

# Magnetotactic bacteria: Environment biotechnological applications

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## ABSTRACT

Magnetotactic bacteria (MTB) are wide spread aquatic prokaryotes. They navigate along magnetic field pathways through magnetosomes, which are membrane-bound intracellular structures containing iron-based magnetic crystals. The process of MTB isolation requires a container to collect sediment and water from natural environments like a freshwater pond. MTB possess crucial magnetic characteristics that are exploited in various areas, including MRI diagnostics, magnetic hyperthermia, targeted drug delivery, and additional medical applications. Environmentally, they assist in wastewater treatment by eliminating radionuclides, organic contaminants, and heavy metals. Furthermore, the extensive surface area of their magnetic particles enhances adsorption of organic pollutants such as organophosphate pesticides. This study provides a concise review of MTB, covering their morphology and selected biotechnological applications.

**Keywords:** magnetotactic bacteria (MTB), magnetosome, magnetotaxis, biotechnological applications of MTB.

## INTRODUCTION

Magnetotactic bacteria (MTB) are Gram-negative bacteria, aquatic prokaryotes that can align themselves with earth magnetic fields, due to intracellular magnetosomes, which is a membrane bound magnetic nanocrystals (Figure 1). MTB were first described by Salvatore Bellini in Pavia, Italy in the late 1950s. After, he noticed bacteria in bog sediments consistently, orienting themselves toward the magnetic north, named it magnetosensitive bacteria (Bellini, 2009). In 1970s, Richard Blakemore, independently, rediscovered MTB in Massachusetts. He was the first who found that these bacteria had magnetosome structures within their cells, and could orient themselves and sense magnetic fields (Blakemore, 1975).

MTB are generally present in aquatic environment, typically found in lakes, water columns and sediments, where redox gradients exist (Bazylinski et al., 2013). They present

a valuable model organism, making lakes an ideal platform for detection, purification and numerous advantages for studying biomineralization and magnetic sensing (Lin and Wu, 2021). MTB and their magnetosomes have high potential in biomedical research, where they can be used extensively in drug delivery systems (targeted drug delivery), imaging diagnostics resonance (IMR) and pharmaceuticals (Fernández-Castané et al., 2018). In addition, MTB are hold promise for use in nanotechnology, bioremediation (removing heavy metals from wastewater, elimination of organic pollutants, detoxifying fluids) and several environment biotechnological applications, to address diverse challenges (Gareev et al., 2021).

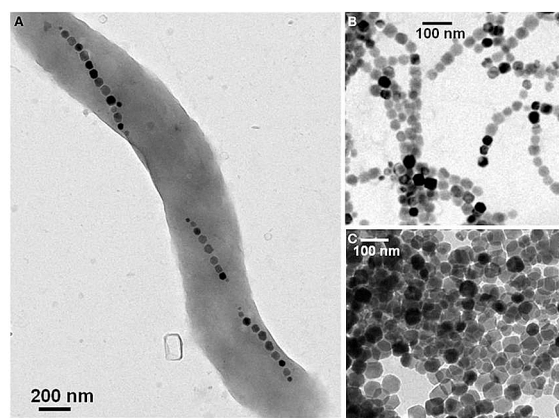
In this context, this review presents and recapitulates various studies conducted on MTB, focusing on the importance of these bacteria and its properties on environmental biotechnology applications.

## CHARACTERISTICS AND PROPERTIES

### Magnetotactic bacteria morphology

MTB are motile micro-organisms, physiologically and morphologically diverse. They prevalent in naturally occurring water (Lin et al., 2017). MTB exhibit a variety of cell morphologies, including rod, vibrio, ovoid, spiral and coccoid shapes as well as multicellular bacteria (Bazylnski et al., 2014).

