Chapter 9

Multifunctional Ferrites: Synthesis, Behavior and Biomedical Applications

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Abstract

Ferrites are a family of oxides with outstanding magnetic properties. Superparamagnetic iron oxide nanoparticles (SPIONs) are widely used in experimentation for various \textit{in vivo} applications. All biomedical applications require high value of magnetization and the average size of particles should be less than 100 nm. To prepare multifunctional ferrite nanoparticles, sol-gel auto combustion synthesis technique was adopted. It was found that Cd-Ni substitution results in improving the saturation magnetization and reducing the coercivity values favorable for hyperthermia treatment. In this review, we have discussed magnetic parameters with increasing heating potential of nanoparticles.

Keywords

Magnetization, Multifunctional Ferrites, Magnetic Hyperthermia, SPION, Specific Absorption Ratio

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1. Introduction

Material science encompasses numerous disciplines, namely, Physics, Chemistry, Biology and Engineering and, is a real knowledge domain in nature [1]. The evolution of material science is usually an indicator of man's progress. Their urge to enhance the existing and replace the obsolete with novel materials often results in fewer resources. The emergence of nanoscience and engineering science as a leading technology of the 21st century has not solely accelerated the growth of material science, but also opened a new window to technology [2]. Today, nanoscience and engineering science become more substitutable with materials technology. Magnetism and magnetic materials are playing a crucial role in one’s life. The magnetic industry is prepared to surpass the semiconductor industry with the proliferation of the latest gadgets based on magnetic materials and new innovations within the scope of nano-magnetism [3].

Nano-magnetic materials already exist in the applications of data storage, sensing element and device technologies; however more and more emphasis is given on exploring these in the life sciences and drug delivery [4]. So, it's solely stated that magnetism and magnetic materials at the nano regime attract the attention of researchers worldwide. It is used in the latest areas of research like spintronic devices; giant magneto resistance (GMR) based sensors, magnetic random access memories (RAMs) and alternative novel gadgets based on nano-magnetism [5].

Nano-science and engineering are providing us a new perceptive and control of matter at the atomic and molecular scale. Especially, nanoparticles have attracted more attention of researchers and techno habitual people due to their outstanding magnetic, optical and electronic properties [6]. The surprisingly small size range of these particles builds them ideal candidature for nano-engineering of surfaces, a large range of nano-sensors, textile industries, especially defense and security purposes and also the production of functional nanostructures. On the basis of nano-engineering size modifications in nanoparticles (NPs) are intrinsically accessible to use in the field of biomedical applications, such as color contrast agents, for magnetic resonance imaging (MRI) and for targeted drug delivery in tumor therapy [7]. New materials are being designed and developed forever so new characterization methods are endlessly developed. In the development of new advance biomedical devices, the dynamic mechanism of the material magnetization has to be showing enough importance to permit any operations required for the device to work [6]. Slow relaxation of the magnetic nanoparticle is therefore essential.

The superparamagnetic nature of iron oxide nanoparticles (SPIONs) plays an important role in magnetic targeting [8]. The identification of the dynamic mechanism of magnetic
relaxation method is the crucial step for the improvement in particle design with the essential in which blood flow exerts a force on it. External magnetic field targets SPIONs to the specific area to settle down over it [9]. The effect of magnetic field theory depends on various parameters like field strength, magnetic field gradient and latent volume of the SPIONs. Often, the gradient of magnetic field can be generated externally using AC-magnetic field [10].

Iron oxide magnetic nanoparticles are the subject of innovative research because of their versatile applications in an area such as biomedical and diagnostics. In the last three decades, the magnificent area of \textit{in vitro} diagnostics has been increased by advanced applications of nanoparticles [11]. The magnetic nanoparticles need alteration to overcome bacterial activity and increase the biocompatibility before the period of implementation for drug delivery applications.

The objectives of this chapter are four folds. The first objective is to synthesize transition metal substituted multifunctional magnetic iron-based Cd\(_x\)Ni\(_{1-x}\)Fe\(_2\)O\(_4\) (\(x = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0\)) spinel ferrites by the sol-gel process using urea as a catalyst. The second objective is to study the basic principle of magnetic heating mechanism and magnetic parameters to increase heating potential. The third one is to characterize SPIONs. The fourth objective is to explore future applications of magnetic nanoparticles in the medical field.

2. **Synthesis of superparamagnetic iron oxide nanoparticles (SPIONs)**

Advance in synthesis of functional magnetic nanostructured materials has attracted tremendous interest in recent years due to their exciting properties and potential technological application in many fields [12]. The sol-gel technique is a chemical route; it offers good control over molecular homogeneity, elemental composition, powder morphology and uniformly nano-sized metal clusters, which is crucial for enhancing the saturation magnetization, coercivity, electrical conductivity and optical reflectance phenomenon of the nanoparticles. These advantages make the sol-gel method a favorable alternative over other chemical methods for the synthesis of ceramics nanoparticles [13].

When the metallic chemicals or ceramic compounds are dissolved in relevant solvent then this mixture is termed as a \textit{sol}. When this \textit{sol} of the metallic compounds is heated, it converts into viscous semi-liquid termed \textit{gel}, from which conclusively the final powder can be obtained. It is very important to note that the mechanism of getting the final product depends on colloidal discipline in which the metallic cations are suspended in the final viscous liquid solution [14].
2.1 Sol-gel auto combustion technique

The sol-gel auto combustion method is widely used for the synthesis of nanoparticles over the other conventional methods. This technique, however, has low processing temperature, fast reaction time, better control over the grain size and better molecular homogeneity. To synthesize nanoparticles, the following steps are required;

Step (i) – Appropriate amounts of nickel nitrate (Ni(NO₃)₂·6H₂O), iron nitrate (Fe(NO₃)₃·9H₂O), and cadmium nitrate (Cd(NO₃)₂·6H₂O) with Fe : Ni : Cd molar ratios of (2 : 1-x : x) are dissolved into 20 ml. de-ionized water under constant stirring. Urea powder is used as fuel, added in mixed solution of metal nitrates under constant stirring to prepare homogeneous compositions. This solution is often referred to as “precursor” since it is the basis of the following steps that lead to the final powder compound.

Step (ii) - This is an essential step to remove most of the solvent. The aqueous solution of metallic ions is gradually heated at 80 °C for 2 h on a hot plate under constant stirring to convert the solution into rigid brownish color gel. The gel is highly viscous in nature.

Step (iii) - The dry ash was obtained after the gel was heated in the microwave oven at power 800 watts for three minutes. This burnt ash forming compounds were crushed using a mortar and pestle for 6 h to obtain the final product.

Fig. 1 Flow chart to prepare CdₓNi₁₋ₓFe₂O₄ ferrite powder.
Step (iv) - This burnt powder was calcined in a muffle furnace at 800 °C for 4 h. After calcinations, again the powder was crushed for 3 h. The resultant powder is the required nano crystalline ferrite sample which is ready to use for characterization.

