International Journal of Engineering Research-Online
A Peer Reviewed International Journal
ISSN: 2321-7758 http://www.ijoer.in editorijoer@gmail.com
Vol.14., S1, 2026
January

Special issue

ISSN: 2321-7758

Magnetic Nanoparticles and Biomedical Applications

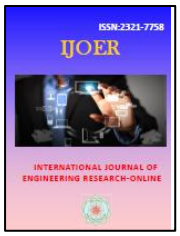
K. Sreelatha*[1], K. Anil Kumar[1], D. Sreenu[1], Deepti Bhargav[1], P. Anusha[1], S. V. G. V. A. Prasad[2]

[1] Department of Physics, Ch. S. D. St. Theresa's College for Women (Autonomous), Eluru–534003, Andhra Pradesh, India

[2] Department of Physics, P. R. Government College (Autonomous), Kakinada–521001, Andhra Pradesh, India

*Corresponding Author: srilatha.prathap@gmail.com

DOI: 10.33329/ijoer.14.S1.84



Abstract

Due to their numerous and substantial uses in biology and medicine, magnetic nanoparticles have garnered a lot of attention lately. Nature itself provides early examples of their functionality through magneto-tactic bacteria and homing pigeons, where nanoscale magnetic materials enable geomagnetic orientation. The distinctive physicochemical properties of magnetic nanoparticles arise from their nanometric dimensions, typically comprising only a few hundred to a few thousand atoms, resulting in behaviour markedly different from bulk magnetic materials. In biomedical science, these nanoparticles are exploited for magnetic separation techniques, enhancement of magnetic resonance imaging (MRI) contrast, and cancer therapy approaches such as magnetic hyperthermia. The performance of magnetic nanoparticles in such applications is strongly affected by factors such as surface chemical characteristics, magnetic dipolar interactions, particle dimensions, and morphology. Advances in chemical synthesis methods have enabled the production of magnetic nanoparticles with controlled size, narrow size distribution, and surface passivation using organic molecules, which are essential for stability, biocompatibility, and self-organisation. Such control not only optimizes individual particle behaviour but also enables collective effects in two- and three-dimensional assemblies, further expanding their biomedical potential.

Keywords: Magnetic nanoparticles, MRI, magnetic separation, hyperthermia.

I. Introduction

Magnetic nanoparticles (MNPs) have a wide range of applications in biology and medicine due to their unique size-dependent magnetic properties and their ability to respond to external magnetic fields. Nature provides some of the earliest examples of their functional relevance, as several organisms—including magnetotactic bacteria and homing pigeons—utilize magnetic nanoparticles to navigate along the Earth's magnetic field, underscoring the

biological significance of nanoscale magnetism. At the nanoscale, materials typically comprise only a few hundred to a few thousand atoms, leading to physical and magnetic properties that differ substantially from their bulk counterparts. In MNPs composed of materials such as cobalt, nickel, or iron oxides, size reduction induces phenomena such as superparamagnetism, enhanced surface effects, and altered magnetic anisotropy. These properties are particularly valuable in biomedical applications, where a controlled magnetic response and minimal remanence are required.

In biomedical contexts, MNPs are extensively employed in separation techniques that exploit their tendency to move toward stronger magnetic fields. In magnetic resonance imaging (MRI), the local magnetic fields generated by nanoparticles alter the resonance behavior of nearby protons, enhancing image contrast. Magnetic hyperthermia is another key application, in which cancer cells are selectively destroyed by heating nanoparticles exposed to oscillating magnetic fields. Interactions among MNPs depend on parameters such as particle size, shape, surface charge, magnetic dipole moment, and surface functionalization. To ensure stability and biocompatibility, nanoparticles are commonly coated with organic surfactants or polymers, which prevent aggregation and allow further functionalization with biomolecules—an essential step for applications in biological fluids and living tissues.