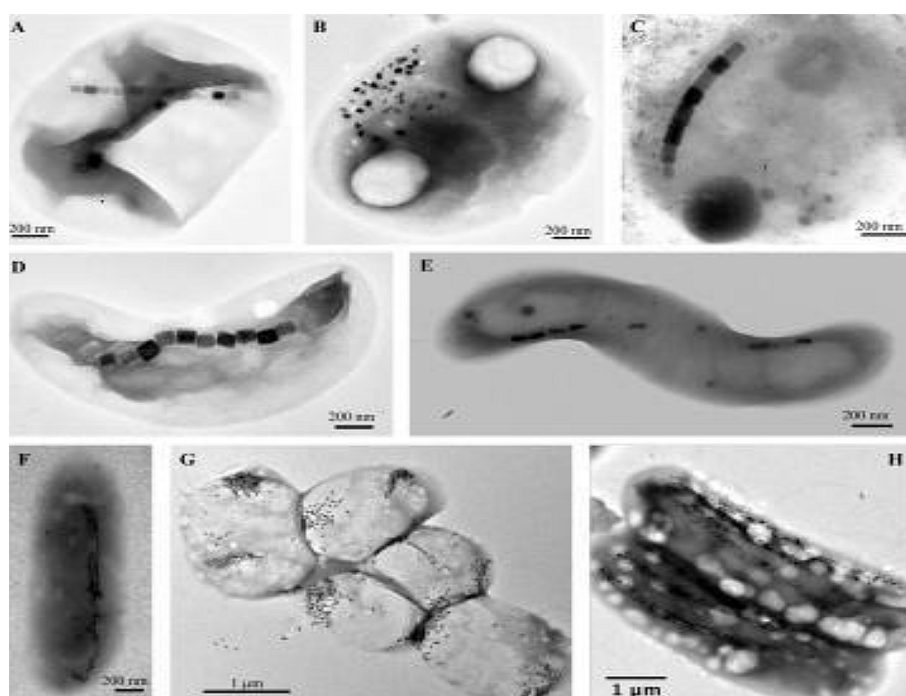
These micro-organisms, possess an intracellular structures known as magnetosomes, organelles essential for the magnetotactic movements bacteria. Magnetosomes are made up of magnetic crystals obtained by mineralizing iron oxide to form magnetite ( $\text{Fe}_3\text{O}_4$ ), or from iron sulfide to form greigite ( $\text{Fe}_3\text{S}_4$ ). Magnetic crystals are enveloped by a double membrane, composed mainly of phospholipids, known as the magnetosome membrane. Some external proteins are not observed in cytoplasmic membranes, they are recognized as specific for magnetosome membranes (Raschdorf et al., 2018; Ben-Shimon et al., 2021). Although the magnetite and greigite crystals of magnetosomes could have different morphologies. Magnetosomes are generally configured in chains inside the cell, by enhancing its magnetic dipole moment, the cell aligns itself with magnetic field lines as it navigates (Toro-Nahuelpan et al., 2019) (Figure 2).



**Figure 1.** Transmission electron microscopy images of a single magnetotactic bacterium (A) of chains of magnetosomes extracted from whole magnetotactic bacteria (B) of individual magnetosomes detached from the chains by heat and SDS treatment (C) (Alphandéry, 2014).

### Bio-mineralization process

The bio-mineralization process of magnetosomes is prominent traits associated with these micro-organisms. The process involves the uptake of external iron through siderophores and transport proteins, followed by its accumulation in magnetosome vesicles *via* transmembrane iron transporters. Ferrous ion (iron II), at neutral pH, is very soluble (up to 0.1 mol/L) and can be assimilated by MTB

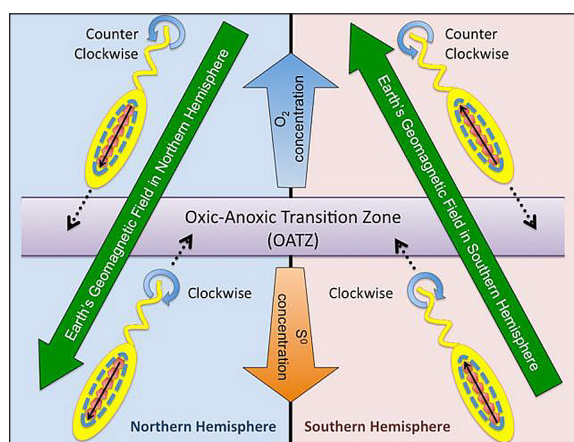


**Figure 2.** Electron transmission observations of different MTB morphologies and magnetosome chains (Lefèvre et al., 2013)