3. Theoretical aspects of magnetic relaxation

Magnetic relaxation is a process to generate heat for the treatment of tumors cells. Magnetic particle relaxation adoption was first studied by R Medal et al. in the year 1957 [14] and still researchers have been engaged in the same area. Recently, it has been found that magnetic nanoparticles are more effective in the field of cancer treatment as compared to other radiation therapy [22-24]. A minimum clinical trial required that magnetic nanoclusters should be biodegradable, chemically stable and well dispersed in ionic cellular cytoplasm. Most significant, in biomedical environment they must exhibit excellent superparamagnetic properties [15]; therefore, magnetic behavior of nanoparticles has become the first crucial step in feasible design for in vivo applications. It was found that the magnetic characterizations of magnetic nano-composites are strongly correlated with their thermal dissipative relaxation behavior. The dynamics mechanism of magnetic particles, dispersed in liquid medium in general, involves two fundamental relaxation mechanisms regarding the alignment of the magnetization vector with an applied external magnetic field: Brownian and Néel relaxation [16].

3.1 Brownian relaxation mechanism

The Brownian relaxation occurs by the physical rotation of particles suspended in a fluid in response to an applied magnetic field. The corresponding Brownian relaxation time ($\tau_B$) is given by the following equation,

$$\tau_B = \frac{3V_{hyd}}{k_BT} \eta$$  

A complex magnetic nature expressed by the dynamic response of ferromagnetic nanoparticles suspended in a liquid. This complex magnetic nature varies with a small variable magnetic field with frequency ($\nu$) [17]. Nevertheless, the dynamical susceptibility $\chi(\nu)$ depends upon the particle relaxation mechanism and relaxation times of magnetization [18]. Therefore, the relaxation time $\tau_B$ is experimentally accessible from the frequency ($\nu$) dependant complex magnetic susceptibility of the poly-dispersed ferrofluids system of non- interacting rigid dipoles suspended in a liquid carrier. This term define as Debye terms with specific relaxation time:
\[
\chi(\nu) = \frac{1}{3V\mu_0k_BT} \sum_{i=1}^{N} \frac{m^2}{1-2\pi\nu\tau_B}
\]

Here, ‘\(V\)’ is the average volume of the spherical particles, and ‘\(m\)’ is the giant magnetic moment of single domain particle.

### 3.2 Néel relaxation mechanism

The Néel relaxation of particle is defined as the magnetic vector that may rotate within the particle with regard to relaxation time about crystal axis in the liquid [19].

Néel relaxation time (\(\tau_N\)) is given by the following equation,

\[
\tau_N = \tau_o \exp \left( \frac{\Delta E}{k_BT} \right)
\]

Where, \(\tau_o\) is a constant usually approximated as 10\(^{-9}\) s, and the Néel relaxation time (\(\tau_N\)) varies exponentially with (\(\Delta E\)), the potential energy barrier assuming uniaxial identical non interacting particles.

\[
\Delta E = KV(1 - h)^2
\]

Here, \(h = (H/H_k)\) is the reduced field, \(H\) is the external magnetic field and \(H_k\) is the internal field due to anisotropy. In real ferro-fluids there is always a distribution of energy barriers due to a distribution of the magnetic anisotropy constant \(K\) as well as of the volumes of the magnetic particle cores \(V\).

On the other hand magnetic anisotropy energy displays an influence on thermal energy. If the magnetic anisotropy energy is more with respect to thermal energy (\(K > \Delta E\)) then magnetic dipoles are no longer allowed to perform oscillations. Finally, the Néel relaxation becomes inconsequential. In this limit the MNPs can be considered as rigid particles having constant magnetic moment firmly attach to it. In this rigid dipole model, the torque is created by the magnetic moment due to the external driving magnetic field, which is transferred to the rigid particle. In an oscillating magnetic field, for instance, the MNPs have initiated oscillations with their Néel relaxation and finally will rotate as Brownian [20].

On the basis of relaxation time model, nanoparticles with relaxation time much faster than the measured time are called ‘superparamagnetic nanoparticles’ [21]. Some nanoparticles that do not relax by the Néel relaxation mechanism within the measurement
time period are called ‘blocked particles’ and they do not contribute to the magnetization change within the considered time window.

In the hyperthermia process, when an external magnetic field is applied to the serum then heat energy is generated due to work done by the MNPs with relaxation time. Simultaneously, the generated energy dissipated locally by the magnetic nanoparticles. A high dissipation rate is achieved if both Néel and Brownian relaxations equally contribute [22]. To address the contribution of both relaxations, magnetic moment and particle rotations have to be considered. For that reason, the total effective relaxation time constant ($\tau$) is given by the following equation:

$$\tau = \frac{(\tau_N \tau_B)}{(\tau_N + \tau_B)}$$  \hspace{1cm} (5)

However, such a construction of the arithmetical equation for the fast mechanism appears unbelievable, particularly for colloidal magnetic nanoclusters. An external applied magnetic field, the inter-particle dipole-dipole interactions within a single nanocluster may outcome in an effective moment to physically oscillate the nano-cluster. Even though the Néel relaxation time constant ($\tau_N$) of the cores must be shorter than the Brownian relaxation time constant ($\tau_B$) of the respective nanocluster, it is observed that the Brownian dynamics is always dominant at low frequency region [23].

According to the practical approach of magnetic particles in a fluid, the rotation of the magnetic dipole moment between different easy axes in Néel relaxation and Brownian relaxation have described rotation of entire particles. Fig. 2 shows the Néel rotation Vs. Brownian rotation of magnetic fluid components of the magnetic relaxation mechanism.

In recent years, few researchers discussed several practical and theoretical issues related to important aspects of relaxation time. It is very important to study temperature variation of the nanoparticles suspension during an applied external AC magnetic field, and the different models of fitting the experimental data to extract the nanoparticles heating power. From the study of Rudolf Hergt et al. [24], for particle diameter of 50 nm one may estimate experimental data, calculated anisotropy is about 1.5 J/kg, at frequency of 300 kHz and finally measured heating power of 450 W/g for the full hysteresis loop (100 kA/m). According to O'Grady et al. [25], the time-dependent magnetization of cobalt ferrofluids at 77 K using zero field cooling VSM and observed logarithmic time dependence of magnetization. Determination of relaxation time distribution of the colloidally dispersed nano-owes by Philip B et al. [26], produces distinct peaks in experimentally accessible time duration successively found. The Brownian relaxation is indicated by the peak of large time range, while the other peak of small time range can be
attributed to Néel relaxation. Liquid dispersive solution measurements were carried out on the SPIONs offers fair hydrodynamic size distributions.

![Diagram of Néel rotation Vs. Brownian rotation mechanism of a magnetic fluid. (A) Néel rotation, (B) Brownian rotation.](image)

**Fig. 2** Néel rotation Vs. Brownian rotation mechanism of a magnetic fluid. (A) Néel rotation, (B) Brownian rotation.

![Diagram of energy barrier for the single domain particles and relaxation processes.](image)

**Fig. 3(a)** Representation of energy barrier for the single domain particles, (b). Relaxation processes that influence the heating properties of magnetic nanoparticles.
Cayless et al. [27] reported Néel relaxation measurement in fine particle system at 4.2 K using RF SQUID magnetometer in a time window 60 s and 3600 s. The magnetic relaxation study prevails that ln(t) is collinearly dependent on relaxation for the compounds freeze prior while in samples frozen in zero fields did not show linearity [28]. Bogardus et al. [29] studied the relaxation of ferro-fluid liquid within the time range using a special measurement system.

