KSÜ Mühendislik Bilimleri Dergisi, 29(3), 2026
Araştırma Makalesi

KSU J Eng Sci, 29(3), 2026
Research Article

Kahramanmaras Sutcu Imam University
Journal of Engineering Sciences

Geliş Tarihi : 25.02.2026
Kabul Tarihi : 26.06.2026

Received Date : 25.02.2026
Accepted Date : 26.06.2026

PREPARATION OF FLOWER-SHAPED IRON OXIDE NANOPARTICLES VIA POLYOL METHOD

POLİOL YÖNTEMİYLE ÇIÇEK ŞEKLİNDE DEMİR OKSİT NANOPARÇACIKLARININ HAZIRLANMASI

Yeliz AKPINAR [1,2*] (ORCID: 0000 - 0001-7321-1421)
N.Tülün GÜRAY[3] (ORCID: 0000-0003-4572-1429)
Mürvet VOLKAN [2] (ORCID: 0000-0001-5112-9486)

[1] Kırşehir Ahi Evran University, Faculty of Arts and Science, Department of Chemistry, Kırşehir, Türkiye
[2] Middle East Technical University, Department of Chemistry, Ankara, Türkiye
[3] Middle East Technical University, Department of Biological Science, Ankara, Türkiye

*Sorumlu Yazar / Corresponding Author: Yeliz AKPINAR, yeliz.akpinar@hotmail.com

ABSTRACT

The development of nanotechnology has played a key role in shaping materials science over the past century by enabling the identification, characterization, and processing of matter at the atomic level. These advancements are extending human life expectancy and improving quality of life in fields such as healthcare and technology. Nanomaterials are generally defined as structures in the 1–100 nm size range, and nanoparticles constitute an important class of these materials. Magnetic nanoparticles play critical roles, particularly in biomedical applications (such as targeted drug delivery and magnetic hyperthermia), due to their unique magnetic properties. Iron oxide nanoparticles with different crystal structures, such as magnetite, maghemite, and hematite, can be synthesized via wet-chemical methods. Since the crystal structures, shapes, and sizes of such nanoparticles directly affect their magnetic properties, they must be designed to suit their intended application. In this study, flower-shaped maghemite nanoparticles with an average size of 13.5 ± 3.6 nm were synthesized via the polyol method for use in magnetic hyperthermia therapy, a future research project. Optimization studies were conducted throughout the process, and TEM, XRD, and VSM methods were utilized for characterization.

Keywords: Magnetic nanoparticles, nanotechnology, polyol method.

ÖZET

Nanoteknolojinin gelişimi, maddenin atomik seviyede tanımlanmasını, karakterize edilmesini ve işlenmesini sağlayarak malzeme biliminin son yüzyıla damgasını vurmasında etkili olmuştur. Bu gelişmeler; sağlık ve teknoloji gibi alanlarda insan ömrünü uzatmakta ve yaşam kalitesini artırmaktadır. Nanomalzemeler genellikle 1-100 nm boyut aralığındaki yapılar olarak tanımlanır ve nanoparçacıklar bu malzemelerin önemli bir sınıfını oluşturur. Manyetik nanoparçacıklar, benzersiz manyetik özellikleri sayesinde özellikle biyomedikal uygulamalarda (hedefli ilaç salımı ve manyetik hipertermi gibi) kritik roller üstlenir. Magnetit, maghemit ve hematit gibi farklı kristal yapılarına sahip demir oksit nanoparçacıkları, ıslak kimya yöntemleriyle sentezlenebilmektedir. Bu tür nanoparçacıkların kristal yapıları, şekil ve boyutları manyetik özelliklerini doğrudan etkilediğinden, kullanım amacına uygun olarak tasarlanmaları gerekir. Bu çalışmada; gelecekte çalışılması planlanan manyetik hipertermi tedavisinde kullanılmak üzere, 13.5 ± 3.6 nm ortalama boyutta, çiçek formunda maghemit nanoparçacıkları poliol yöntemiyle sentezlenmiştir. Süreç boyunca optimizasyon çalışmaları yürütülmüş; karakterizasyon amacıyla TEM, XRD ve VSM yöntemlerinden yararlanılmıştır.

Anahtar Kelimeler: Manyetik nanoparçacık, nanoteknoloji, poliol metodu

This work is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0).