via non-specific pathway. Conversely, due to the poor solubility of ferric ion (iron III), the majority of micro-organisms utilize iron chelators to capture, dissolve, and assimilate ferrous ion (Dieudonné et al., 2019). In addition, the siderophore synthesized by low-molecular-weight MTB has a high binding affinity for iron. They facilitate ferric ion dissolution *via* mechanisms driven either by ligands or protons, which break down iron oxides (Bazylnski et al., 2014; Dieudonné et al., 2019).

### Biogeographical distribution

Magnetotactic bacteria are widespread across the globe, occurring on every continent. They are usually present in the sediments of freshwater, brackish, marine, and hypersaline environments and within the chemically stratified water columns of these ecosystems (Bazylnski and Frankel, 2004; Werckmann, 2022). The appearance of MTB, interestingly, their occurrence is not necessarily linked to elevated iron concentrations in the environment, but instead to the existence of an oxic-anoxic transition zone (OATZ or OAI). OATZ is typically forms where oxygen gradients from the surface contrast with reduced compounds, such as sulfate-reducing species, in sediments or water columns (Frankel, 1997) (Figure 3). In chemically stratified sediments or aquatic environments, MTB are predominantly found at/or slightly below the OATZ. Typically, MTB that synthesize magnetite ( $\text{Fe}_3\text{O}_4$ ) are found at or near the OATZ, while those that generate greigite ( $\text{Fe}_3\text{S}_4$ ) reside in reducing environments, positioned below the OATZ in the anoxic sulfuric zone (Dieudonné et al., 2019;



**Figure 3.** A diagram depicting the mechanism by which magnetotactic bacteria use magnetotaxis to swim to the OATZ (OAI) in Earth's northern and southern hemispheres (Chen et al., 2012)

Ghaisari et al., 2017). Additionally, within this interface, different MTB species occupy distinct depths, with particular chemical parameters prevailing at that level (Lin et al., 2013).

### Magnetotaxis

MTB have a unique property known as magnetotaxis, whereby they orient themselves along the earth's geomagnetic field lines. This trait is categorized into two forms: polar and axial.

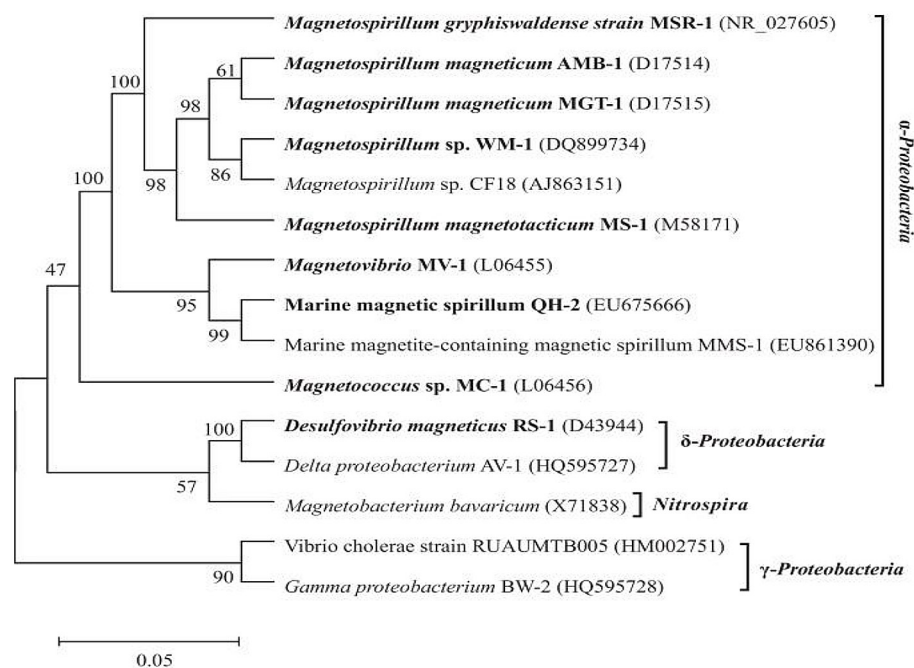
In polar MTB, movement is directed either northward or southward based on the structural arrangement of intracellular magnetic crystals, while axial MTB propel themselves alternately in forward and backward directions (Bazylnski, 2014). Northern MTB, primarily located in the northern hemisphere, are generally migrate toward the south pole of a magnet bar, whereas those in the southern hemisphere align with the north pole (Zhu, 2018) (Figure 3).

