# Synthesis, Characterization and Magnetic Study of PEG-Coated Magnetite (Fe<sub>3</sub>O<sub>4</sub>) Nanoparticles

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#### Abstract

The chemical co-precipitation process was used to synthesize the magnetite Fe<sub>3</sub>O<sub>4</sub> nanoparticles and different quantities of biocompatible polymer polyethylene glycol (PEG) were effectively used to coat the nanoparticles. The x-ray diffraction (XRD) patterns of PEG coated and uncoated Fe<sub>3</sub>O<sub>4</sub> nanoparticles demonstrated the good crystalline nature of the particles. With the use of Fourier transform infrared (FTIR) spectroscopy, the presence of the PEG layer on Fe<sub>3</sub>O<sub>4</sub> was established. Transmission electron microscopy (TEM) pictures demonstrated that, despite occasional agglomeration, the morphology of magnetite Fe<sub>3</sub>O<sub>4</sub> nanoparticles is spherical with uniform grain size and high dispersibility. PEG can be used to minimize the particle size and the agglomeration. The Vibrating Sample Magnetometer (VSM) data illustrates how PEG bonding at the magnetic nanoparticle surface affects the reduction of Fe<sub>3</sub>O<sub>4</sub> nanoparticles with controllable magnetic properties and an advantageous size show great promise for biosensor applications.

#### 1. Introduction:

Due to their biocompatibility and usage in MRI contrast enhancement, magnetic iron oxide NPs, particularly magnetite (Fe<sub>3</sub>O<sub>4</sub>) and maghemite (-Fe<sub>2</sub>O<sub>3</sub>), have drawn a lot of attention [1-8] such as in tissue repair, immunoassay, biological fluid detoxification, hyperthermia, targeted drug administration, cell separation, and more. This has led to the current availability of various iron oxide NP-based commercial solutions for human diagnostics. However, the rising use of magnetite NPs may come with hazards and harmful consequences, especially if they are utilized without being properly characterized as biological agents. It has long been understood that excess iron in the human body might contribute to the development of cancer. The production of reactive oxygen species (ROS), which can directly harm DNA, proteins, or lipid molecules, has also been linked to the presence of iron. Despite the fact that iron oxide nanoparticles (NPs) are often well tolerated in living things, the right surface modification, particle size,

and core-ligand composition can have a significant impact on how the body reacts. For these reasons, biocompatible polymer molecules (like polyvinyl alcohol, dextran, etc.) are typically used to surfacemodify or coat magnetite nanoparticles (NPs) [9-11]. This improves the NPs' colloidal stability in physiological media, lowers their toxicity, and significantly lengthens the blood circulation half-life by reducing protein absorption on the NP surface.

Particularly long polymeric chain polyethylene glycols (PEGs), which are highly water-soluble and largely nontoxic, have found important uses in the structure stabilization and distribution of therapeutic biological molecules, which is crucial in the field of drug development [12-14]. Therefore, it would be crucial to create any method for a quick and efficient method for the manufacture of PEG coated iron oxide NPs. The PEG-based modifications of magnetic NPs have been subject to a wide variety of coating techniques, but the synthesis pathway has remained more or less complex up to this point and necessitated the employment of particular atmospheric conditions. As an illustration, various functionalization of PEG with the carboxylic acid, poly (TMSMA-r-PEGMA), or folate receptor have been described as effective surface modifiers, where the employment of strict reaction conditions as well as a nitrogen atmosphere is a crucial necessity. There is other literature describing the synthesis of PEGcoated magnetite nanoparticles at reflux temperatures (over 200 °C). On the other hand, the surface modification process described in this study can be carried out in water at ambient temperature and without necessitating any strict conditions. It is well known that bigger NPs with a diameter larger than 200 nm circulate quickly. In contrast, very small NPs (with a diameter much below 10 nm) are eliminated from the body's systems very fast by renal clearance. In order to have the greatest stability and the longest possible circulation period, a size between 10 and 200 nm should be the ideal. In fact, it has been demonstrated in the literature that NPs with a diameter below 150 nm can be administered intravenously without risk [15, 16].

In this paper, we report the coating of PEG of different molecular weights (1500, 4000, 10000 and 20000; represented as PEG1.5K, PEG4K, PEG10K and PEG20K, respectively, in the text) on Fe<sub>3</sub>O<sub>4</sub> NPs of average size  $8 \pm 2$  nm using sonication as the sole peptizing technique with high level of monodispersity keeping the hydrodynamic radii in the range of ~70–140 nm in aqueous medium. We adopted sonication as a cost-effective substitute for other time-consuming preparation methods because it has been widely employed to create innovative materials. It is observed from the figure that FC and ZFC magnetization curves are split below the block temperature [(TB), the transformation temperature from ferromagnetism to superparamagnetisam)].