Recent advances in chemical synthesis have enabled the production of MNPs with precise size control and narrow size distributions, which are critical for reproducible biomedical performance. Furthermore, the ability of MNPs to self-assemble into two- or three-dimensional structures gives rise to collective magnetic properties that differ from both individual nanoparticles and bulk materials, influencing heating efficiency in magnetic hyperthermia as well as magnetic responsiveness in separation and imaging applications.

2. Natural Occurrence of Magnetic Nanoparticles

2.1 Magnetotactic Bacteria

Magnetotactic bacteria contain chains of magnetic nanoparticles, most commonly magnetite (Fe_3O_4) (Fig. 1) [1]. These particles typically have diameters smaller than the critical radius at which a single-domain magnetization state is the most stable, effectively forming nanoscale permanent magnets. As a result, the bacteria can sense and align with the Earth's magnetic field. The main component of the Earth's magnetic field is horizontal, oriented toward the poles, with a vertical component approximately ten times weaker. By propelling themselves with flagella along the appropriate orientation of the field lines, the bacteria migrate to deeper, oxygen-poor waters, which provide an optimal environment for their survival. Notably, the vertical component of the Earth's field has opposite orientations in the northern and southern hemispheres, yet the bacteria's orientation mechanism continues to function even if the magnetization of the nanoparticles is reversed.

Magnetotactic bacteria produce nanoparticles that are remarkably uniform in size and shape, making them highly suitable for technological applications. The protective protein shell surrounding the particles ensures uniform suspensions and prevents aggregation. This natural precision has inspired novel approaches in nanotechnology, including the potential direct functionalization of these biologically synthesized nanoparticles with specific proteins for targeted applications [2].

Fig. 1 Chains of magnetic particles (*dark*) Inside a magneto-tactic bacterium. *Scale bar*: 1µm

2.2 Pigeon Homing

Homing pigeons are believed to use two primary mechanisms for orientation: a navigation map, which represents a mental image of previously traversed locations, and a magnetic compass, often referred to as the inclination compass. Recent research by British and German scientists has provided compelling insight into the magnetic sensing mechanism [1]. Magnetic nanoparticles, with diameters ranging from 1 to 5 nm, aggregate into micron-sized clusters in the pigeons' beaks (Fig. 2). These clusters consist of superparamagnetic nanoparticles that can become significantly magnetized even in the weak geomagnetic field.

Interactions between these magnetized particles lead to structural changes: rows of particles perpendicular to the field tend to elongate slightly, whereas rows aligned with the field may contract. These mechanical changes generate signals at nearby nerve endings, which are then transmitted to the brain. Because the attractive or repulsive forces between the particles depend on the strength of the magnetic field rather than its polarity, the resulting neural signal is independent of the sign of the Earth's magnetic field. However, this magnetic sensing alone does not provide all the spatial information necessary for orientation. Consequently, pigeons rely on both their magnetic compass and a mental navigation map to accurately determine direction and location.

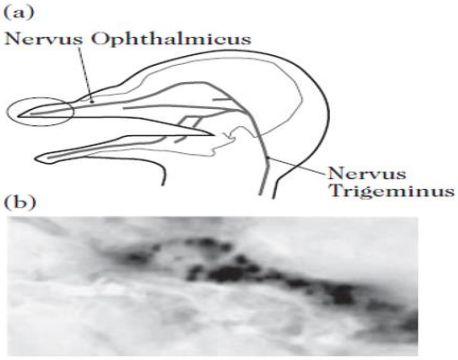


Fig. 2 Clusters of magnetic nanoparticles observed in the beak of a pigeon [*dark regions* in (b), where the *scale bar* represents 10 μ m] and region in which these clusters are distributed [*ellipse* in (a)]

.

3. Biomedical Applications of Magnetic Nanoparticles

3.1 Magnetic Distancing

.