The environmental impact of magnetotaxis is significant, as magnetotactic bacteria (MTB) are essential for the biogeochemical cycling of iron and sulfur, due to their mineral forming activities (Hossain et al., 2024). Their magnetosome chains frequently survive as magneto-fossils within sediment layers, which are critical indicators of ancient habitats and potential biosignatures in the pursuit of extraterrestrial life (Lefèvre and Bazylnski, 2013).

### Oxygen sensitivity

MTB are generally micro-aerophilic prokaryotes, that live in low oxygen conditions. So far, the majority of bacteria identified are classified under the class of  $\alpha$ -proteobacteria, with the remaining ones belonging to  $\gamma$ -proteobacteria,  $\delta$ -proteobacteria, Nitrospirae and Candidate Omnitrophica phylum (Lin et al., 2017). Several MTB strains have been successfully isolated and cultured (Figure 4).

The ongoing influence of this ancient microbial trait of MTB in driving scientific and technological progress is demonstrated. For instance of magnetotaxis research, which is a dynamic interdisciplinary field that integrates microbiology, biophysics, and materials science. As well, the current applications of MTB which include targeted drug delivery, environmental remediation, advancements in nanotechnology and other ecological and biotechnological applications (Bazylnski and Frankel, 2004; Faivre and Schüler, 2008).



**Figure 4.** Phylogenetic relationships of MTB. Pure cultures MTB are indicated in bold characters (Yan et al., 2012)

## BIOTECHNOLOGICAL APPLICATIONS OF MTB

Magnetotactic bacteria have important biotechnological applications. In aquatic environments, they become part of iron and sulfur biogeochemical cycling, by making magnetosomes capable of filtering and trapping some pollutants. Therefore, MTB are a good candidates for bioremediation of contaminated environments.

### Environment applications

The issue of water pollution is one of the world's major environmental concerns. In recent years, the remarkable efficiency and cost-effectiveness of nanotechnology in removing heavy metals, radionuclides, and organic pollutants have made it a focal point of attention. The enhanced adsorption of pollutants and their efficient removal from wastewater are largely attributed to the broad surface area and magnetic characteristics of magnetic nanoparticles (Ali et al., 2018; Jiang, 2019). According to Lin et al., (2017), MTB can identify the magnetic pole within rocks that possess high concentrations of magnetic minerals.

Furthermore, their high abundance, substantial specific surface area, and ease of use contribute to their effectiveness, and straightforward pollutant separation capabilities of MTB and

magnetosomes, make them promising for various environmental applications (Fernández-Castané et al., 2018; Wang et al., 2020).

### Removing heavy metals from wastewater

The discharge of heavy metals into natural water bodies poses a significant risk to organisms and human health. It is therefore imperative to extract these metals from wastewater, to lessen their harmful effects and enable the recycling of these elements. Since their discovery, many researchers have studied the recycling of heavy metals using MTB. Various techniques, including activated carbon adsorption, electrochemical processes, physicochemical treatments, and biological methods are commonly utilized to control heavy metal concentrations in rejected waters (Kiran et al., 2018; Jiang et al., 2019; Li, 2021; Liu et al., 2019). Nevertheless, the low recovery rate requires toxic and expensive reagents.