## 2. Experimental Section

#### 2.1. Materials

All of the PEG polymers and ferric chloride hexahydrate (FeCl<sub>3</sub>.6H<sub>2</sub>O) were purchased from Sigma-Aldrich in the United States. We bought ferrous sulphate heptahydrate (FeSO<sub>4</sub>.7H<sub>2</sub>O) from MERCK in India. Pellets of NaOH were purchased from the Sisco Research laboratory in India.

#### 2.2. Synthesis of the Bare and PEG-Coated Magnetic NPs:

PEG-coated NPs were created using a straight-forward two-step co-precipitation method. Under nitrogen protection, FeSO<sub>4</sub>.7H<sub>2</sub>O and FeCl<sub>3</sub>.4H<sub>2</sub>O were first dissolved in water at molar ratios of 1:2. The resulting deep orange mixture was swirled at 60°C for 30 minutes. The aforementioned heated solution was then gradually mixed with a 25% aqueous NaOH solution while being added in dropwise fashion over a tenminute period. It was discovered that particle production causes an instantaneous colour change from dark orange to black. After another 30 minutes of stirring, the mixture was cooled to room temperature. Magnetic decantation was used to get rid of the solvent. To remove any remaining salts employed during the co-precipitation from the iron dispersion, the particles were washed numerous times with water. To acquire the magnetically decanted magnetite NPs, the final supernatant was taken.

The above-mentioned wet magnetic NPs were then combined with a 40 to 50% (w/v) aqueous solution of PEG of the desired molecular weight (PEG1.5K, PEG4K, PEG10K, and PEG20K), and then sonicated for 1.5 min. at room temperature with an ultrasonic probe (3 pulses of 30 s each, operated between 3 and 5 W). The solid product was rinsed with water to remove unreacted PEG by magnetic separation after the supernatant was removed by centrifugation at 10,000 rpm. The finished product was then dried for several hours at room temperature. The coated NPs will be referred to throughout the text as PEG1.5K-NPs, PEG4K-NPs, PEG10K-NPs, and PEG20K-NPs, for PEG1.5K, -4K, -10K, and -20K coating, respectively. A comparable approach without the PEG addition step was used to prepare bare NPs without any PEG stabilization for comparison.

#### 2.3. Characterizations:

Using CuK $\alpha$  ( $\lambda = 1.5406$  Å) radiation and a Rigaku Smart Lab X-ray diffractometer running at 9 kW (200 mA X 45 kV), the solid powders' X-ray diffraction patterns were captured. A NETZSCH 409 C thermal analyzer was used to perform TG/DTA tests on the solid samples. Samples were put into an alumina crucible and heated to between 40 and 600 °C at a rate of 5 °C per minute. A Nicolet 380 FTIR spectrometer was used to record the FTIR spectra of the solid samples using the KBr pellet method.

Using a Tecnai G2 30ST (FEI) running at 300 kV, measurements of the transmission electron microscopic (TEM) type were performed. A copper grid covered in carbon was treated with tiny droplets

of a water-ethanol solution (1:9 v/v) containing the least quantity of solid material. The grid was dried for two to three hours in an air oven at 40  $^{\circ}$ C before the TEM testing. The magnetic characteristics of the solid materials were evaluated using a Lakeshore-7407 vibrating sample magnetometer (VSM).

## 3. Results and Discussions:

#### 3.1. General:

PEG-coated Fe<sub>3</sub>O<sub>4</sub> NPs samples are darkbrown hygroscopic solids, and are readily dispersible in water to form stable and monodisperse solutions as confirmed by DLS measurements. The fact that bare Fe<sub>3</sub>O<sub>4</sub> NPs are entirely insoluble in water indicates that PEG coating is the reason of this finding in this particular instance [17-24]. The scattered particles' hydrodynamic sizes were discovered to be between 70 and 140 nm. Up to 30 days, the size of the particles remained monodispersed (single DLS peak) without any discernible precipitation. This demonstrates the extremely stable properties of the PEG coated NPs in dispersions, which is advantageous for biological research where the NPs must be stable in aqueous media for extended periods of time. At normal temperature, NPs with PEG coats of various molecular weights, have demonstrated magnetic properties. When a piece of magnet is placed next to the powdered samples, they are discovered to be easily attracted to it. The aqueous solutions exhibit magnetic response in a room as well as the particles is drawn to the magnet from a temperature, a uniform aqueous dispersion.



Fig. 1. Change in hydrodynamic diameter for the PEG coated NPs in aqueous medium with respect to time (as measured by DLS). The molecular weights of PEGs are mentioned in the corresponding sample names. The error bars are calculated using three independent measurements. The particle sizes appeared to be almost unchanged up to 30 days in the dispersions.

