapies because it triggers several biological processes that can be taken advantage of to increase their efficacy.

Magnetosomes exhibit high heating efficiency under alternating magnetic fields within the clinical limits, constituting ideal candidates for magnetic hyperthermia. The performance of magnetosomes has been tested successfully in vitro, causing a decrease in the number of living cells and hampering the ability of cancer cells to grow (Muela et al. 2016); and in vivo, inhibiting tumor growth in mice bearing glioblastoma xenografts (Alphandéry et al. 2017).

Due to the potential of magnetite nanoparticles as magnetic hyperthermia agents, efforts have been focused on increasing their efficiency. Given that this parameter is related to the anisotropy, the size, shape, composition, and arrangement of the magnetic nanoparticles could be altered to enhance their potential. For instance, it has been demonstrated that doping biogenic magnetic nanoparticles, for example, Geobacter sulfurreducens with transition metals (e.g., cobalt, zinc) tunes their magnetic anisotropy, yielding efficient agents to be used in magnetic hyperthermia (Céspedes et al. 2014). The arrangement of biogenic nanoparticles is also a parameter to consider. In this line, the heating efficiency of MTB has been shown to be higher than that of isolated magnetosomes, likely due to the effective anisotropy derived from the chain arrangement. The bacteria show heating efficiency values that compare very well to some of the highest values reported in the literature for iron oxide–based nanoparticles, and MTB-mediated magnetic hyperthermia has shown to effectively affect cell in vitro viability and growing ability of cancer cells in vitro (Gandia et al. 2019).

Drug Delivery Carriers
MTB have all the features necessary to make ideal drug delivery carriers. Given their magnetic behavior, they could be externally guided to the tumor area where they could release the drug that had been previously attached to their surface. Moreover, MTB are motile, thanks to one or more flagella, have a preference for microaerobic/anaerobic regions (e.g., the tumor environment), and can sense and respond to chemical stimuli (Fdez-Gubieda et al. 2020). Given these properties, MTB are being studied to act as biomedical nanorobots. The magnetotactic bacterial strain Magnetococcus marinus MC-1 has been successfully functionalized with drug-loaded nanoliposomes and guided toward hypoxic regions of colorectal xenografts (Felfoul et al. 2016). In this study, 55% of the injected bacteria penetrated into the tumor, which was a great improvement compared with the targeting efficiency of other nanocarriers.

Contrast Agents for Imaging
Magnetosomes also offer great potential as medical diagnosis tools. As with other magnetic nanoparticles, they can be used as magnetic resonance imaging (MRI) contrast agents as they have a very high relaxivity, which enhances the contrast in this technique. Based on in vitro relaxometry measurements, magnetosomes show an improved MRI contrasting performance over commercially available iron oxide magnetic nanoparticles, leading to a significant gain in MRI sensitivity. The potential of magnetosomes as MRI contrast agents has been thoroughly demonstrated in vivo (Mériaux et al. 2015).

Magnetic particle imaging (MPI) is an emerging imaging technique for detecting magnetic nanoparticles within the body. The principle is quite different from that of MRI as in this technique, magnetic fields are used to create a signal from the nanoparticles. Because there are no magnetic nanoparticles within the body, the signal only comes from the injected magnetic nanoparticles, thus providing very specific information about their localization. Therefore, if magnetic nanoparticles are used in biomedical applications, this technique will be ideal to localize in real-time the location of the injected magnetic nanoparticles. Magnetosomes have also been proposed as tracer materials for MPI where they have shown an improved resolution over the currently used commercial tracer Resovist® (Kraupner et al. 2017). The performance of magnetotactic bacteria Magnetospirillum gyrophthalmense MSR-1 as contrast agents for MPI in mice has also been tested. For this technique, mutant bacteria that do not arrange their magnetosomes in chains have been shown to provide a better MPI signal and resolution (Makela et al. 2022).