4. Key role of magnetic parameters to affect heating potential

In magnetism, there is a fundamental dissimilarity between intrinsic and extrinsic properties. Intrinsic properties such as the particle size effect, the magnetocrystalline anisotropy ($K$) and Curie temperature ($T_C$) are realized on atomic length and time scale. They can, in general, be considered as equilibrium properties. While, extrinsic magnetic properties, such as the coercivity ($H_C$), remanence ($M_r$), saturation magnetization ($M_s$) etc. reflect real structural morphology of the magnet. Therefore, for the influence of heating potential, intrinsic and extrinsic parameters are very essential to study.

Here we describe for better understanding and possible improvements in intrinsic as well as extrinsic parameters models on the basis of various magnetic behaviors.

4.1 Intrinsic parameters

In order to develop a relaxation model for the magnetic heating mechanism in the SPIONs, it is a prerequisite to know accurately the intrinsic magnetic parameters of the magnetic nanomaterials such as the particle size effect, magnetocrystalline anisotropy constant and Curie temperature, etc.

4.1.1 Particle size effect

In general study, magnetic hysteresis loss and relaxation loss are two mechanisms that are responsible to dissipated thermal energy in ferro fluid. In primary level, these mechanisms are studied in bulk materials of particles size $\approx 1\mu m$. In practice, particles in bulk form or larger in size affect many biomedical applications and they do not form a stable colloidal as well as very difficult to dispersed within tumors [16, 19]. In addition, inside the body bacterial defense mechanisms may activate due to larger particle size [20].

Hysteresis loss factor increases its utility in particles greater than their critical grain size, which forms strong magnetic behavior within particles, and it shows ferromagnetism. Nano particles of less than 20 nm size show superparamagnetic nature with single domain structure and so hysteresis losses become quickly negligible. Therefore, in this
range, iron oxides particles show both Néel relaxation as well as Brownian relaxation mechanism.

Generally, for Brownian relaxation the most suitable particles range between 10 nm to 100 nm. Brownian relaxation prefers larger size range particles. The Néel relaxation occurs due to magnetic orientation within the magnetic particles therefore it is most significant in the smaller size particles. Nevertheless, without consideration of magnetic anisotropy constant this division cannot occur [30].

The suitable value of the total magnetic anisotropy constant (K) for magnetic nano particles in the range of about 20 kJ/m$^3$, then the MNPs below 7 nm diameter fail to satisfy this condition and can’t generate significant heating. Therefore for Néel relaxation, the dominant mechanism, which is directly, depends upon particle diameter between 7 to 15 nm. Within this range, Néel relaxation carries an exponential dependence on the particles volume (Eq. 1). To generate large thermal energy using the Specific Absorption Ratio (SAR) is extremely sensitive to the dimension of (spherical) nanoparticles.

### 4.1.2 Anisotropy

The magnetic anisotropy is a directional dependent. If the MNPs possess magnetically anisotropic nature then it is very complicated to find magnetization equilibrium. In an anisotropic condition, an easy axis plays a vital role in saturation magnetization. In agreement with the nature of magnetic moments easy axis behavior, one can classify the various anisotropies like magnetically crystalline anisotropy, the shape anisotropy, stress anisotropy, and the exchange anisotropy.

According to anisotropic conditions, when an external magnetic field is applied to the magnetic materials, magnetic dipoles align to the direction of an easy axis within the particles [8]. Its dynamics have anticipated on the basis of classical approximation. It is observed that alignment of micro-spin is greatly influenced by the thermal fluctuations originating from the couples of the spin [5, 9–16]. MNPs dissolved in a viscous liquid. Fig 3(a) shows that the transition takes place between magnetic dipole moment to the easy axis of the MNPs to a state with anisotropic energy dependant free rotation.

The uniaxial anisotropy energy $E (\theta)$ is a simple type of magnetic anisotropy, that helps to identify the combined effects of both surface and volume anisotropy (Eq. (6)):

$$E(\theta) = (K_VV + K_S S) \sin^2 \theta$$

(6)
Where $K_V$ is the volume anisotropic constant, $V$ is volume the particle, $K_S$ is the surface anisotropy constant, $S$ is the particle surface and $\theta$ is the angle between the vector of the particles magnetic moments ‘$m$’ and an anisotropic axis.

In absence of surface anisotropy, magnetic anisotropy energy for volume of the material is given by eq. (7):

$$E(\theta) = (K_V V) Sin^2\theta$$  \hspace{1cm} (7)

In general, an external magnetic field is present, rotation of the individual particle’s magnetic moment has been reached to the orientation corresponding to stability having a minimum energy, requires overcoming an energy barrier, $\Delta E \sim K_V V$. On the basis of magnetic anisotropy, derived from the above equations, one conclude that high oscillations performed by the MNPs that provide large energy dissipation in the given liquid. Fig. 3 (a) shows the dependency of magnetic energy of magnetic particles upon the direction of its magnetization vector [18].

**4.1.3 Curie temperature**

The Curie temperature ($T_c$) is the temperature above which ferromagnetic materials behave as paramagnetic materials with losing permanent magnetic order and the magnetism completely disappears. In hyperthermia treatment, Curie temperature shows a crucial role in the generation of heat within a tumor cell. It is observed that when tumor cells are exposed to a temperature between 42 °C – 47 °C (315 K– 319 K), the cells are destroyed [13-15]. Hence, it is favorable temperature for the nanoparticles which does not exceed this level. In actual practice, it is very difficult to measure the temperature of cells correctly. To overcome this difficulty, we can use the type of nano particles those depend upon Curie temperature. Thus when nanoparticles reached to Curie temperature, they automatically lose their magnetic property itself. Hence, without removing oscillating external magnetic field, heating get stop. Therefore it is called self regulated temperature.

With the aim to improve self regulated hyperthermia treatment, the researchers have responsibility to synthesize new materials and structures of MNPs. Here we have discussed some of the reported research work on controlling ($T_c$) on MNPs. Under the title of ‘self control hyperthermia’ Martirosyan et al. [32] studied theoretically the role of structural parameters and compositions on ($T_c$) of superparamagnetic nano particles. It becomes clear that reducing the particle size might result in a decrease of ($T_c$). It was suggested by Apostova et al. [33] that introducing magnetic nanoparticles in the
ferromagnetic materials result in lower \(T_c\). It witnessed because of reduction of the exchange magnetic interactions between the magnetic ions in the NPs. [33].

### 4.2 Extrinsic parameters

The most important extrinsic properties \(i.e.\) properties not only depend on the compositions, inter-metallic phases and crystal structures, but also depend on production parameters as \(e.g.\) heat treatment, particle size etc., can be evaluated from the full hysteresis loop as a function of temperature. Typical data deduce from a hysteresis loop are not only the saturation magnetization, the remanence magnetization, the coercivity but also the initial magnetization curve after thermal demagnetization.