MTB exhibit a strong bioadsorption capacity for various heavy metals present in wastewater. The disposal rates of heavy metals range from 38.6% to 100%, excluding mercury ( $Hg^{2+}$ ). Research on MTB mediated heavy metal disposal has predominantly concentrated on single metals, particularly aurum ( $Au^{3+}$ ), chromium ( $Cr^{6+}$ ), and copper ( $Cu^{2+}$ ), with few studies addressing the simultaneous elimination of multiple heavy metals in wastewater. In practice, MTB are mainly employed to recover

Au<sup>3+</sup> from contaminated water (Song et al., 2007; Song et al., 2008; Cai et al., 2011).

Chromium (Cr<sup>6+</sup>) is a worldwide water contaminant due to its extreme toxicity, mutagenic, and carcinogenic effects. MTB have been shown to adsorb Cr<sup>6+</sup> more effectively than distinct bacteria (e.g., *Pseudomonas* spp.). With biomass concentrations ranging from 4 to 100 g/L, MTB can achieve rapid removal of Cr<sup>6+</sup>/Cr<sup>3+</sup> typically in less than 60 minutes, and can also reduce adsorbed Cr<sup>6+</sup> to Cr<sup>3+</sup> (Wang and Sun, 2005; Qu et al., 2014).

Moreover, research has shown that MTB can achieve nearly complete recovery of Pb<sup>2+</sup>, Ni<sup>2+</sup>, Fe<sup>3+</sup> (or Fe<sup>2+</sup>), and Mn<sup>2+</sup> due to their strong affinity for these ions (Wang and Sun, 2005; Liu et al., 2018).

### Elimination of organic pollutants from wastewater

Attracted to organic substances, MTB are capable of extracting pollutants from water when exposed to a magnetic field (Ambashta and Sillanpaa, 2010; Vargas et al., 2018). Furthermore, studies have shown that MTB can break down organic pollutants in water through enzymatic processes (Bahaj et al., 2002). Example of extracts of bacterial magnetosomes which are used to degrade ethylparaoxon, a frequently utilized organophosphate pesticide (Ginet et al., 2011). Research indicates that immobilizing a pair of related enzymes (for example, endoglucanase and  $\beta$ -glucosidase), along with a cellulose-binding domain on the magnetosome, can significantly enhance cellulose degradation (Honda et al., 2015).

### Removal of radionuclides from wastewater

MTB have been shown to have a strong affinity for accumulating radionuclides and removing them from wastewater. MTB produced iron sulfide surfaces offer a suitable platform for radionuclide storage. MTB from ponds and streams are collected and the efficiency of radionuclide removal from wastewater is studied. A recovery rate of 40% of plutonium (Pu) is observed by MTB separated under static adsorption (Bahaj et al., 1998). MTB fields applications for bioremediation are diverse. Over the past few years, some studies show that these bacteria play a role in some critical metal recycling: *Magnetospirillum magnetum* strains contribute to the extraction of rare earth elements (e.g., neodymium (Nd), dysprosium (Dy))

from electronic waste, with an efficiency of 80% towards a circular economy (Rudnik, 2026). In addition, it is demonstrated that MTB functionalized via hydrophobic ligands trap aromatic hydrocarbons in seawater, with an adsorption capacity of 45 mg/g and rapid magnetic recovery (Martinez-Boubeta et al., 2021). Environmental biotechnological applications of MTB are not limited to bioremediation techniques. In fact, there is a growing need for environmental monitoring and conservation. Several studies have shown that MTB can play a significant contribution in this area.

### Environmental monitoring

In aquatic environments, MTB act as bioindicators to track redox conditions. Iron and oxygen gradient, two substances that define OATZ interfaces in sediments or water columns, are associated with their presence. This ability to reflect biogeochemical dynamics, makes MTB valuable tools for monitoring the health of natural or degraded environments.

For instance, *Magnetospirillum* sp. populations in the Seine estuary, peak at particular depths. That may be considered redox transition zones, which are conditions that are necessary for the iron cycle and favorable to microbial activity (Lefèvre et al., 2014).

The expression of reporter genes, allow genetically engineered, to react to hydrocarbons, pesticides and other contaminants for real time monitoring of contaminated water and soil.

