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Review Paper

Magnetotactic bacteria and their application in environmental clean-up: A review

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Abstract

Magnetotactic bacteria are a miscellaneous cluster of microorganisms having geomagnetism aided navigation property against applied magnetic field. This oneness is because of the presence of intracellular organelles magnetosomes comprising a membrane-bound crystals of magnetic iron minerals which are formed due to partial reduction of ferric iron in the iron-rich environment. It can biomineralize magnetic particles into uniform size structure, which has gained much more attention over chemically synthesized magnetic nanoparticles. The advantage of this bacteria over other microorganisms are that they are non-pathogenic,motile and easily isolated from the environment. With implications in various fields, including evolutionary biology, biogeochemistry, and nanotechnology, research on MTB and their magnetosomes has steadily increased since they were described by Richard Blakemore in 1975. Regardless of wide acknowledgment, there is still the lesser-known application of magnetotactic bacteria in remediation of wastewater. This review paper deals with the diversity of magnetotactic bacteria and their application in environmental clean-up.

Keywords: Magnetotactic bacteria, Magnetosomes, Nanoparticles.

Introduction

A heterogeneous group of prokaryotes, namely magnetotactic bacteria posses a unique characteristic of membrane-bound iron minerals known as magnetosomes[1]. These membrane-bound iron mineral have strong magnetization capability and are aligned in a chain like orientation which is close to the axis of cell motility[2]. MTB are nanometer-sized, membrane-bound crystals of magnetite or greigite[3]. The presence of magnetite-producing MTB is found mainly at or very close to the OAI while greigite-producing MT is present below the OAI, in the sulfide anoxic zone[4,3]. Several studies investigated that presence of MTB is mainly restricted where pH is neutral. It has been found out by Lefevre et al.[5] a thermophilic, uncultured magnetotactic bacterium was present in hot springs in northern Nevada having survival temperature of 63^0C. Similarly, this same group was isolated from different aquatic habitats in California, including hypersaline and extremely alkaline Mono Lake[6]. MTB rotates along applied geomagnetic field lines with the help of magnetosomes by rotating their helical flagella. This ability to move parallel to geomagnetic lines is known as magnetotaxis from which magnetotactic word arise. Salvatore Bellini first discovered this microorganism[7]. He found a navigating microorganism towards earth's north pole and later named it as ‘magnetosensitive bacteria[8]. The abundance of these bacteria is found in the sediments of many freshwater and marine habitats. MTB commonly found at the oxic–anoxic interface (OAI) of the water column in the sediments or slightly below the OAI of sediments or chemically starified water columns[4]. The detection of MTB is quite easy in environmental water and sediments samples because of their magnetic behavior. Regardless of the high profusion of their occurrence their isolation and cultivation are still very difficult to carry out. Researchers have been carried out to resolve this issue. Due to advancement in technology the cultivation of MTB is somehow become easy and research is still going on to find out their special characteristics, their application in various fields. This review paper deals with the different diversity of magnetotactic bacteria and places from which they are isolated and their application in environmental clean-up in the removal of different contaminants.

Diversity of MTB

Being diverse in nature, these MTB possess diverse, sometimes exceptional morphotypes in water and sediment samples. Theses bacteria have a variety of cell morphology comprising of coccoid, rod-shape, vibrioid, spirilloid and multicellular[9]. The MMPs and a very large rod provisionally named "*Ca. Magnetobacterium bavaricum*" are two unique variety of morphotypes[10]. The MTBs have flagella for their motility and have a cell wall structure similar to Gram-negative bacteria, but there is some exception in the case of *Nitrospirae* phylum which is having complex cell wall structure[11]. The flagellar arrangement differs from polar, bipolar, or in tufts in different MTB group. The difference in magnetosome also differs among different MTB group. The alignment of magnetosomes in one or more chains parallel to the axis of the cell is commonly seen in most of the MTB. But the alignment is sometimes magnetosomes with aggregates or clusters in some of the MTB, usually present at one side of the cell[12]. The presence of polyphosphate, elemental sulfur, or poly-hydroxybutyrate (PHB) are common in MTB present in natural environment[13]. The diversity of MTB comprises of *Alpha-, Gamma-,* and *Deltaproteobacteria* classes of the *Proteobacteria* phylum, several uncultured species are affiliated with the *Nitrospirae* phylum, and one, strain SKK-01, was assigned to the candidate division OP3, part of the *Planctomycetes-Verrucomicrobia-Chlamydiae* (PVC) bacterial superphylum[14]. Table-1 is showing different strains of MTB isolated from a different location and with different isolation techniques.

Alphaproteobacteria: This class of MTB comprises of two orders namely, the *Rhodospirillales*[15], and the *Magnetococcales*[16]. The ability of MTB to biomineralize cuboctahedral and Elongated prismatic magnetite crystals belongs to *Alphaproteo bacteria* class, and the species include genus *Magnetospirillum*[17]. *Magnetotactic Alphaproteo bacteria* are ananerobes or obligate microaerophiles, or both[18].