#### **3.2. X-ray Diffraction Studies:**

To determine the crystal phases that were present in the samples, the dried powder samples of uncoated and PEG-coated NPs were subjected to XRD examinations. The XRD pattern of an example PEG-coated Fe<sub>3</sub>O<sub>4</sub> sample (PEG10K-NPs) is shown in Fig.5.2, together with uncoated Fe<sub>3</sub>O<sub>4</sub> NPs (Fig. 2, curve b), and free PEG10K (Figure 2A, curve c). The PEG10K-NPs pattern (Figure 2A, curve a) displayed all of the key peaks associated with Fe<sub>3</sub>O<sub>4</sub>. As seen in the case of bare NPs (Fig. 2, curve b), the  $2\theta = 30.1$ , 35.5, 43.2, 57.2, 62.7, and 74.3 can be allocated to the Fe<sub>3</sub>O<sub>4</sub> (JCPDS#190629)'s (220), (311), (400), (511), (440), and (533) planes, respectively [25]. In the case of the PEG10K-NP, several tiny peaks caused by the PEG polymer are seen together with one prominent peak at  $2\theta = 23^{\circ}$  (Fig. 2, curve a). This outcome validated the PEG surface modification of the Fe<sub>3</sub>O<sub>4</sub> NPs.



Fig. 2 XRD patterns of PEG10K-NPs (a), bare Fe<sub>3</sub>O<sub>4</sub> NPs (b) and PEG10K (c)

#### **3.3. FTIR Measurements:**

To know about the modification of the NPs by the PEG molecules FTIR spectra were performed as solids dispersed in KBr matrix. The spectra of bare Fe<sub>3</sub>O<sub>4</sub>, free PEG20K and PEG20K-NPs are shown in Fig. 3. The bare Fe<sub>3</sub>O<sub>4</sub> NPs showed characteristicbands related to the Fe–O vibrations near 618 cm<sup>-1</sup> (shoulder) and 569 cm<sup>-1</sup> (Fig. 3, curve a). Similar peaks have been observed in the spectra of the PEG20KNPs (at 633 cm<sup>-1</sup> and 569 cm<sup>-1</sup>; Fig. 3, curve c), but not observed in that of solid PEG20K (Fig. 3, curve b). Apart from that, a broad –O–H stretch around 3450 cm<sup>-1</sup>, a sharp –C–H stretch around 2885 cm<sup>-1</sup> and a sharp



-C-O stretch around 1105 cm<sup>-1</sup> are observed in both PEG and the PEG coated NPs (Fig. 3, curves b, c), revealing the presence of PEG residue in the final product [26, 27]. However, these peaks are not observed in the spectrum of bare Fe<sub>3</sub>O<sub>4</sub> NPs. These results clearly showed surface modification of Fe<sub>3</sub>O<sub>4</sub> NPs with PEG.



Fig. 3 FT-IR spectra of the bare NPs (a), PEG20K (b) and PEG20KNPs (c). The characteristic Fe–O stretching is shown by arrows. Y axes have been shifted for clarity

#### 3.4. TG/DTA Measurements:

The results of the thermal analysis experiments have further confirmed the presence of the PEG polymer in the finished product. Fig. 4 depicts exemplary thermogravimetry (TG) curves for two PEG-coated samples, PEG20K-NPs and PEG4K-NPs, as well as one differential thermal analysis (DTA) curve for PEG4K-NPs. PEG4K-NPs and PEG20K-NPs' TG curves [Fig. 4 (a) and (b)] demonstrates a slight endothermic weight loss of 1% within the first 125 °C. The loss of the water molecules can be connected to this. The thermal conversion of Fe<sub>3</sub>O<sub>4</sub> to  $\gamma$  Fe<sub>2</sub>O<sub>3</sub> may be responsible for the subsequent slight weight gain (1%) in the temperature range of 125–155 °C (this area of the TG curves is shown in the inset with magnified scale).



Due to the increase in oxygen content during the thermal transformation of Fe<sub>3</sub>O<sub>4</sub> into Fe<sub>2</sub>O<sub>3</sub> (2Fe<sub>3</sub>O<sub>4</sub> $\rightarrow$  3 $\gamma$  Fe<sub>2</sub>O<sub>3</sub>), this slight weight rise in the result can be substantiated [28, 29]. The DTA of PEG4K-NPs displays measurements with TG/DTA for this conversion. The results of the thermal analysis investigations have added to the evidence that the finished product contains PEG polymer. Thermogravimetry (TG) is a differential thermal analysis (DTA) curve of PEG20K-NPs and PEG4K-NPs curves, two PEG coated samples, and PEG4K-NPs are shown as examples in Fig. 4. The TG curves of PEG4K-NPs and PEG20K-NPs demonstrate a small endothermic weight loss of 1% within the first 125 °C [Figs. 4 (a) and (b)].