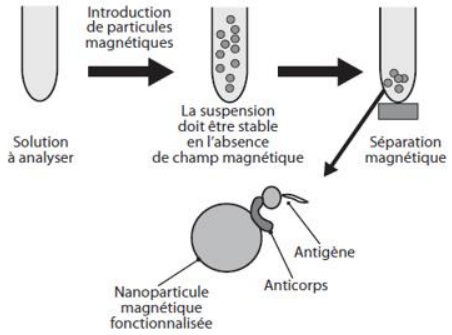


Fig. 3 Magnetic separation of different substances

A well-established analytical approach involves associating particles with specific target elements or microorganisms in a solution. For example, micrometric latex particles can be functionalized with antibodies [3] and then introduced into the solution. If the solution contains microorganisms recognized by the antibodies, these microbes bind to the particles, resulting in agglutination. This phenomenon indicates the presence of the target bacterium.

When the microorganism is present at very low concentrations, immunomagnetic separation techniques are employed to enhance detection (Fig. 3) [4]. In this method, magnetic nanoparticles replace latex beads, allowing the target bacteria to attach to the magnetic particles. The particles are then captured and concentrated by passing them through a column subjected to a magnetic field, facilitating detection due to the increased local concentration. Compared to micrometric particles, nanoparticles offer several advantages, including biocompatibility, non-toxicity, and reduced sedimentation [5]. However, their smaller magnetic moments make them more challenging to manipulate in magnetic field gradients. Recent studies have demonstrated that carefully designed configurations can generate sufficiently strong field gradients to overcome this limitation [6].

3.2 Magnetic Nanoparticles as MRI Contrast Agents

Magnetic resonance imaging (MRI) is based on the phenomenon of nuclear magnetic resonance, observed when atomic nuclei possess a nuclear magnetic moment [10]. In a magnetic field applied along the z-axis, the nuclear moments precess with angular frequency $\omega = \gamma B$, where γ is the gyromagnetic ratio. For nuclei with spin $S = 1/2$, there are two possible states, whose populations at temperature T are governed by Boltzmann statistics. Nonequilibrium populations can be induced by applying electromagnetic radiation of energy $E = h\omega = h\gamma B$. The system returns to equilibrium after the radiation is turned off, characterized by the longitudinal relaxation time T_1, while interactions between nuclei and local magnetic field inhomogeneities give rise to transverse relaxation time T_2.

MRI primarily exploits the nuclear spins of protons in water and lipids due to their high abundance in the human body. Differences in relaxation times enable tissue contrast, but intrinsic contrast is sometimes insufficient. Magnetic nanoparticles can be administered intravenously as contrast agents to enhance image quality [4]. For instance, in liver imaging, tumors appear brighter on MRI because they do not absorb nanoparticles, whereas healthy tissue absorbs them and appears darker [7].

3.3 Magnetic Nanoparticles in Tumor Therapy

Significant progress has been made in understanding the genetic and molecular mechanisms underlying tumor formation over the past two decades. However, certain malignancies remain resistant to conventional therapies [7]. Magnetic hyperthermia provides an alternative approach by locally heating tumors to 42–46 °C, increasing their susceptibility to chemotherapy or radiation. Superparamagnetic single-domain nanoparticles are widely employed for this purpose [2]. These nanoparticles are often conjugated to targeting ligands, such as folic acid, to selectively bind tumor cells (Fig. 4).

Upon exposure to an alternating magnetic field, the nanoparticles' magnetization reverses in phase with the field, generating localized heat that permeates the surrounding tissue. Nanoparticles of approximately 5 nm in size reduce sedimentation and facilitate transport through the bloodstream into tissues. Furthermore, their superparamagnetic nature prevents agglomeration, a problem commonly observed in ferromagnetic particles due to dipole interactions [2].

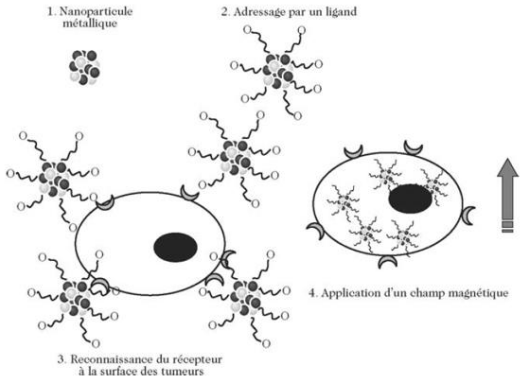


Fig. 4. Selective heating of tumorous cells targeted by magnetic nanoparticles

Table: Magnetic Nanoparticles Used in Combination Therapies for Enhanced Cancer Treatment