The genus Magnetospirillum: Having a respiratory form of metabolism and being a chemoorganoheterotrophes, magnetospirillum utilizes carbon and electrons from organic acids as their source[19]. Under anaerobic condition or at very low oxygen level, magnetite synthesis occurs in Magnetospirillum species, where nitrate acts as the substitute to oxygen[20]. The different magnetospirillum species include *Magnetospirillum gryphiswaldense*, uses electrons from reduced sulfur compounds for autotrophic and mixotrophic growth[21]. *Magnetospirillum magnetotacticum*, which is an obligate microaerophile that need oxygen even in the presence of nitrate for their growth[22].

Magnetotactic cocci: Magnetotactic cocci are coccoid-to-ovoid cells having two flagellar bundles on the falttened side. Even in the negligible presence of sulfur in samples of the environment, these Magnetotactic cocci contain sulfur globules for autotrophic and mixotrophic metabolism using reduced sulfur compounds. *Magnetococcus marinus* and strain MO-1, are two cultured magnetococci, that are obligately microaerophilic and grow autotrophically on sulfide[23] and thiosulfate in which *Magnetococcus marinus* utilizes the reductive tricarboxylic acid cycle for carbon dioxide fixation and autotrophy[24]. It has the capability of nitrogen fixation based on the nitrogenase activity, and the growth requires acetate as the electron and carbon source[25].

Deltaproteobacteria: *Deltaproteobacteria* of MTB consists of two orders, the *Desulfovibrionales* and the *Desulfobacterales*. This class of MTB has both greigite and magnetite -producing MTB.

Magnetotactic Multicellular prokaryotes: MMPs are multi-celled magnetotactic prokaryotes of 3 to 12 micrometer in diameter[26]. Most MMPs are spherical, though some are pineapple or ovoid shaped in morphology[27], and they come out to have an acellular, central compartment[28]. Many of the recent findings suggested three types of MMPs namely, "*Candidatus* Magnetoglobus multicellularis, "*Ca. Magnetomorum litorale*"[29], and "*Ca. Magnetananas tsingtaoensis*". The presence of MMPs is found ranging from brackish to hypersaline aquatic environment. Recent findings have demonstrated that nonmagnetic MMPs have moderately low salinities (5 to 11 ppt) as they are presence is also found in springs and lakes but have similar characteristics like MMPs that they are sulfate reducers[30]. A different characteristic bearing MMPs family is *Desulfobacteraceae* as it constitutes multicellular organisms having different size and morphologies and biomineralize either magnetite or greigite.

Gammaproteobacteria: From China, two species of cultured *Gammaproteobacteria* are investigated namely, strains BW-2 and SS-5, and two uncultured strains are isolated[31]. The characteristics of BW-2 strain were the cells with a unsheathed bundle of seven flagella having greigite-producing rods[31]. The strain uses sulfide and thiosulfate as their electron donors so that they can grow chemolithoautotrophically. The strains also show nitrogenase activity. Strain SS-5 were found in the hypersaline aquatic environment and had a single polar flagellum. They also have property to grow chemolithoautotrophically but are likely to grow heterotrophically on succinte. Their growth is negligible on nitrogenase activity. Both the strains are mesophilic, microaerophilic rods and can biomineralize either elongated prismatic crystals of magnetite in their magnetosomes[31].

Nitrospirae: Four types of uncultured MTB of this genera are found from different locations. *Ca. Magnetobacterium bavaricum* originated from sediment samples from Lake Chiemsee and Lake Ammersee in southern Germany[32], strain MHB-1 isolated from the sediment of the Waller See, Germany[33], *Ca. Thermomagnetovibrio paiutensis* strain HSMV-1, from Gerlach, NV 7, *Ca. Magnetoovum mohavensis* strain LO-1 from freshwater sediments of Lake Mead, NV. Dimensions of *Ca. Magnetobacterium bavaricum* are large rods of 1 to 1.5 [34] micrometer having single flagella. The presence of magnetosomes ranges from 600 to 1000 having bullet shaped crystals and are organized in three to six braid-like bundles of multiple chains[11].

The cells exhibit polar magnetotaxis and their movement requires an average speed of 40 micrometer/s, having flagellar structure wounded around the cell. The presence of this bacterium is mainly in OAI of sediments and is microaerophilic, sulfide-oxidizing bacteria as it contains sulfur-rich globules[35]. A rod-shaped bacterium Strain MHB-1 posses crystals of bullet shaped magnetite magnetosomes of multiple chains. Uncultured *Ca. Thermomagnetovibrio paiutensis* strain HSMV-1was present in hot spring of temperature between 32°C and 63°C having single flagellum for motility. *Ca. Magnetoovum mohavensis* strain LO-1are ovoid in shape and have a single polar bundle of sheathed flagella. Being gram-negative bacteria, this strain has a three-layered cell wall.