#### 4.2.1 Saturation magnetization

To carry out systematic information about the magnetic properties of sample, the magnetic hysteresis curve is often recorded till saturation of magnetic moment region [34]. The magnetic saturation \(M_s\) value is a characteristic of magnetic materials. Therefore large \(M_s\) value gives more authority to control magnetic moment of the MNPs. This valuable property of MNPs becomes applicable for treatment of cancer cells using an external magnetic field. On the other hand, \(M_s\) also depends on temperature. It was recorded that, magnetic moment shows fluctuation with change in temperature. For high temperature or above \(T_c\) the magnetic nature of MNPs disappears and shows non-magnetic behavior. To overcome this problem Bloch’s suggested the formula known as Bloch’s law. He examines that on the basis of Bosse - Einstein temperature condensation the variation in \(M_s\) value as the function of temperature is given by [35]:

\[
M_s(T) = M(0) \left[1 - \left(\frac{T}{T_0}\right)^\alpha\right]
\]

(8)

Where, \(T_0\) is the temperature for zero magnetization \((M_s = 0)\) and \(M(0)\) is the \(M_s\) at zero Kelvin. Several studies discussed the temperature dependence of the saturation magnetization in MNPs and reported deviations from Bloch’s law at low temperatures [36].

The Bloch’s law could be due to the magnetic particles interaction, variation of particle size, core cladding interactions and surface disordered that influences the surface anisotropy and asymmetric anisotropy of the particles. Chantrell \textit{et al.} derived a relation for time dependant magnetization of system of nanoparticles after magnetization in the external magnetic field \(H\) for a time \(t\). It was found that saturation magnetization is directly proportioning to log ratio between the sum of \(T_c\) and \(T\) to an absolute temperature
(T), Where (T_c) is the Curie temperate [37]. Finally we conclude that saturation magnetization is one of essential parameter for hyperthermia treatment.

4.2.2 Magnetic coercivity and remanence magnetization

Fig. 4 represents magnetic hysteresis loops of paramagnetic, superparamagnetic and ferromagnetic materials. The nanoparticles with superparamagnetic state having negligible remanence and coercivity possess a huge magnetic moment and appear like a giant paramagnetic atom which responds very quickly to magnetic fields oscillation. The essential condition for hyperthermia application, MNPs possesses high value of saturation magnetization, which results in improving thermal energy dissipation by the MNPs to the tumor cells. The various simulations were conducted by E. Obaidat et al. [38] to establish that the coercivity of given magnetic materials depends on the frequency of external oscillating magnetic field. When the external magnetic field is directed towards anisotropic easy direction with $\phi = 0$, then the results convey good agreement for the coercivity parameter [30]. These results are obtained by the following equation:

$$\mu_0 H_c = \mu_0 H_K \left(1 - K^{1/2}\right)$$

For random orientation case,

$$\mu_0 H_c = 0.48 \mu_0 H_K (1 - k^n)$$

Where, $n = 0.8$ and magnetic coercivity dimensionless parameter ($k$) that includes temperature and takes in to account the comprehensive rate of magnetic field. The various simulations methods studied by T. Nattermann et al. [39] to investigate the dynamic hysteresis area with various temperatures and frequency range [39]. The researcher also deduces suitable formula to calculate the area of the major loops using Stoner-Wolffth based model [16]. It is analytically estimated that the oscillation of whole MNPs with an external applied magnetic field the easy axis was assigned to be fixed [40, 41]. Finally they conclude that, the result is in fair agreement with the Néel relaxation theory.
Fig. 4  Hysteresis loops of paramagnetic, superparamagnetic and ferromagnetic materials.

5. Characterization

The structural analysis of the synthesized samples was carried out using X-ray diffraction (XRD) technique. X-ray diffraction patterns of all samples were recorded at room temperature using X-ray diffractometer (Bruker AXS D8 Advance XRD System, Cu-κα radiation, λ=1.5406 Å). The scanning 2θ range was between 20-80° (scan step of 0.02°). The unit cell parameter was determined using the Cellref software [8] and, the crystallite size was calculated from full width half maxima (FWHM) value of the reflection peak broadening using the Debye-Scherer’s formula, [9]. The IR spectra of all samples were recorded at room temperature in wavenumber range of 400-4000 cm⁻¹ using a FTIR spectrometer (Thermo Nicolet, Avatar 370). Surface morphology was examined using SEM micrographs and an energy dispersive spectroscopy technique (EDX, SEM- JEOL-6100) was used for elemental analysis. The recorded SEM micrographs assist to find out average particle size distribution using histogram curves. The average size of particles was calculated through a statistical analysis performed by counting about 250 particles by assuming spherical geometry. To identify the morphology of materials and to investigate their internal structure, transmission electron pictures were recorded using a TEM (JEOL-100), working at 100 kV and equipped with a high resolution sensitive camera. A vibrating sample magnetometer (Lakeshore VSM 7410) was used to record magnetic hysteresis loops of prepared samples under an applied magnetic field of up to ± 15 kilo Gauss and magnetic parameters were obtained from magnetic hysteresis loops. For hyperthermia treatment, magnetic particles were tested heating potential using a magnetic induction heating instrument.
5.1 Structural analysis

5.1.1 XRD analysis

Phase and structure of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (0.0 $\leq x \leq 1.0$) ferrites were elucidated by X-ray diffraction technique and the obtained XRD patterns are shown in Fig. 5. XRD patterns of NiFe$_2$O$_4$ and CdFe$_2$O$_4$ were well matched with standard JCPDS file numbers 10-0325 and 22-1063 of ferrites. It can be seen that the observed peaks are sharp, reflecting highly crystalline character of the prepared samples. The reflection peaks were indexed as (220), (311), (222), (400), (422), (511), (440), (620) and (533), which are characteristics of single phase cubic spinel structure. XRD analysis confirms formation of cubic spinel phase with space group $Fd\bar{3}m$ (227). It is interesting to note that the XRD peaks shift towards small diffraction angle as shown in Fig. 6. Basically we have just focused on the average shifting of individual peaks of various spectra. We can conclude that (311) prominent peak shows larger shift towards lower diffraction angle. On the basis of Bragg’s Law we conclude that shifting of diffraction peaks with an increase in Cd content (x) may be attributed to larger ionic radii of Cd$^{2+}$(0.97 Å) compared to Ni$^{2+}$ cations (0.69 Å) [33, 34]

![Fig. 5 XRD patterns of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (0.0 $\leq x \leq 1.0$) spinel ferrites](image-url)
Fig. 6 Shifting of (311) peak towards lower 2θ value.