INTRODUCTION

Nanotechnology is an innovative approach that enables the creation and examination of materials at the molecular scale. This methodology has elucidated the complexities of nature across various domains, including energy, environment, health, and electronics. Nanodevices and nanocomposite materials developed via nanotechnology improve quality of life and longevity, thereby fostering the expansion and advancement of nanotechnology (Jyoti Rajput & Kashish Saroj, 2025). Over the past 50 years, polymers, ceramics, metals, and metal compounds, including oxides and sulfides, have been used to fabricate nanomaterials for biological applications (Atik et al., 2025; Durmuş, 2024).

Nanoparticles are structures with dimensions below 100 nanometers in at least one dimension. Magnetic nanoparticles comprise pure metals, including cobalt, nickel, manganese, and iron, as well as their oxides or composites. Iron oxide nanoparticles are used for many purposes, including biomedical applications and catalysts (Ayranpınar et al., 2023).

Iron oxide nanoparticles, as minerals, occur naturally. There are multiple types of iron oxide nanoparticles, each exhibiting distinct magnetic and structural properties. The primary forms are hematite, magnetite, and maghemite. Their crystal structure consists of closely packed planes of oxygen anions with iron cations occupying octahedral or tetrahedral interstitial positions (Yousif et al., 2023). Hematite, α-Fe_2O_3, is the most recognized iron oxide and the predominant polymorph found naturally in minerals, commonly appearing in rocks and soils. It is an oxide exhibiting weak ferromagnetic or antiferromagnetic properties at ambient temperature. α-Fe_2O_3 possesses a corundum-type rhombohedral structure (Baabu et al., 2022). For this reason, this type could not be used for applications concerning magnetic properties. Another type, magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), are the most popular iron oxide nanoparticles for nanotechnology applications. Both have a spinel-type crystal structure with a face-centered cubic unit cell, but they differ greatly in their sub-lattice stoichiometry and cation distribution. In the inverse spinel structure of magnetite, Fe(III) ions randomly occupy the tetrahedral and octahedral sites, while Fe(II) ions are restricted to the octahedral sites only. On the other hand, the thermally unstable maghemite phase contains structural vacancies in its cation sublattice, with only two-thirds of the available sites occupied by Fe(III) ions. The vacancy pattern allows for a highly ordered configuration with a repeating sequence of two occupied sites followed by one vacant site (Coduri et al., 2020; Teja & Koh, 2009).

The synthesis technique for magnetic nanoparticles is crucial for their magnetic characteristics and behaviors. The size distribution, shape, particle dimensions, crystal structure, morphology, and surface characteristics can be regulated by altering synthesis processes (Salunkhe et al., 2014). Size control is important for the magnetism of magnetic nanoparticles because paramagnetic nanoparticles are size-dependent. When iron oxide nanoparticles (Fe_3O_4 (magnetite) or γ-Fe_2O_3 (maghemite)) reach small sizes (about 10–20 nm), they exhibit superparamagnetic behavior, thereby enhancing their efficacy for numerous applications. Owing to their robust magnetic properties, iron oxide nanoparticles were initially employed in biological applications for magnetic separation, magnetic targeting, and magnetic hyperthermia(Singh et al., 2021). Another factor influencing magnetic properties is shape. The shape of magnetic nanoparticles has two distinct effects, particularly in applications where magnetism is a factor, such as magnetic hyperthermia. On the one hand, anisotropy is observed; on the other hand, it affects the particle's interaction with its environment. According to studies by Gavilán et al., flower-shaped iron oxide nanoparticles have shown better magnetic properties and higher SAR values than cube-, disk-, and spindle-shaped iron oxide nanoparticles (Gavilán et al., 2021).

The polyol method is an alternative technique for synthesizing iron oxide nanoparticles. The higher dielectric constants, the capacity to dissolve inorganic substances, and the high boiling temperatures of polyols create optimal conditions for synthesis. The primary mechanism of this approach is the hydrolysis of chelate-metal alkoxide complexes at high temperatures in alcoholic solutions (Khulbe et al., 2023). There are many polyols for use for this purpose. They affect the size and shape of nanoparticles. Diethylene glycol (DEG), triethylene glycol (TEG), and tetraethylene glycol (TTEG were examples of solvents and stabilizers for polyol methods. The research by Hachani et al. demonstrated that DEG, TREG, and TEG facilitate the production of spherical iron oxide nanoparticles of approximately 6 nm, 10 nm, and 13 nm, respectively (Hachani et al., 2016). In other terms, polyol functions as a solvent, reducing agent, and stabilizer. This process yields non-aggregated nanoparticles with varying sizes and compositions, as kinetic participation can be easily controlled using the thermal-decomposition technique (Hemery et al., 2017). The polyol technique offers the advantage of stability in aqueous environments due to a labile solvent

layer, eliminating the need for any surfactants and coating ingredients, making it acceptable for biomedical applications.