S No	Drug / Therapy	Magnetic Nanoparticle System
1	Acyclovir	Fe_3O_4 magnetic nanoparticles
2	Magnetic drug targeting / magnetic hyperthermia	Magnetic nanoparticles (Fe_3O_4)
3	Doxorubicin	methoxy poly(ethylene glycol)-grafted carboxymethyl chitosan

4	Doxorubicin	Gelatin/Fe_3O_4–Alginate
5	Doxorubicin	(Fe_3O_4) magnetic nanoparticles
6	Doxorubicin	Magnetic nanoparticles (Fe_3O_4) / inhomogeneous magnetic pulses
7	Doxorubicin	Starch/Octanoic/superparamagnetic iron oxide
8	Doxorubicin	SPIONs/PLGA–AS1411 aptamer
9	Doxorubicin	Magnetic iron oxide nanoparticles (MIONs) / hyperthermia therapy / chemotherapy
10	Doxorubicin	Graphene oxide (GO) and magnetic iron oxide nanoparticles
11	Doxorubicin	SPIONs / DSPE-PEG2000
12	Doxorubicin	SPIONs / rPAA / PEG / dodecyl amine graft
13	Erlotinib	Mesoporous magnetic nanoparticles / folic acid
14	Erlotinib	Methotrexate / chitosan-magnetic nanoparticles ferrofluid
15	Gemcitabine	Magnetic nanoparticles (Fe_3O_4) / metformin / pHLIP
16	Methotrexate	PEG-chitosan-iron oxide nanocomposites
17	Methotrexate	Magnetic nanoparticles (MNPs) / Fe_1−xMnxFe_2O_4
18	Methotrexate	PLGA magnetic nanoparticles (Fe_3O_4)
19	Methotrexate / Doxorubicin	Dendritic chitosan-mPEG-coated Fe_3O_4
20	Methotrexate	Folic acid-chitosan core-shell nanoparticles
21	Telmisartan	Magnetic nanoparticles (Fe_3O_4) / chitosan
22	Zidovudine	$NiFe_2O_4$ / poly(ethylene glycol) / lipid nanoparticles
23	Photothermal effect / chemotherapy (Doxorubicin)	Porous carbon-coated Fe_3O_4 / hyaluronic acid
24	Hyperthermia / Doxorubicin	Iron oxide nanocubes
25	5-Fluorouracil	Fe_3O_4-grafted dextran with N-vinylcaprolactam and N-vinylimidazole
26	Hyperthermia	Cobalt-zinc ferrite nanoparticles (Co_1−xZnxFe_2O_4)
27	Hyperthermia	$Zn_{0.3}Fe_{2.7}O_4$ / SiO_2
28	Hyperthermia	Hydroxyapatite-coated iron oxide nanoparticle
29	Magnetic hyperthermia	Manganese ferrite nanoparticles
30	Hyperthermia	Mn–Zn ferrite nanosphere

31	Hyperthermia	Magnesium-incorporated maghemite (γ-Fe_2O_3)
32	Hyperthermia	Polymethylmethacrylate / Fe_3O_4
33	Hyperthermia	Hydroxypropyl methyl cellulose / polyvinyl alcohol / Fe_3O_4
34	Magnetically mediated energy delivery	Iron oxide core / glucose
35	Hyperthermia	Magnetic nanoparticles (Fe_3O_4)
36	Hyperthermia	Magnetic mesoporous silica nanocarriers
37	Photodynamic therapy / hyperthermia	Magnetic nanoparticles (Fe_3O_4)-hyaluronic acid (AHP)
38	Radiation therapy	Au / Iron oxide
39	Gemcitabine	Iron oxide nanoparticles / anti-CD44 antibody
40	Imaging-guided cancer therapy	Erythrocyte membrane-coated iron nanoparticles
41	Magnetically guided drug delivery	Fe_3O_4@Zirconium phosphate core-shell nanoparticles
42	Superparamagnetic hyperthermia	Magnetite nanoparticles (Fe_3O_4)
43	Gene therapy	Magnetic nanoparticles (Fe_3O_4) / polyethyleneimine (PEI)
44	Blood–brain barrier	Magnetic nanoparticles (Fe_3O_4)
45	Chemo / hyperthermia therapy	Tragacanth gum / polyacrylic acid / Fe_3O_4 nanoparticles