Fig. 7 Reitveld refinement pattern of NiFe$_2$O$_4$ ferrite sample.
Table 1 Structural parameters of CdxNi1-xFe2O4 (0.0 ≤ x ≤ 1.0) ferrite sample.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Molecular weight</th>
<th>Lattice parameter</th>
<th>Bulk density</th>
<th>X-Ray density</th>
<th>Porosity</th>
<th>Particle Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiFe2O4</td>
<td>1162.00</td>
<td>8.3501</td>
<td>3.445</td>
<td>5.349</td>
<td>35.00</td>
<td>12.81</td>
</tr>
<tr>
<td>Cd0.2Ni0.8Fe2O4</td>
<td>1166.34</td>
<td>8.4811</td>
<td>3.280</td>
<td>5.330</td>
<td>33.40</td>
<td>14.10</td>
</tr>
<tr>
<td>Cd0.4Ni0.6Fe2O4</td>
<td>1169.87</td>
<td>8.5183</td>
<td>5.000</td>
<td>5.500</td>
<td>32.10</td>
<td>14.47</td>
</tr>
<tr>
<td>Cd0.6Ni0.4Fe2O4</td>
<td>1173.40</td>
<td>8.6125</td>
<td>3.452</td>
<td>5.550</td>
<td>31.80</td>
<td>19.48</td>
</tr>
<tr>
<td>Cd0.8Ni0.2Fe2O4</td>
<td>1176.94</td>
<td>8.6630</td>
<td>3.375</td>
<td>5.668</td>
<td>30.45</td>
<td>21.66</td>
</tr>
<tr>
<td>CdFe2O4</td>
<td>1180.47</td>
<td>8.7382</td>
<td>3.592</td>
<td>5.733</td>
<td>27.34</td>
<td>23.19</td>
</tr>
</tbody>
</table>

The full width at half-maximum (FWHM) of the strongest XRD peak (311) value was estimated to calculate average crystallite size of this synthesized powder using the Debye-Scherer's formula,

\[ D = \frac{0.9 \lambda}{\beta \cos \theta} \]  

Where \( D_{xrd} \) is crystalline size, \( \lambda \) is denoted as wavelength of Cu-\( k\alpha \) radiation; \( \beta \) is the FWHM and \( \theta \) is the diffraction angle of strongest characteristic peak. Crystalline size \( D_{xrd} \), Lattice constant \( a \), X-ray density \( D_x \) and surface area \( S \) were determined from the XRD patterns and are depicted in Table 1. The typical values of crystalline size were found to be 12.81 – 23.19 nm, which are in good conformity with the reported value by M. Arshad et al. [42]. This indicates that impurity free Cd-Ni ferrites were obtained at 800 °C. Similar results have revered that, in case of Cd-Zn ferrites prepared by soft chemical synthesis method [26], here an increase in the lattice parameter directly affected by the cadmium concentration.

The Rietveld’s refinement pattern of NiFe2O4 ferrite nanoparticles was done using the Full Proof Suit software and obtained pattern is shown in Fig 7. Here, Successive refinement of the structural analysis such as cation distribution, occupancies, particle size and lattice parameter was estimated through the least square method. The peak shape was set as to be pseudo-Voigt with range for calculation of single reflection in the unit of FWHM (full width half maxima) equal to 8. Here the red color lines with dots circles represent an experimental data and a black solid line shows measured intensities. The difference between measured and calculated intensities represented at the bottom by the blue line. The fitness of pattern has been checked for given XRD data. The goodness of fit (GoF) is defined as:
\[ GoF = \frac{R_{wp}}{R_{exp}} \]  

(12)

Where \((R_{wp})\) is the weighted residual error and \((R_{exp})\) is the expected error in the pattern. Refinement has been continually refined until convergence was reached for a low value of \((GoF)\), which was confirmed by the goodness of refinement. We have observed low values of \(GoF\) in between 4.36 to 5.13, which justify the goodness of refinement [43]. The obtain lattice parameter values from the refinement are listed in Table 1. It is observed that the lattice parameter increases with increasing concentration of Cd\(^{2+}\) ions. As pointed out by F S. Tehrani et al. [44], that variation in ionic radii could be attributed due to discrepancy between ionic radii Cd\(^{2+}\) (0.97 Å) and Ni\(^{2+}\) (0.69 Å). In addition to the shift of prominent peak (311) towards small diffraction angle with Cd\(^{2+}\) content \((x)\) may be credited with larger lattice parameter. It is observed that that the XRD analysis of the studied compounds are in good agreement with the Rietveld refinements for the cation distribution reported by S.V.A. Prasad et al. [45].

5.1.2 FTIR analysis

The recorded FTIR spectra at room temperature in the wave number range of 4000-380 cm\(^{-1}\) for the Cd-Ni ferrite samples are shown in Fig. 8. In the IR band, variation in spectrum is usually assigned to vibrations of ions in the crystal [46, 47]. Two main broad cation-oxygen bands are seen in the IR spectra of Cd\(_x\)Ni\(_{1-x}\)Fe\(_2\)O\(_4\) \((x = 0.4 \text{ and } 0.8)\) spinel ferrites between 540-600 \((v_1)\) and 390-450 \((v_2)\). In the present case, the peaks appear at 410 cm\(^{-1}\) and 420.1 cm\(^{-1}\) \((v_2)\) and 579.14 cm\(^{-1}\) and 559.25 cm\(^{-1}\) \((v_1)\) in \(x = 0.4 \text{ and } 0.8\) compositions, respectively [48].

The broad band near 3450 cm\(^{-1}\) corresponds to O-H stretching vibrations ascribed to water molecules present in a sample. Sabale et al. [49] reported an IR spectroscopy study for the application of hyperthermia treatment and agreements with the above mentioned respected band assigned values. The shift in the band positions indicates that the Cd\(^{2+}\) ions have been incorporated in the spinel lattice, which helps the formation of nanocrystalline Cd\(_x\)Ni\(_{1-x}\)Fe\(_2\)O\(_4\) spinel ferrites and shifting of metallic cation from tetrahedral to the octahedral site of Cd\(^{2+}\). The distribution of metallic cations generates a compressive strain between the two sites (A and B sites). This transformation of cation distribution depends on the variation of lattice constant and bond lengths [50].
The variation observed in both $v_1$ and $v_2$ which caused by the perturbation to take place in the Fe$^{3+} - O^{2-}$ bonds by the replacement of ions as shown in Table 3. It is observed that the free energy play a vital role in transformation of cations. Unless their free energy has a minimum rate the migration of ions between the two sites are possible.

5.2 SEM micrographs

Typical FE-SEM images of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ ($x = 0.4$ and $0.8$) samples annealed at 800 °C are shown in Fig.9. It is clear from Fig.9 that formed grains have non homogeneous distribution and an almost non uniform shape in the range of 12 to 40 nm as shown in histogram plot in Fig.10. The FE-SEM micrographs shows that formed grains size are affected by the concentration with increasing grain size listed in Table 1. M. G. Naseri et al. [51] showed that the inter cooperation between magnetic nano particles showed particle clusters area in images. It is also observed that function of calcinations temperature has favorable for grain size agglomeration.
5.3 Elemental analysis by EDX

The element composition of the synthesized $\mathrm{Cd}_x\mathrm{Ni}_{1-x}\mathrm{Fe}_2\mathrm{O}_4$ ($x = 0.4$ and $0.8$) spinel ferrites has been investigated by the energy dispersive X-ray analysis (EDX) and obtained spectra are shown in Fig. 11. The EDX spectra of $\mathrm{Cd}_x\mathrm{Ni}_{1-x}\mathrm{Fe}_2\mathrm{O}_4$ ($x = 0.4$ and $0.8$) confirmed the presence of Cd, Ni, Fe, and O in the sample. For both ($x = 0.4$ and $0.8$) samples, the EDX result shows almost the same ratio of chemicals taken in stoichiometry. The atomic weight percentage of obtained elements are listed in Table 2, for both ($x = 0.4$ and $0.8$) samples found values matched to the expected composition ratio. Actually the measured Fe/Ni atomic ratio was found to be very close to the $\mathrm{Cd}_x\mathrm{Ni}_{1-x}\mathrm{Fe}_2\mathrm{O}_4$ ($x = 0.4$ and $0.8$) compositions [49].
Fig. 11 EDX spectra of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (x = 0.4 and 0.8) spinel ferrites.