This study aimed to prepare flower-shaped maghemite nanoparticles via the polyol method for magnetic hyperthermia treatment. Based on the literature, different polyol and co-solvent systems were developed. For this purpose, maghemite nanoparticles in flower shape were prepared using triethylene glycol: diethanolamine (TEG: DEA) as the polyol and co-solvent, and optimization studies were conducted.

EXPERIMENTAL

Materials and Instruments

Ferric chloride hexahydrate ($FeCl_3.6H_2O$, ≥97%, SIGMA-ALDRICH) Ferrous chloride tetrahydrate ($FeCl_2.4H_2O$, ≥99%, SIGMA-ALDRICH) Triethylene Glycol, ≥99%, SIGMA-ALDRICH) Sodium hydroxide (NaOH, puriss., meets analytical specification of Ph. Eur., BP, NF, E524, 98-100.5%, pellets, SIGMA-ALDRICH); Diethanolamine $(HOCH_2CH_2)_2NH$, 98.5%, ALDRICH) Ferric nitrate nonahydrate ($Fe(NO_{3)3}$, ≥98%, SIGMA-ALDRICH); nitric acid (HNO_3, ACS reagent, 70%, SIGMA-ALDRICH); diethyl ether ($(C_2H_5)_2$ O, ≥99.7%, MERCK MILLIPORE); acetone (CH_3COCH_3, ≥99.7%, CARLO ERBA REAGENTS) were used for the preparation of maghemite nanoparticles.
For the polyol synthesis, a Labheat heating mantle equipped with a temperature controller was used. Morphological characterization of the nanoparticles was performed using a FEI Tecnai G2 Spirit BioTwin transmission electron microscope (TEM) operated at 120 kV at the METU Central Laboratory. TEM analyses were performed on 200-mesh holey carbon-coated copper grids. Before analysis, samples were deposited onto the grids and allowed to dry at room temperature for 24 h. Magnetic measurements were performed at the METU Central Laboratory using a Vibrating Sample Magnetometer (VSM) integrated into a Cryogenic Limited Physical Property Measurement System (PPMS). Approximately 300 mg of maghemite powder was prepared for analysis, and magnetization measurements were conducted at 5 K and 298 K.X-ray diffraction (XRD) patterns were recorded using a Rigaku MiniFlex diffractometer equipped with Cu-Kα radiation (λ = 1.54056 Å). Data were collected over a 2θ range of 10–90°.

Figure 1. Experimental Setup of Polyol Methods

Flower-shaped γ-Fe_2O_3 nanoparticles were produced using the polyol approach (Hugounenq et al., 2012). In contrast, TEG was used as the solvent. The experimental setup is illustrated in Figure 1. 1 mmol of $FeCl_3 \cdot 6H_2O$ and 1 mmol of $FeCl_2 \cdot 4H_2O$ were dissolved in a combination of 10 g of triethylene glycol (TEG) and 10 g of diethanolamine (DEA). 0.16 g of NaOH (Fe/OH^- molar ratio was adjusted to 0.5) was incorporated into a mixture of 5 g of TEG and 5 g of DEA while stirring at room temperature. After 1 hour of stirring, the temperature increased to 220 °C. The mixture was cooled to room temperature, precipitated, and separated from the reaction medium with a magnet. The precipitate was magnetically washed with a 20 mL ethanol: ethyl acetate (1:1; v:v) mixture. After magnetic separation, the washing medium was removed, and the precipitate was treated with 20 mL of 10 % nitric acid to remove any remaining iron hydroxides. In the final stage, the particles after magnetic separation were added to a 5.0 mL water solution containing 2.05 g $Fe(NO_3)_3$, stirred, and heated to 80°C for 45 min. In the final step, the black color of the precipitate changed to brown. The precipitate was collected with a magnet, treated with 20 mL of 10 % nitric acid, and washed with 20 mL of acetone and diethyl ether separately. After the washing procedure, flower-

shaped γ-Fe_2O_3 NPs were dispersed in deionized water. The polyol composition and the reflux duration were optimized. These are presented in Table 1.

