Materials Science and Engineering C 68 (2016) 919–928

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Review

Magnetotactic bacteria and magnetosomes – Scope and challenges

Jobin John Jacob, K. Suthindhiran *

Marine Biotechnology and Bioproducts Lab, School of Biosciences and Technology, VIT University, Vellore 632014, India

A R T I C L E I N F O

Article history:
Received 29 March 2016
Received in revised form 24 June 2016
Accepted 19 July 2016
Available online 20 July 2016

Keywords:
Geomagnetism
Magnetotactic bacteria
Magnetosome
Nanotechnology

A B S T R A C T

Geomagnetism aided navigation has been demonstrated by certain organisms which allows them to identify a particular location using magnetic field. This attractive technique to recognize the course was earlier exhibited in numerous animals, for example, birds, insects, reptiles, fishes and mammals. Magnetotactic bacteria (MTB) are one of the best examples for magnetoreception among microorganisms as the magnetic mineral functions as an internal magnet and aid the microbe to move towards the water columns in an oxic–anoxic interface (OAI). The ability of MTB to biomineralize the magnetic particles (magnetosomes) into uniform nano-sized, highly crystalline structure with uniform magnetic properties has made the bacteria an important topic of research. The superior properties of magnetosomes over chemically synthesized magnetic nanoparticles made it an attractive candidate for potential applications in microbiology, biophysics, biochemistry, nanotechnology and biomedicine. In this review article, the scope of MTB, magnetosomes and its challenges in research and industrial application have been discussed in brief. This article mainly focuses on the application based on the magnetotactic behaviour of MTB and magnetosomes in different areas of modern science.

Contents

1. Introduction

Nanotechnology has revolutionized a wide array of high performance devices in biomedical diagnostics and various biotechnological applications [1–3]. The superior physical, chemical and biological properties of

---

* Corresponding author at: Marine Biotechnology and Bioproducts Lab, SBST, VIT University, Vellore, India.
E-mail addresses: ksuthindhiran@vit.ac.in, sudhindhira@gmail.com (K. Suthindhiran).

http://dx.doi.org/10.1016/j.msec.2016.07.049
0928-4931/

such structures lead to considerable focus on the research of nanoparticles (NPs) [4,5]. In particular magnetic nanoparticles (MNPs) have attained much attention on account of the prospect to control their properties utilizing magnetic field [6]. However industrial applications based on nanoparticles require uniform morphology with narrow size distribution [7,8]. Contrary to the common belief, the MNPs synthesized by co-precipitation (synthetic nanoparticle) do not possess the properties required in various technologically important applications [9]. Controlling the structural, morphological, and chemical properties of nanomaterials is one of the most difficult problems faced by nanotechnology [10]. On the other hand biogenic magnetic nanoparticles (magnetosomes) extracted from magnetotactic bacteria (MTB) fulfil all the requirements with regard to size, morphology, biocompatibility and magnetisation capabilities [8,11–13].

Magnetotactic bacteria are a group of aquatic prokaryotes that have the ability to navigate along the magnetic field lines of Earth's magnetic field with the aid of intracellular organelles called magnetosomes [14,15]. Magnetosomes are crystals of magnetic iron mineral comprising of either magnetite (Fe_3O_4), or greigite (Fe_3S_4) arranged in chains [16,17]. Magnetosomes are nanometer-sized iron crystals surrounded by lipid bilayer membrane and arranged in a chain or chains adjacent to the plasma membrane [18,19]. These biogenic nanoparticles are synthesized under strict genetic control with a uniform shape, size and dispersion. The crystal size normally falls in a range about 35–120 nm, which is within the stable single magnetic domain (SD) [14,20,21]. The uniform size range and morphology exhibited by magnetosome crystals extracted from different strains show the high degree of control the bacteria exert in the biosynthesis of magnetosome [15,22].

MTB inhabit commonly at the oxic–anoxic interface (OAI) of the water column in the sediments. The presence of magnetosomes helps the bacteria in locating favorable growth conditions at or just below the OAI of aquatic sediments [23]. The chain-like arrangement of magnetosomes inside the cell maximises the magnetic dipole moment and helps the bacteria to utilize earth's magnetic field for course and route [24]. MTB was first reported by S. Bellini in 1963 in a publication of the Microbiology Institute [25,26]. R P Blakemore rediscovered the bacterial magnetoreception in his revolutionary paper and hence denoted the beginning of these wonder bacteria named Magnetotactic bacteria [27]. Blakemore's rediscovery was based on the northward migration of certain microorganisms present in water drops along magnetic field lines. Using transmission electron microscopy (TEM), he documented that the bacterial cells contained chains of elongated iron crystals consisted of magnetite (Fe_3O_4) and coined the name magnetosomes [27]. Such magnetic moment of bacteria was extraordinary and soon attracted considerable attention that led to more research in MTB to find varying morphological and phylogenetic characteristics [21,28].