Table 2 Atomic and weight percentages.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Weight %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd$<em>x$Ni$</em>{1-x}$Fe$_2$O$_4$</td>
<td>x = 0.4</td>
<td>x = 0.8</td>
</tr>
<tr>
<td>O K</td>
<td>25.55</td>
<td>25.35</td>
</tr>
<tr>
<td>Fe K</td>
<td>43.34</td>
<td>41.34</td>
</tr>
<tr>
<td>Ni L</td>
<td>13.57</td>
<td>05.32</td>
</tr>
<tr>
<td>Cd L</td>
<td>17.55</td>
<td>27.98</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

5.3.1 TEM micrographs and SAED patterns

The TEM micrographs of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (x = 0.4 and 0.8) ferrites are shown in Fig. 12. The TEM images of the samples show agglomerated nanocrystallites of quasi-spherical shape dispersed uniformly over the surface having size ranges approximately between 20 nm to 60 nm. N. Sharma et al. [47] reported that magnetic nanoparticles of ferrites are generally found agglomerated due to the attraction force among magnetic nanoparticles [48]. The observed particle size data from TEM micrographs of mixed Cd-Ni (x = 0.4 and 0.8) ferrites are in fair agreement with the particle size determined from XRD data. For more clarity, the high-resolution electron microscopy (HR-TEM) was used to check crystalline quality by observation. It is clearly observed from the HR-TEM micrographs (Inset of Fig. 12) that a set of parallel fringes across the crystal structure. These uniformity distributed fringes prominently show the symmetric arrangement of lattice places. Finally, we conclude that good formation of spinel polycrystalline structure with proper chemical compositions, without Frenkel defects, such as plane dislocations, point defects, crystalline stacking faults, grain boundary defects such as amorphous outer-shell [48]. The Selected Area Electron Diffraction (SAED) patterns of both (x = 0.4 and 0.8) samples are shown in Fig. 13, indicating that formed Cd-Ni nanocomposites are well
crystallized. No other rings except for the preferred planes are found in SAED pattern. No other rings except for the preferred planes are found in the pattern.

Fig. 12 Transmission Electron Micrographs of $\text{Cd}_x\text{Ni}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.4$ and $0.8$) spinel ferrites.

Fig. 13 Selected area electron diffraction (SAED) patterns of $\text{Cd}_x\text{Ni}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.4$ and $0.8$) spinel ferrites.

5.4 Magnetic properties

The magnetic hysteresis loops of $\text{Cd}_x\text{Ni}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.2$, $0.4$, $0.6$ and $0.8$) nanoparticles were recorded using a vibration sample magnetometer (VSM, Lakeshore 7410) at 300 K under an applied magnetic field up to ± 15 kG. Fig. 14 (a) shows relation between magnetization and applied magnetic field ($M-H$ loops). It can be attributed to the competition of ferromagnetic ions such as $\text{Fe}^{3+}$ and nonmagnetic ions such as $\text{Cd}^{2+}$ ions in the occupancy of the tetrahedral and octahedral sites. Fig. 14 (b) shows the hysteresis
loops up to $H = \pm 1$ kG. As expected, they exhibited superparamagnetic behavior. The variation in the value of the ($H_C$) with Ni$^{2+}$ depends on the concentration and particle size. It can be explained on the basis of domain structure, cation distributions and the anisotropy of the crystals [53]. The narrow loop area of the magnetization curve shows the soft magnetic nature of prepared samples. The values of saturation magnetization ($M_s$), coercivity ($H_c$) were calculated from hysteresis loops and magnetic parameters listed in Table 3. It is clear from Table 3 that saturation magnetization ($M_s$) decreasing with Cd$^{2+}$ contents i.e., the maximum value of ($M_s$) is found in the Cd$_{0.2}$Ni$_{0.8}$Fe$_2$O$_4$ sample. Akash et al. also found similar results in Cd-Zn doped nickel ferrite [53].

![Magnetic hysteresis loops](image)

**Fig. 14 Magnetic hysteresis loops of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (0.2 \leq x \leq 0.8) spinel ferrites.**

**Table 3 Cationic distributions and magnetic parameters of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (x = 0.2, 0.4, 0.6 and 0.8) spinel ferrites.**

<table>
<thead>
<tr>
<th>Cd Content ($x$)</th>
<th>Cation distributions</th>
<th>Crystallite size (nm)</th>
<th>Lattice parameter (Å)</th>
<th>Saturation magnetization (emu/g)</th>
<th>Coercivity (Gauss)</th>
<th>Magnetic moment (Am$^2$)</th>
<th>SQR ($M_r/M_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>(Cd$<em>{0.2}$Fe$</em>{0.8}$)$<em>{oct}$ [Ni$</em>{0.4}$Fe$<em>{1.6}$]$</em>{oct}$</td>
<td>14.10</td>
<td>8.4811</td>
<td>51.70</td>
<td>90.93</td>
<td>2.27</td>
<td>0.0015</td>
</tr>
<tr>
<td>0.4</td>
<td>(Cd$<em>{0.4}$Fe$</em>{0.6}$)$<em>{oct}$ [Ni$</em>{0.3}$Fe$<em>{1.7}$]$</em>{oct}$</td>
<td>14.47</td>
<td>8.5183</td>
<td>48.99</td>
<td>80.62</td>
<td>2.24</td>
<td>0.0016</td>
</tr>
<tr>
<td>0.6</td>
<td>(Cd$<em>{0.6}$Fe$</em>{0.4}$)$<em>{oct}$ [Ni$</em>{0.2}$Fe$<em>{1.8}$]$</em>{oct}$</td>
<td>19.48</td>
<td>8.6125</td>
<td>22.86</td>
<td>56.36</td>
<td>1.089</td>
<td>0.0007</td>
</tr>
<tr>
<td>0.8</td>
<td>(Cd$<em>{0.8}$Fe$</em>{0.2}$)$<em>{oct}$ [Ni$</em>{0.1}$Fe$<em>{1.9}$]$</em>{oct}$</td>
<td>21.66</td>
<td>8.6630</td>
<td>4.90</td>
<td>35.02</td>
<td>0.243</td>
<td>0.0010</td>
</tr>
</tbody>
</table>
The saturation magnetization ($M_s$) of Cd-Ni nanoparticles (at 300K) calculated from magnetic hysteresis loops for $x = 0.2, 0.4, 0.6$ and $0.8$ $M_s$ were found to be 51.7, 48.99, 22.86 and 4.90 emu/g, respectively. These values are less than the corresponding values reported by Karanjkar M. et al. for bulk Cd-Ni ferrites [54]. The nanoparticles revealed almost zero retentivity and low coercivity. The saturation magnetization in magnetic materials depends on combination of several factors as discussed in below sections.