APPLICATION OF BIOGENIC MAGNETITE IN INDUSTRIAL CATALYSIS
Catalysts are critical to modern society. It is estimated that catalysis plays a part in up to 90% of all chemical processes with approximately 80% of all manufactured products by volume involving catalysis at some point during their production. The economic impact of these processes is estimated to underpin 30%–40% of global GDP, playing a key role in the production of pharmaceuticals; biofuels; petrochemicals; polymers; food, flavors, and fragrances; and catalytic convertors. Catalysts are also critical for the transition toward a low-carbon economy, for example, in the synthesis of sustainable fuels and design of more efficient catalysts to reduce carbon emissions and waste generated by current industrial processes. Within this context, it is also highly desirable that catalyst synthesis itself is sustainable. This is particularly important in the synthesis of heterogenous catalysts, as they are required in approximately 80% of catalytic processes. Biogenic magnetite fulfills such criteria because of the relatively low cost and benign microbial synthesis method, for example, by species of DIRB of the genera Geobacter and Shewanella (Fig. 3C). The organic coating on biogenic magnetite also makes the nanomaterials amenable to surface functionalization with other catalytic metals, such as Pd (Fig. 3D), and may even play a direct role in facilitating catalysis (Coker et al. 2010). The high surface area of biogenic magnetite provides a high number of potential reactive sites available to take part directly in catalysis or interact with supported catalytic species. Simple magnetic recovery of magnetite enables the materials to be used, recovered, and reused in potential catalytic processes, further limiting waste and costs. The potential application of magnetite nanomaterials in a range of catalytic processes has been explored, including in the upgrading of heavy oil and the production of fine chemicals.

Upgrading of Heavy Oil
Depletion of conventional oil resources has led to unconventional sources, such as heavy oil and bitumen, becoming increasingly attractive to extract. However, these resources are costly to produce, transport, and refine because of their high viscosity, presence of high–molecular weight compounds, and high content of metals (Carrillo and Corredor 2013). In situ upgrading of these resources can enhance the production and oil quality whilst retaining the unwanted contaminants or by-products, such as heavy metals and heteroatoms, in the reservoir. The THAI-CAPRI process (toe-to-heel air injection; catalytic upgrading process in situ) combines thermally enhanced oil recovery with in situ catalytic upgrading of the recovered heavy oil (Brown et al. 2016). However, challenges can arise from
the high production of coke, catalyst deactivation, and pore plugging during the CAPRI process. Nanoparticulate catalysts can alleviate some of these challenges because of their high surface area and dispersion throughout the combustion zone. The use of nanoparticulate biogenic magnetite as a possible low-cost, sustainable catalyst for upgrading heavy oil was investigated by Brown and co-workers. Biogenic magnetite was found to catalyze a 97.8% decrease in viscosity of the feed oil, which was increased to 99.4% when the biogenic magnetite was functionalized with surface associated Pd (9.5 wt%) (Brown et al. 2016). Although this level of upgrading was found to be similar to previously tested catalysts, the biogenic magnetite and Pd-functionalized biogenic magnetite resulted in a decrease in coke formation, a by-product that can potentially deactivate the catalyst.

**Heck Coupling**
The “Heck reaction” is a palladium-catalyzed C-C coupling with wide-ranging industrial importance in the preparation of molecules for pharmaceuticals, agrochemicals, and functional materials (Tarnowicz-Ligus and Trzeciak 2018). Recovery of the palladium used to catalyze these reactions is clearly highly desirable to avoid loss of the precious metal. The presence of an organic coating and reactive Fe(II) at the surface of biogenic magnetite provides a mechanism for the adsorption and reductive deposition of Pd(0) with the biogenic magnetite acting as a nanoparticulate support that can be easily and efficiently recovered because of its magnetic nature. Coker demonstrated that biogenic magnetite functionalized with Pd displayed equal or greater catalytic activity in a model Heck coupling reaction compared with a commercial colloidal palladium catalyst. The Pd-functionalized biogenic magnetite catalyst was magnetically recovered and its recyclability tested over four cycles with only minimal loss in activity (Coker et al. 2010).