Magnetosomes functionalized through specific ligand attachment, enable the magnetic separation of pollutants, including lead together with microplastics and polyfluoroalkyl substances (PFAS). Chitosan magnetosomes demonstrate maximum 90% lead (Pb) desorption from wastewater (Sun et al., 2024). Also, Bacterial magnetosomes are incredibly sensitive biosensors, that exploit heavy metals, induced reductions in magnetosome synthesis and inhibition of motility, to identify toxicity (Li et al., 2021).

## MTB OTHER APPLICATIONS

### Medicine applications

MTB and their magnetosomes have high potential biomedical researches. Their efficient magnetic navigability has attracted attention,

where they are used extensively in drug delivery systems (targeted drug delivery and as nanocarriers), magnetic resonance imaging (MRI) diagnostics, magnetic hyperthermia, due to their biocompatibility and strong homogeneous magnetic properties (Alphandéry, 2011; Alphandéry, 2014; Ren, 2023). Moreover, MTB are capable of being incorporated into monocytes and granulocytes through phagocytosis, which permits their magnetic separation from blood (Martins et al., 2021). MTB can, also, be engineered to deliver anticancer drugs to the sites of tumors, enhancing treatment efficacy and reducing the side effects (Alphandéry, 2020). Bioactive compounds can be conjugated to the magnetosome envelope; such a feature plays a vital role in numerous therapeutic applications. It has been shown that MTB are able to enhance the precision of drug delivery to tumors (Alsharedeh et al., 2024; Dieudonné et al., 2019). Also, MTB-derived magnetite is employed for applications such as enzyme immobilization, the generation of magnetic antibodies and the quantification of IgG antibodies (Yan et al., 2012). Additionally, DNA-coated MTB magnetite is utilized as a vehicle for gene delivery into cells (Vargas et al., 2018).

### Nanotechnology and materials science applications

A new paradigm in materials science and nanotechnology has been created by magnetotactic bacteria (MTB) and their magnetosomes. MTB can bioreduce, biosynthesize, and biomineralize very homogeneous single domain magnetic nanoparticles in ambient settings. These naturally occurring nanostructures include characteristics like monodispersity, regulated shape, high crystallinity, and surface functionality, that are otherwise exceedingly challenging, to achieve using conventional synthetic approaches (Faivre and Schüller, 2008). Magnetosomes can be found in chains, often induced by a cytoskeletal filament called MamK (Komeili, 2007). Natural chain formation is highly beneficial for the creation of magnetic nanowires and nanoribbons, which are essential parts of their production of spintronic devices, high density magnetic memory, and magnetic sensors (Faivre and Schüller, 2008). Additionally, MTB are valuable for studying soft magnetic materials, including Si-Fe sheets and amorphous Co-based ribbons (Yan et al., 2012). Moreover, preserved magnetosomes provide valuable insights into the

origin of the geomagnetic field and function as magnetic proxies for reconstructing past climates (Heslop et al., 2013).

The research studies presented, report clearly, the significant role that MTB can play in various biotechnological applications fields. But their practical applications remain limited; since culturing these bacteria and synthesizing nanoparticles is still difficult, due to the nature presence of MTB in aquatic environments and their fastidious growth requirements. Future studies could optimize the media and environmental conditions, to improve the growth and amount of MTB productions, which will help to increase their use and accessibility for applied studies. Considering their verified ability to biosynthesize and produce magnetosomes, future studies on the capability for bioremediation, targeted drug, magnetic resonance imaging, environmental monitoring and nanotechnology, need to be pursued. Expanding the sampling of the broad number of marine and sedimentary systems, can help with the understanding the ecological diversity and distribution of MTB.

### CONCLUSION

MTB are unique microorganisms characterized by their intracellular magnetosomes and magnetotactic behavior, which enable precise navigation in aquatic environments. These features make MTB valuable for a wide range of biotechnological applications, including environmental bioremediation of heavy metals, organic pollutants, and radionuclides; monitoring of redox conditions; development of nanoscale magnetic materials; and targeted drug delivery. Despite their potential, practical applications are limited by challenges in large-scale cultivation and the stability of magnetosomes, which require further investigation. Overall, MTB represent a versatile model system with promising applications across environmental, biomedical, and materials science fields, highlighting the importance of continued interdisciplinary research.

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