1) Very small particles in the distribution and/or pinning of spins on the surface of the particles,

2) Cation redistributions of metallic ions among octahedral and tetrahedral sites,

3) Canted spins within the sub lattice and,

4) Curie temperature of samples [55].

According to Neel’s ferrimagnetic model, total magnetic moments of nanoparticles basically depends on cations distribution over two sub lattices (tetrahedral (A) site and octahedral (B) site) which have opposite alignments [56]. Therefore, the total magnetic moments ($n_B$) is given as;

$$n_B = M_{oct} - M_{tet}$$ (13)

Where, $M_{oct}$ and $M_{tet}$ are the magnetic moment on octahedral and tetrahedral sites, respectively. According to Neel’s theory the magnetic moment is zero for Cd$^{2+}$, 2 $\mu$B for Ni$^{2+}$ and 5 $\mu$B for Fe$^{3+}$ ions.

Our main objective of present investigation is to study the effect of non magnetic Cd$^{2+}$ substitution on magnetic properties of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ ($x = 0.2, 0.4, 0.6$ and $0.8$) spinel ferrites. Magnetic properties study showed that substitution of Cd$^{2+}$ and replacement of magnetic Ni$^{2+}$ can exhibit supermagnetism. It can be seen from Table 3 that the saturation magnetization of the synthesized nanocrystals has declined continuously with the increase in Cd$^{2+}$ ions. These results agree with FTIR analysis, Reitveld XRD analysis, and cation distributions. In general NiFe$_2$O$_4$ ferrite having mixed spinel structure and CdFe$_2$O$_4$ ferrites having normal spinel structure; where Cd$^{2+}$ ions with zero magnetic moment prefers tetrahedral sites while magnetic Ni$^{2+}$ and Fe$^{3+}$ ions prefer octahedral sites [57].

According to the Reitveld analysis and magnetic study (Table 3), magnetic Ni$^{2+}$ occupied on octahedral site which affects the presence of Fe ions causes transfer of Fe$^{3+}$ ions from octahedral to the tetrahedral site. This increase concentrations of Fe$^{3+}$ ions in tetrahedral
sites hence reduction in magnetization at the octahedral sub-lattice. This induces disorientation in the magnetization of the nanocrystals. This could be explained on the basis of net magnetic spin moment due to two sites interactions. The magnetization of B sub-lattice decreases, while for the A sub-lattice increases with substitution of higher magnetic moment of Fe$^{3+}$ (5 $\mu$B) as compare to Cd$^{2+}$ (0 $\mu$B). Consequently, this results in decrease of the net overall magnetization due to antiferromagnetic coupling. Since magneto crystalline anisotropy affects the coercivity ($H_c$) of magnetic particles. The SQR ($M_r/M_s$) values for all samples are listed in Table 3; all samples possess the SQR < 0.5 confirmed the formation of multi domain structure. Thus these nanoparticles have shown superparamagnetic behavior (at 300 K) [58].

Desai et al. [58], investigated the high field saturating behavior of bulk and nano CdFe$_2$O$_4$ ferrite indicates the presence of two components, (a) superparamagnetic and (b) antiferromagnetic. The Mössbauer spectroscopy investigation of CdFe$_2$O$_4$ showed superparamagnetic behavior. In this study characteristically be described as a transformation from multi-domain to the single-domain structure [25, 38, 78]. MNPs having single domain structure and superparamagnetic characteristics at room temperature are very useful for biomedical applications as targeted drug delivery [41], bio-molecule separation [42] and magnetic resonance imaging systems [43] etc.

6. Heat generation with managing magnetism: specific absorption ratio (SAR)

The specific absorption rate (SAR) or specific loss power (SLP) is defined as the amount of energy dissipated by the MNPs per unit mass of the particles per unit time. Therefore, measurement of specific loss power indicates an estimation of increase in temperature of the NPs in response to the applied magnetic field and hence to simultaneously observe the efficiency of the NPs. There are several physical parameters like the magnetic field strength, the magnetic field gradient, hysteresis squareness ratio and dimensional magnetic properties of the nanoparticles etc. affect effectiveness of therapy [59]. In actual practice, oscillatory magnetic field generates magnetic field gradient and that modifies the main magnetic force exerted on NPs.

6.1 Magnetic hyperthermia measurement by calorimetric method

In order to compare different materials, it is necessary to define a parameter that describes how these materials respond to external AC magnetic fields. As such, most hyperthermia experiments use a parameter called the specific absorption ratio (SAR). The SAR can be described as the absorption of electromagnetic energy per unit mass when exposed to a particular field frequency [60].
The SAR can be mathematically defined as: to evaluate the hyperthermia properties of magnetic nanoparticles, “Calorimetric Effect” is the most commonly adopted method. In this technique, a high frequency AC magnetic field of specific amplitude is applied externally for a specific time interval and finally it raises temperature of the sample as shown in Fig. 15. The magnetic induction heating system consists of water coolant to control external temperature within the coil. A high power radio frequency (200 to 400 KHz) is supplied through helical spring consist of water coolant coil, called as magnetic induction heating system. A fiber optical temperature probe is typically used to measure accurate temperature of the sample holder. A thermally insulated container is used to keep a sample to avoid heat loss to the environment during the measurement, and the heating efficiency can be measure as Specific Loss Power (SLP) is directly calculated from the temperature derivative over time at instant $t = 0$ as,

$$\text{SAR} = \frac{CV_s}{m} \frac{dT}{dt}$$

(14)

Where, ‘$C$’ is defined as the volumetric specific heat capacity of the sample solution, ‘$m$’ is the mass of the given sample, ‘$V_s$’ is the volume of the sample, and ‘$dT/dt$’ is the change in temperature versus time curve’s slope.