Table 1. Optimization Parameters for Synthesizing Flower-Shaped Iron Oxide Nanoparticles via Polyol Methods

Experiment Number	Stoichiometric ratio of polyol (TEG:DEA)(w:w)	Heating Slope (from 25°C to 220°C), °C/min	Reflux time (220°C)
A	1:0	1	2h
B	1:1	1	2h
C	1:1	1	1 h
D	1:1	1	0.5 h

RESULTS and DISCUSSIONS

The polyol approach is an efficient preparation technique for oxide nanoparticles. Temperature, precursor characteristics, solvent, and reaction duration are critical elements for producing nanoparticles with tunable size and morphology. This study employed the polyol method to produce flower-shaped γ-Fe_2O_3 NPs. Initially, only TEG was used as a solvent and stabilizer, without a co-solvent (DEA). Reflux was conducted at 220 °C for 2 hours. The heating rate was 1 °C/min (Table 1. A). The disintegration of particles at the conclusion of the reaction, caused by aggregation formation, was noted. The formation of metal oxides from chelated TEG complexes is irreversible. Hydrolysis processes in TEG are followed by rapid nucleation and nanocrystal growth.

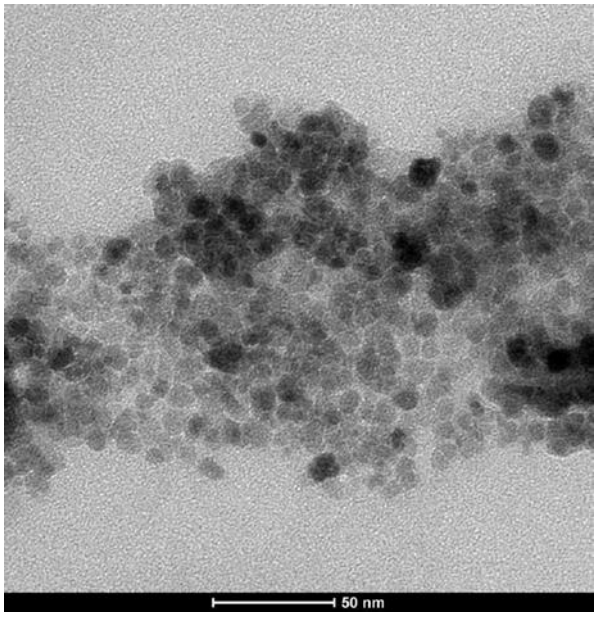

Figure 2. TEM Images of Nanoparticles Synthesized with the Polyol Method: the Solvent Is TEG: DEA (1:0, w/w), with A Heating Rate of 1 °C/Min and A Reflux Temperature of 220 °C. The reflux time is 2 h.

The coalescence of very small nanocrystals and the internal recrystallization of nanoparticles occur during the aging period (Caruntu et al., 2004). Transmission Electron Microscopy (TEM) was employed for the characterization of the particles, as illustrated in Figure 2. The TEM images indicate that uniformly sized spherical particles were generated with a size range of 10 nm, contrary to the anticipated flower-like particles.

A co-solvent was selected for the reaction to decelerate the reaction rate and achieve a flower shape. The TEG: DEA mixture (1:1) was used as the polyol, and reflux times were set to 0.5, 1.0, and 2.0 hours. The reflux temperature and heating rate remained unchanged (Table 1, (B, C, and D). In all optimization experiments, the use of a co-solvent reduces the hydrolysis of the metal at the interface between the solid oxide and the metal complexes in solution. When TEG was employed, internal recrystallization occurred favorably without mass transfer, and the TEG-metal oxide complex became irreversible. Conversely, when DEA was used as a co-solvent, the hydrolysis reaction proceeded at a reduced rate, leading to the formation of small nanoparticles that subsequently agglomerated into larger nanoparticles through secondary recrystallization (Hachani et al., 2016).