The preliminary research works carried out on MTB targeted on the diversity of MTB from various saline lagoons around the world and in optimising the methodology for the isolation and characterization of MTB and so on. During the molecular era, the study of MTB was conducted to address the questions such as how MTB construct their magnetic compass needles. Likewise, how MTB evolved from a common ancestor with magnetosome genes and what kind of role the membrane proteins play for the biomineralization process [23,29,30]. Nowadays due to the development of magnetic nanoparticle-based biomedical and nanotechnology applications, novel biomaterials have been encouraged by advanced technological innovations. The unique magnetic, physical and optical characteristics made it a good candidate for a broad range of scientific and technical applications [31–33]. The goal of this review is to provide an overview of the current knowledge of magnetotactic bacteria and magnetosomes, functionalisation of magnetosomes and their biotechnological applications based on their unique properties.

2. Magnetotactic bacteria

MTB are morphologically, physiologically and phylogenetically diverse group of microorganisms that are characterized by the movement along geomagnetic field lines in a process called Magnetotaxis. Many morphotypes of MTB have been identified including spirilla, cocci, rod-shaped, bean-shaped, vibrios, ovoid and more complex multicellular bacteria [23,27]. Most of the isolates are Gram-negative bacteria and are found in almost all type of aquatic environments. Phylogenetic analysis of cultured and uncultured MTB so far identified has been classified under the *Alpha-*, *Gamma-*, *Delta-*classes of *Proteobacteria* phylum and with the *Nitrospirae* phylum [34]. MTB inhabit in marine, estuarine and freshwater habitats where vertical chemical concentration gradient exists. In the natural environment, they have a preference to inhabit in the OAI that implicates the uppermost fraction of un-stratified sediments based on the environment [14]. Although MTB has been identified from various natural environments, the fastidious growth nature and special culture conditions hindered their isolation and cultivation in laboratory condition [23].

Most cultured species of MTB are either microaerophilic or anaerobic that grows chemolithoautotrophically using reduced sulphur compounds as electron sources [23]. All cultivated MTB found to have respiratory system unable to ferment sugars but utilize certain organic acids as a source of electron and carbon. Most of the isolated and cultured and characterized magnetotactic bacteria belong to genus *Magnetospirillum*, which is found in the fresh water habitat. The genus *Magnetococcus*, *Magnetovibrio* and rod-shaped *Candidatus bavaricum* are some of the other identified MTB [35]. Based on the genetic analysis the genus *Magnetospirillum* is well characterized compared to the other genus of MTB. The three strains of *Magnetospirillum* for instance *Magnetospirillum gryphiswaldense* (MSR-1) [36], *Magnetospirillum magneticum* strain (AMB-1) [37], and *Magnetospirillum magnetotacticum* strain MS-1 [38] are well characterized and completely sequenced. The other well-studied strains of MTB are *Magnetococcus marinus* strain MC-1, and *Magnetovibrio blakemorei* strain MV-1. Although other MTB strains such as *Candidatus Magnetobacterium bavaricum* [39], *Desulfovibrio magneticus* strain RS1 [40] and *Magnetospira sp.*QH2 [41] are available in axenic culture, complete genome sequencing is not available. *Magnetospirillum* sp. VITRJS1 [42], *Magnetospirillum* sp. VITRJS2, VITRJS3, VITRJS4, VITRJS5, VITRJS6 and VITRJS7 are some of the MTB strains isolated from the Indian subcontinent [43].

3. Magnetosomes

Magnetosomes are nano-sized magnetic iron mineral synthesized intracellularly by MTB. This bacterial nanoparticle is surrounded by lipid bilayer membrane called magnetosome membrane (MM). Magnetosomes are made up of an organic magnetosome membrane and inorganic magnetite in a controlled manner [18]. The inorganic core of magnetosome is either magnetite (Fe_3O_4) or greigite (Fe_3S_4) with varying morphologies [14]. The arrangement of magnetosome as a single chain increases the magnetic dipole moment of the bacterial cell. The organic phase of magnetosome has been formed as vesicles originated from the inner membrane [18]. The synthesis of the organic magnetosome membrane and inorganic magnetite core is under strict genetic control by a process called biomineralization. During the first few years of research magnetosome magnetite crystals were believed to have spherical shape, but later it was found that MTB biomineralize it in different size and shape [44]. The morphology of magnetosome magnetite crystal varies based on the bacterial strain from which it is extracted. Transmission electron microscopy (TEM) or high-resolution transmission electron microscopy (HRTEM, Fig. 1) has been commonly used to study the morphology and crystal structure of magnetosomes [45]. The shapes include cubo-octahedral, bullet-shaped, elongated prismatic and rectangular morphologies [45].

The bacterial nanoparticles (BNPs) show unique property such as narrow and species specific size distribution [46]. Magnetosome biosynthesis is a complex process that involves three main steps (i) invagination of cytoplasmic membrane, (ii) uptake of iron and (iii) nucleation and maturation of magnetite crystals. Based on functional genome