Conclusion

Magnetic nanoparticles constitute a unique class of functional nanomaterials, whose size-dependent magnetic behavior enables a broad range of biological and biomedical applications. Natural systems, such as magnetotactic bacteria and homing pigeons, provide compelling evidence of the biological relevance and efficiency of nanoscale magnetic materials for orientation and sensing. In biomedical science, these nanoparticles have demonstrated significant utility in magnetic separation, enhancement of magnetic resonance imaging (MRI), and cancer treatment via magnetic hyperthermia. Their performance is strongly influenced by parameters such as particle size, morphology, surface chemistry, and magnetic interactions, all of which can now be precisely tailored through advanced synthesis methods. Surface passivation and functionalization are critical for ensuring nanoparticle stability, biocompatibility, and targeted interactions with biological systems. Moreover, the ability of magnetic nanoparticles to self-organize into ordered assemblies introduces collective magnetic effects, further enhancing their functional efficiency. Overall, magnetic nanoparticles have emerged as indispensable tools at the interface of nanotechnology, physics, and medicine, offering both diagnostic and therapeutic advantages.

Future Scope

The future of magnetic nanoparticles in biomedicine lies in the development of

multifunctional nanoplatforms that integrate diagnosis, therapy, and real-time monitoring within a single system. Advances in synthesis techniques are expected to produce particles with tighter size control, higher magnetic efficiency, and improved reproducibility suitable for clinical applications. Smart, stimuli-responsive surface coatings will further enhance targeted delivery and controlled drug release. Combining magnetic nanoparticles with molecular imaging, gene therapy, and immunotherapy may open new avenues for personalized medicine. Continued research into collective magnetic phenomena and nanoparticle self-assembly is anticipated to improve hyperthermia efficiency and generate next-generation contrast agents. Comprehensive studies on long-term toxicity, biodegradation, and clearance mechanisms will be essential to ensure safe clinical translation. With interdisciplinary collaboration and regulatory support, magnetic nanoparticles are poised to play a transformative role in future diagnostic and therapeutic technologies.

References

[1]. Davila, A. F., Hoppensteadt, F. C., & Keeton, W. T. (2003). A novel model of a magnetoreceptor in homing pigeons. *Physics and Chemistry of the Earth, 28*, 647–652.

[2]. Tartaj, P., Morales, M. P., Veintemillas-Verdaguer, S., Gonzalez-Carreño, T., & Serna, C. J. (2003). Magnetic nanoparticle preparation for biomedical applications. *Journal of Physics D: Applied Physics, 36*, R182–R197.

[3]. Diat, O., & Roux, D. (1993). [Title not provided]. *Journal de Physique II, 3*, 9–18.

[4]. Roux, D., Diat, O., & Babonneau, F. (2004). Nanotechnologies and new medicines. *Current Medicinal Chemistry, 11*, 169–177.

[5]. Juliano, R. L. (1988). Factors affecting the clearance kinetics and tissue distribution of liposomes, microspheres, and emulsions. *Advanced Drug Delivery Reviews, 2*, 31–54.

[6]. Martin, C. R., & Mitchell, D. T. (1998). Nanomaterials in analytical chemistry. *Analytical Chemistry News and Features*, 322–328.

[7]. Chiannilkulchai, N., Panit, S., & Limtrakul, P. (1990). Hepatic tissue distribution of doxorubicin-loaded nanoparticles. *Cancer Chemotherapy and Pharmacology, 26*, 122–126.