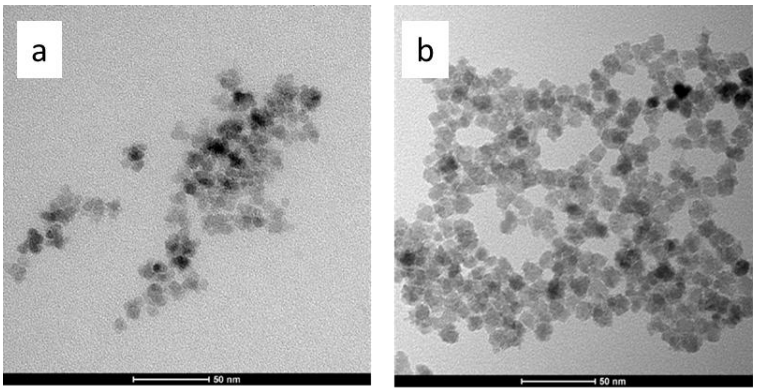

Figure 3. TEM Images of Nanoparticles Synthesized with the Polyol Method: The Solvent Is TEG: DEA (1:1, w:w), With A Heating Rate of 1 °C/min and A Reflux Temperature of 220 °C. The Reflux Time Is **a.** 2h (Table1. B) and **b.** 1h (Table1. C).

As shown in the TEM images in Figure 3.b, no flower-like shape was observed due to the 1-hour reflux time; the small particles clumped together, forming a buckyball-like appearance. Even though flower-like patterns are observed when the reflux duration is increased to 2 hours, the agglomeration remains at a very high level, as seen in the TEM image in Figure 3.a (Hugounenq et al., 2012).

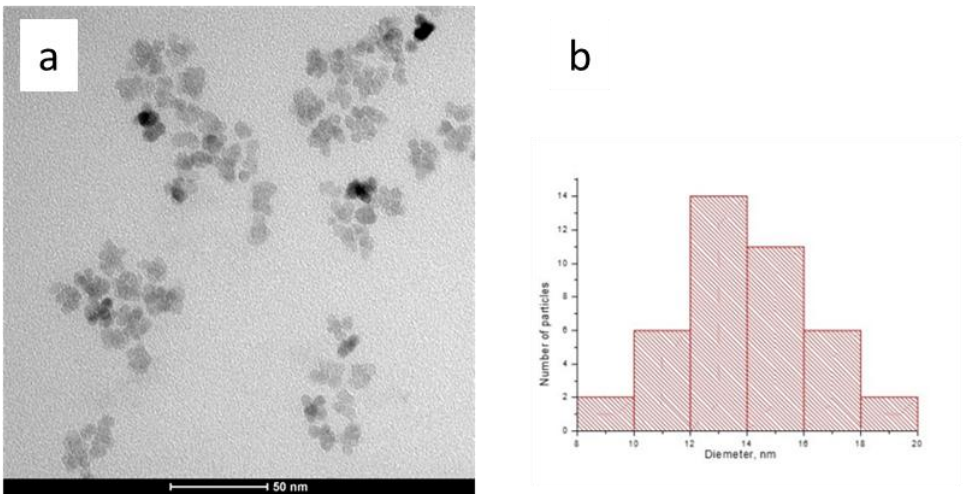

Figure 4. TEM Images of Nanoparticles Synthesized with the Polyol Method: The Solvent is TEG: DEA (1:1, v/v), with a Heating rate of 1 °C/min and a Reflux Temperature of 220 °C. The Reflux Time is 0.5 h (Table1.D), and **b.** Size Distribution Histogram for the Particles Presented in **a.**

As indicated by the TEM images in Figure 4.a, a reduction in reflux time correlates with a decrease in aggregation, resulting in the formation of more dispersed flower-shaped structures. Consequently, a reflux time of 0.5 hours was determined to be the optimal environment for synthesizing flower-like iron oxide nanoparticles of appropriate size. As shown in Figure 4.b, the particle size distribution ranges from 9 to 19 nm, with an average particle size of 13.5 ± 3.6 nm. X-ray diffraction (XRD) was employed for characterizing the crystal structure of maghemite nanoparticles, as illustrated in Figure 5.

The diffraction peaks observed at 2θ values of 30.48°, 35.70°, 57.34°, and 62.94° were indexed to the (206), (119), (1115), and (4012) Bragg reflections, respectively, as shown in Figure 5. These reflections are consistent with the characteristic diffraction pattern of tetragonal γ-Fe_2O_3 (maghemite) (JCPDS Card No. 25-1402) and agree with the literature (Labbi et al., 2021; Rajput et al., 2017).