Fig. 4 Thermal studies showing the TG curves for PEG4K-NPs (a), PEG20K-NPs (b); and DTA curve of PEG4K-NPs (c). Inset shows the mass loss of a and b in expanded scale in the temperature range 40–200 °C. The % mass losses are consistent with the molecular weight of the PEG molecule.

#### 3.5. TEM study:

To discover the specifics of the structure, (TEM) was carried out on both the PEG-coated and bare NPs. The low-resolution images of naked  $Fe_3O_4$  nanoparticles demonstrate the presence of spherical NPs that are around 8–10 nm in size. Clear lattice fringes related to magnetite ( $Fe_3O_4$ ) can be seen in the associated high-resolution image. SAED pattern support the existence of ( $Fe_3O_4$ ).

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Fig. 5 TEM of PEG4K-NPs showing (a) bright-field image, (b) HRTEM of the circled part of (a) and (c) SAED pattern

Figs. 5.(a)–(c) display TEM images of PEG coated sample (PEG4K-NPs). The low-resolution bright field image [Fig. 5 (a)] revealed that the PEG-encapsulated NPs are primarily spherical and have an average size of around 8 nm, which is comparable to bare NPs. However, huge PEG encapsulations contain a variety of NP numbers as the core. It appears that the magnetic attraction between a number of NPs keeps them together as aggregates to form the cores. The lattice fringes on the particles and the surroundings, along with the thick PEG encapsulation, make it challenging to obtain a high-resolution image of each individual NP. The high resolution TEM does allow for the identification of one primary crystal plane for both magnetite (220) and PEG, which is indicated in Fig. 5. The copper grid used for TEM research is where the Cu peaks are found. It appears that the magnetic attraction between a numbers of NPs keeps them together as aggregates to form the cores. The lattice fringes on the particles and the surroundings, along with the thick PEG encapsulation, make it challenging to obtain a high-resolution image of each individual NP. The high resolution TEM does allow for the identification of one primary crystal plane for both magnetite (220) and PEG, which is indicated in Fig. 5 (b). The SAED pattern [Fig. 5 (c)] is complicated with large number of spots indicating aggregations in various places. Although most of the rings/spots from Fe<sub>3</sub>O<sub>4</sub> could be identified, identifications of PEG could not be achieved from the SAED because the strongest PEG line appears closer to the central bright zone of SAED [Fig. 5(c)].

#### 3.6. Magnetic Response Study:

Themagnetic field vs moment (M–H) measurements of the solid samples are performed at both 300 K (room temperature) and 80 K with the magnetic field swept back and forth between +20 and -20 kOe. The saturation magnetic moments obtained are 50 and 43 emu g<sup>-1</sup> at 300 K and 60 and 46 emu g<sup>-1</sup> at 80 K, for PEG4K-NPs and PEG20K-NPs respectively, as shown in the Fig. 6. However, the saturation magnetic moment values for the bare NPs are found to be 140 and 160 emu g<sup>-1</sup> at 300 and 80 K, respectively. It is well known that any change in NPs' magnetic properties is principally influenced by two key variables: (i) size change and (ii) surface state change [30-34]. The differences in the magnetic characteristics can be attributed to the surface alterations by big PEG polymer molecules since no appreciable size change has been caused by the PEG coating. The temperature dependence of the magnetization for the PEG4K-NPs and PEG20K-NPs field-cooled (FC) and zero-field-cooled (ZFC) curves is depicted in the bottom inset of Fig. 6.



Fig. 6. Magnetization response with increasing and decreasing applied magnetic field for PEG-coated NPs at 300 K. Top and bottom insets show the hysteresis loops at 80 K and the FC/ZFC curves with increasing temperature

The fact that the TB is higher than room temperature in all of our samples—approximately 351 K for PEG4K-NPs and PEG20K-NPs and 362 K for bare  $Fe_3O_4$  NPs—further supports the explanation for the NPs' ferromagnetism at ambient temperature. From the perspective of the TB, it is also possible to assert that the magnetic properties of coated NPs have softened relative to naked NPs. In comparison to naked  $Fe_3O_4$  NPs, the PEG coated NPs can be thought of as fairly soft magnetic materials and may find useful applications in the biological investigations, as soft magnetic materials are very relevant in the biomedical fields [35].

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### 4. Conclusion

Here, we present a quick and simple environmentally friendly synthetic method for making  $Fe_3O_4$  nanoparticles coated with PEG molecules of various molecular weights. The moderately soft magnetic nature of the highly water dispersible coated NPs with appropriate hydrodynamic radii at room temperature may be a crucial characteristic for their usage as biomedically significant magnetic materials. These NPs are stable in aqueous medium. When working with magnetic NPs in biological systems, where the protection of biomolecules from the toxicity produced by the magnetic NPs would be important, this may very well be a protective measure to be adopted.

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