Magnetotactic Eukaryotes: A euglenoid shaped alga, was found earlier from water samples from a coastal mangrove swamp, Brazil having well-organized chains of bullet shaped magnetite crystals and was identified as *Anisonema platysomum*[36].

Magnetotactic bacteria in environmental clean-up

A lot of researches have been carried out in terms of MTB and their magnetic properties, their behavior. MTB have been used for environmental clean-up in many ways by exerting their magnetic behavior. Although environmental clean-up is mediated by many of the processes but removal of contaminants from MTB is quite effective and eco-friendly. Huiping et al.[42] also conducted an experiment to find out the biosorption capacity of Au(III) and Cu(III) by magnetotactic bacteria. The experimental result showed that the maximum biosorption was achieved at decreasing pH of 1-5.5 for Au(III) and 2.0-4.5 for Cu(III) at biomass concentration of 1O.Og.L- 1 and sorption duration of more than 10 min. The maximum adsorption capacity for Au(III) and Cu(III) in single component solution by MTB at an initial metal concentration of 5OOmg.L-1were nearly equal whereas the maximum sorption was attained for Au(III) was observed in the binary system than Cu(III). At an initial concentration of 320mg.L-1in, a mixture of Cu(III) and Au(III) and was more than 95.87% and less than 8.83%, respectively. Qu Y.[43] investigated the use of MTB in the removal of hexavalent chromium from wastewater. The experiment was carried out using the batch-stirred system by a novel culture method of inoculation having varying chromium concentration and different conditions. The results from the experiment showed that the removal efficiency was pH dependent as between pH 5 to 6, the removal of Cr (VI) increases noticeably from 41% to 80%, but with an increase in pH, the removal rate decreases. Hence the best pH for degradation was 6. The decreased removal rate indicates the reduced activity of cell and biomass below and above pH 6. The removal mechanism involves adsorption of Cr (VI) on the surface of the cell. The removal was also maximum when the temperature is 290C i.e.77%, and the removal is 50% when the temperature is between 250C to 500C. The removal of living and dead cells comprises of 77% and 76% within 10 min of contact time, but with an increase in a contact time of 40 min, the removal rate decreases to 53%. Another magnetotactic species, Stenotrophomonas sp. was tested for the removal of Au (III) from contaminated wastewater using a magnetic stirrer by Song et al.[44]. The experiment was conducted for examining biosorption efficiency of magnetotactic species and later a novel device was discovered for separation the biomass from the aqueous solution after biosorption. The result from the experiment showed that the species was capable of biosorping the contaminant. Au(III) was initially removed in 10 min at initial pH of 2.0 80 mg l_1 Au(III) and biomass of 0.74 g l_1 (dry weight). The maximum Au(III) biosorption capacity of Stenotrophomonas sp. were 506, 369 and 308 mg g_1 dry weight biomass at initial pH values of 2.0, 7.0 and 12.0, respectively. The desorption experiment using magnetic separator at different intensities was carried out, and the result was the biomass was recovered almost from the solution and at the intensity of 1200 GS in 180 min the total biomass could be recovered.

Table-1: Different strains of MTB with isolation techniques.

Types of MTB strain	Location	Phylum	Isolation technique	References
Marine magnetic spirillum QH-2	Seawater pond sample at Huiquan Bay Qingdao, China	*Alphaproteobacteria*	Magnetic enrichment and purification	38,39
Desulfovibrio magneticus strain RS-1	Water and Sulphide rich sediments from water way near Kameno river, Western Japan	*Deltaproteobacteria*	Enrichment of MTB by incubating sediment and water in 1:2 proportions in glass bottles without applying external magnetic field	40
Aerobic marine magnetotactic bacterium YSC-1	Yellow Sea Cold Water Mass	-	Magnetic enrichment and colony formation on marine medium 2216 agar plates	41
Magnetotactic strain WM-1	North-lake in Wuhan	*Proteobacteria*	Incubation and colony formation on agar plates	42
Magnetotactic strain MHB-1	sediment samples, Germany	*Nitrospirae*	Capillary rare track purification method	33
Magnetotactic strain BW-2	Water and sediment samples from spring at Badwater Basin in Death Valley, California	*Gammaproteobacteria*	Capillary rare track purification method	31
Magnetotactic strain SS-5	Water and Sediment samples from Death	*Gammaproteobacteria*	Capillary rare track purification method	31

Conclusion

After the isolation of MTB by Richard P. Blakemore around 30 years ago, a considerable progress has been going in this direction. They are abundant in the natural environment in large number, yet they are difficult to isolate from the environment, but research has been ongoing in regard of this. They are shown to be quite effective in contaminant removal due to the presence of magnetosomes in their structure. The MTB are efficient in the treatment of heavy metals like Cr (VI), Cu(III), Au(III). Certain innovation has also been going to use these bacteria with another type of reactive media to enhance the performance.

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