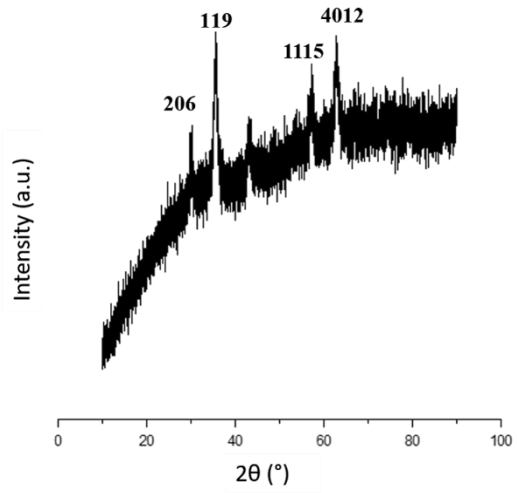

Figure 5. X-ray Diffraction Pattern of Flower-Shaped Iron Oxide Nanoparticles

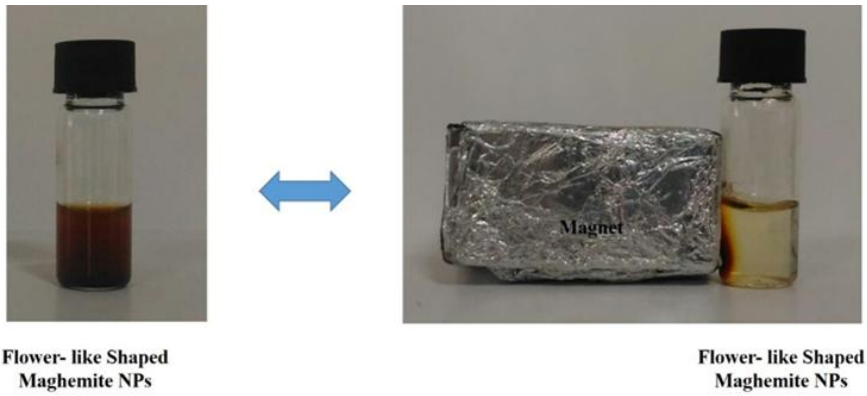

Figure 6. Behavior of Flower-Shaped Iron Oxide Nanoparticles in A Magnetic Field.

Figure 6 illustrates the magnetic behavior of the nanoflower-shaped iron oxide nanoparticles at 25 °C. In the image, one minute after a magnet was placed next to the nanoparticles, all the nanoparticles are seen to have aligned with the magnet.

Magnetization experiments were conducted with a field scan of ±1.1 T at 298 K and 5 K, yielding hysteresis loops for the nanoflower-shaped iron oxide powder (Table 1, D). Nanoparticles exhibit reduced magnetism compared to their bulk counterparts due to the elevated proportion of surface metal ions, which contribute less to the overall magnetization (Kucheryavy et al., 2013). Figure 7 illustrates the magnetization vs magnetic field curves for flower-shaped maghemite at 298K. Nonetheless, nanoflower particles exhibit a saturation magnetization of 64.00 emu/g, which is relatively close to the saturation magnetization (Ms) of bulk maghemite, approximately 80 emu/g (Hugounenq et al., 2012).

The Ms values of our flower-shaped iron oxide nanoparticles were compared with those reported in the literature. As previously mentioned, size plays a crucial role in magnetism. The nanoflowers produced in this study exhibited a mean diameter of 13.5 nm, composed of grains of maghemite measuring 6 nm. In contrast, the tiniest nanoflowers reported by Hugounenq et al. had an average size of 22 nm, with constituent grains of 11 nm. The Ms value determined in our investigation was 64 emu/g, which is nearly equivalent to the Ms value of the nanoflowers (66 emu/g) reported by Hugounenq et al. (Hugounenq et al., 2012). Above the blocking temperature (Tb) of superparamagnetic nanoparticles, the nanoparticles exhibit zero coercivity due to the interplay between magnetocrystalline anisotropy energy and thermal energy. Figure 7 illustrates that the magnetization decreases from a saturation value of 64 emu/g to zero in the absence of a magnetic field, exhibiting no coercivity. This behavior shows that our nanoparticles are superparamagnetic (Hugounenq et al., 2012).