In our experiment, 20 mg/ml ferrite concentration was used. From the initial slope of calorimetric method measurement, SAR has been calculated. Fig. 16 represents the magnetic induction heating curves of Cd$_x$Ni$_{1-x}$Fe$_2$O$_4$ (0.0 $\leq x \leq$ 0.8) spinel ferrite samples. It is observed from Fig.16 that that magnetic induction heating curves are not linearly proportional to an applied magnetic field ($H$), in fact initially it increases fast with time and then after some time it increases very slowly. The variation of SAR with field amplitude changes are observed from linear to second order. The staking curves in increasing ordered which may be credited to changing in the composition of ferrofluids [61]. It is very important to note that for superparamagnetic nanoparticles, SAR result is totally depending upon the relaxation process. These processes in ferrofluids are either due to reorientation of the particle’s dipole moment or due to frictional losses. To find the time verses temperature relation, the relaxation time is given as, the Brownian relaxation time:

$$\tau_B = \frac{3V_{hyd}}{k_B \eta}$$

(15)

and, Néel relaxation time,
\[ \tau_N = \tau_0 e^{\frac{KV}{kT}} \]  

(16)

Where \((\eta)\) is the viscosity of carrier liquid solution, \((r)\) is the hydrodynamic radius of particle, \((k)\) is the Boltzmann’s constant, \((\tau_0)\) is the time constant, \(10^{-9}\) second, \((V)\) is the particle volume, and \((K)\) is the anisotropy constant. The specific loss power \((P)\) corresponding to relaxation i.e. Néel and Brownian and is approximately given by,

\[ P = \frac{(mH\omega\tau)^2}{[2\pi kT\rho V(1+\omega^2\tau^2)]} \]  

(17)

Where, \((m)\) is the particle magnetic moment, \((\omega)\) is the angular frequency, \((H)\) is the AC field amplitude and, \((\rho)\) is the density of the ferrite. At the resonant condition, \(P\) will reach maximum when, \(\omega\tau = 10^5\). In our experimental system given particle size in the range of 10 – 40 nm and an applied AC magnetic frequency \(f = 300\) kHz. Therefore the contribution due to Brownian losses is very small as also confirmed by the polyacrylic gel experiment investigated by Thiesen \textit{et al.} [62]. If the relaxation time depends on volume of sample \((V)\) and anisotropic constant \((K)\) then total loss factor contributed by Néel relaxation in given SAR value [62].

Here, the particle size is obtained from XRD calculation and magnetic moment values are from VSM measurement (Table 3). If we look out over the varying particle size with \(\text{Cd}^{2+}\) concentration \((x)\) then the variation of power factor \((P)\) follows the magnetic dipole moment. The variation of power factor with \(\text{Cd}^{2+}\) content \((x)\) should be the same as magnetic moment until the anisotropy constant \((K)\) does not change with \(\text{Cd}^{2+}\) concentration. The magnetic heating induction graphs (Fig. 16) show the rapid drop of SAR value around \(x = 0.8\) may be due to variation in anisotropy \((K)\) with \(\text{Cd}^{2+}\) concentration \((x)\) are analogous to the results obtained by Penoyer for the variation of \((K)\) with \(\text{Mn} – \text{concentration}\). The SAR value shows the variation in magnetization and anisotropy together with different compositions. It is interesting to note that SAR is enhanced by 20 % in \(\text{Cd}_x\text{Ni}_{1-x}\text{Fe}_2\text{O}_4 (x = 0.0)\) compared to \(\text{Fe}_3\text{O}_4\) [63].
Fig. 15 Schematic diagram of the calorimetric method used to evaluate the heating efficiency of magnetic nanoparticles.

Fig. 16 Magnetic induction heating curves of $\text{Cd}_x\text{Ni}_{1-x}\text{Fe}_2\text{O}_4$ ($0.0 \leq x \leq 0.8$) spinel ferrite samples.

7. Applications of magnetic nanoparticles in medical field

Magnetic nanoparticles (MNP’s) are exhaustively used in many biomedical applications such as targeted drug delivery as internal and external magnetism can be allied to the
target, magnetic contrast agent can be introduced in forming the images by magnetic resonator.

7.1 Hyperthermia using magnetic nanoparticles

There is no involvement of any drug in this type of approach to treating cancer cells; rather heat is induced in MNP’s under the influence of external applied magnetic field. This type of approaches destroys the cancer cells as they are temperature sensitive. The general principle involved in hyperthermia is specific selection of tumor body part for selecting nanostructure targeting agents influenced by external magnetic AC-field, to increases the temperature to above 40 °C emanating tumor dissemination [79].

7.2 Drug delivery

Drug delivery means spreading targeted drugs in proximity to tumor. Various materials are developed for different targets such as dendrimers, plasmon nanoparticles, liposomes, polymer capsules, micelles etc. [64-70]. In totality MNP’s are not at par above its counterpart. MNP’s can be guided using an external applied magnetic field in addition to diverging drugs at the infected site and the whole process can be recorded using magnetic resonance imaging (MRI) technique [71-72].

7.3 Targeting multifunctional carriers

The number of analeptic structures can be attached to the magnetic nanoparticles. While performing delivery to the target magnetic behaviors of nanoparticles provide journey through MRI [55].

7.4 MRI contrast agents

Superparamagnetic nanoparticles are used as contrast agent in MRI. Darkening of weight images is an outcome prime spin-spine relaxation time ($T_2$) of protons in the water in presence of external magnetic field.

7.5 Cardiovascular disease imaging

The composition of nanoparticles by plaques [11, 16] has been helpless to record the lesion-prone arterial sites. The clinical reports on MRI using SPION’s are found to be helpful in calculating the risk of acute chlorosis [74-75] from VCAM-1 targeted peptide series, the specific binding of nanoparticles and MRI contrast showed an enhancement of lesion in mice as well human carotid arteries patches [76-77]. In MRI, as contrast agents magnetic nanoparticles have been proposed for several clinical applications in
cardiovascular medicine including myocardial injury, atherosclerosis and, another vascular disease [72-73].

7.6 Molecular imaging

All molecular and cellular MRI techniques seemed to be non-invasive in vivo characterization and quantify biological process [75]. Molecular imaging allowed highly sensitive and to the point monitoring targets and their active response in carcinogenesis. MRI of micro phase in lymph nodes MNP’s, allowed to record at millimeter level resolution in meta-stables in non-enlarged lymph nodes [14], which is out of reach of detection by other imaging process.

7.7 Conventional chemotherapeutic agents

Conventional drug line doxorubicin and methotrexate etc. can also be encapsulated in MNP’s for treatment in rheumatiod arthritis, breast tumor and malignant posted cancers. The drug loading capacities and its release profile can now be designed and monitored by fixing structural and chemical bonding with the nanoparticles.

8. Limitations of SPIONs for drug delivery

Every new technique had faced various challenges, as well some limitations in actual practice. The challenges associated with the exploitation of magnetic nanoparticles for biomedical treatment as obtain control over in vivo behavior and effects of penetration of the external magnetic field deep into the body. The drug delivery applications contain as part of (i) improving biocompatibility with human body, (ii) achieving control over bio-elimination, (iii) improving drugs targeting on specific body parts, (iv) reduce the polydispersity of the nano particles in body parts.

The difficulties in drug delivery administration is systematic distribution of therapeutic drugs, lack of specific drug availability towards pathological sides, a specific concentration of drugs, non-toxicity and any advance side effect.

Conclusions

Cadmium doped spinel ferrites with composition Cd\textsubscript{x}Ni\textsubscript{1-x}Fe\textsubscript{2}O\textsubscript{4} (x = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0) were synthesized using the sol-gel process. The structural and magnetic parameters were studied; lattice parameter and crystallite size were found to increase, whereas saturation magnetization values were observed to decrease with cadmium substitution. The magnetic analysis of x = 0.2, 0.4, 0.6, 0.8 compositions show that formed ferrites are magnetically soft and possess multi-domain structure.
References