**Catalysts from Waste**
The use of biogenic magnetite to remediate contaminated environments via removal of potentially toxic metals from solution, either via surface adsorption or Fe(II)-facilitated redox transformations, is well documented (as discussed in the “environmental remediation” section above). However, many metals present in waste streams or contaminated environments are useful to society and their recovery and reuse could offer new opportunities to reduce demand and associated costs for raw resources, as well as to address concerns over security of the supply of critical metals. Converting the waste metal into a functional product (e.g., a catalyst) during recovery would add further benefit, valorizing the waste into a highly useful product. For example, biogenic magnetite was used to recover Cu from an industrial waste source in the form of an active catalyst (Kimber et al. 2019). The waste source, a spent lees residue from a whisky distillery, contained elevated Cu concentrations in addition to a range of fermentation products. The biogenic magnetite was shown to rapidly recover the Cu from the spent lees (>97% in less than 1 minute) with the Cu-coated biogenic magnetite then easily recovered magnetically, leaving a Cu-free effluent (Kimber et al. 2019). Following an additional treatment to fully reduce the Cu, the Cu-coated biogenic magnetite was then able to catalyze a range of “click-chemistry” reactions (Fig. 5), which are important in aspects of drug discovery, materials science, and bioconjugation. The applicability of biogenic magnetite to recover metals from more challenging waste streams, such as acidic industrial wastes, and its selectivity for metal recovery from multi-metal containing waste streams remain a potential challenge to this approach to a more circular economy and require further study.

**FUTURE OPPORTUNITIES AND CHALLENGES**
Despite the promise of biogenic magnetite in environmental, biomedical, and industrial applications, a key challenge to its wider adoption in these fields is upscaling the production processes to produce large numbers of particles that still maintain uniform properties. For biological synthesized nanomaterials, low growth yields of the microorganisms often limit the nanomaterial yield that can be produced. Scaling up microbial growth can also suffer from heterogeneity in large growth reactors that could result in nanomaterials of varying size and properties. However, progress has been made to improve yields using bioreactors of up to 50 L, producing biogenic magnetite nanoparticles that still maintain uniform properties. For biologic, biomedical, and industrial applications, a key challenge to its wider adoption in these fields is upscaling the production processes to produce large numbers of particles that still maintain uniform properties. For biological synthesized nanomaterials, low growth yields of the microorganisms often limit the nanomaterial yield that can be produced. Scaling up microbial growth can also suffer from heterogeneity in large growth reactors that could result in nanomaterials of varying size and properties. However, progress has been made to improve yields using bioreactors of up to 50 L, producing biogenic magnetite nanoparticles that still maintain uniform properties.
in significantly larger quantities than previous bench-top studies while also maintaining a narrow size distribution of the synthesized particles (Byrne et al. 2015). Although biomineralization of magnetite nanoparticles can be achieved under environmentally friendly conditions, the use of analytical-grade reagents in these processes can actually result in a net negative environmental impact compared with existing industrial production methods (Sadhu et al. 2017). However, the environmental benefits can be greatly improved if raw materials sourced from waste streams were to be utilized as the microbial feedstock (Sadhu et al. 2017). Such a process offers the potential to close the loop between what is considered a waste and a resource, contributing to the drive toward a more sustainable and circular economy.

In addition to these possible environmental benefits, the ability to tune the properties of biomagnetic nanomaterials presents the opportunity to produce tailored nanomaterials. The particle size, reactivity, and magnetic properties of biomagnetic nanomaterials can all be tailored by controlling the kinetics of their synthesis by microbes or by altering the chemical composition of the feedstock to optimize their properties for environmental remediation and biomedical or industrial applications such as water treatment, cancer therapies, and chemical production (Byrne et al. 2013). Although controlled biosynthesis holds great promise in tuning magnetite properties, the application of such materials in clinical and industrial settings requires further study.

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REFERENCES

Alphandéry E and 6 coauthors (2017) Development of non-pyrogenic magnetosome minerals coated with poly-l-lysine leading to full disappearance of intracellular U87-Luc glioblastoma in 100% of treated mice using magnetic hyperthermia. Biomaterials 141: 210-222, doi: 10.1016/j.biomaterials.2017.06.052


Sadhu et al. 2017


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