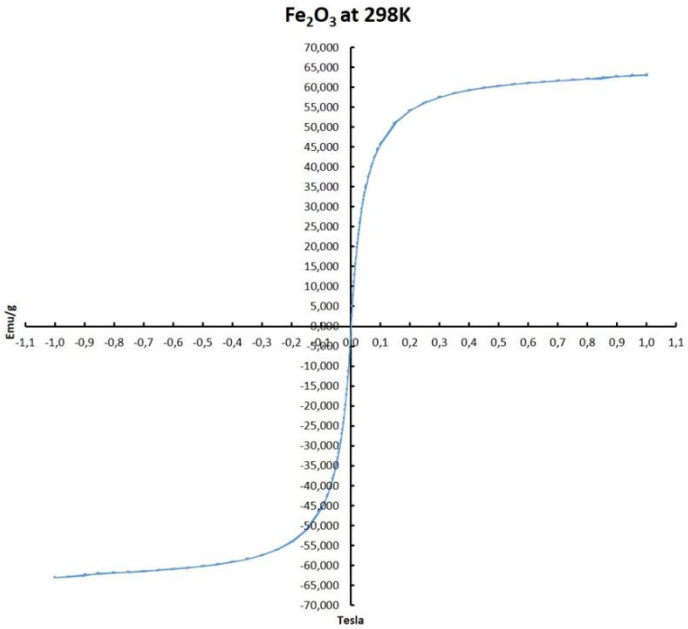

Figure 7. Magnetization vs magnetic field curves for flower-shaped iron oxide nanoparticles (Table 1. D) at 298 K.

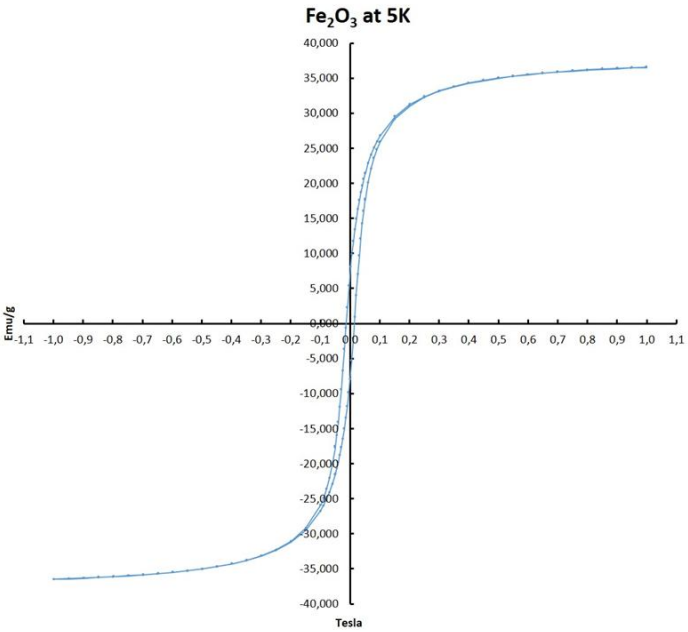

Figure 8. Magnetization vs Magnetic Field Curves for Flower-Shaped Iron Oxide Nanoparticles (Table 1. D) at 5K.

Figure 8 illustrates Ms as a function of the applied magnetic field (H) for nanoflower-shaped maghemite nanoparticles (Table 1 D) at 5K, which is below the Néel temperature (Tb) of maghemite (about 80 K) (Vollath et al., 1995). Generally, at temperatures below the blocking temperature (Tb), the magnetization vector remains stable even in the absence of an external magnetic field, resulting in a coercivity for superparamagnetic nanoparticles that exceeds zero. As expected, these maghemite nanoflowers exhibit hysteresis at 5K, as illustrated in Figure 8. The saturation magnetization (Ms) of the nanoflowers is 36.50 emu/g, and their remanent magnetization (Mr) is 5.00 emu/g.

The magnetic results demonstrate that the superparamagnetic nanoflower particles synthesized in this study exhibit a high Ms value, making them suitable candidates for biological applications, particularly for hyperthermia.

This synthesis is based on the work of Hugounenq et al. However, unlike the previous study, TEG was used as the polyol instead of DEG (Hugounenq et al., 2012). As shown in the literature, these monodispersed nanoparticles exhibit significant superparamagnetism, which is associated with an increase in polyol chain length while maintaining consistent nanoparticle size. The higher relaxivities of iron oxide nanoparticles produced in polyols with longer polyol chain lengths suggest their suitability as contrast agents for MRI applications (Qu et al., 2024).

This study aimed to produce magnetic nanoparticles for use in future magnetic hyperthermia studies. To this end, nanoparticles with high magnetic properties, a maghemite structure, and surface characteristics and dimensions suitable for biomedical applications were prepared. However, the inability to measure SAR values represents a significant limitation of this study. In the future, the prepared particles will be tested for SAR values at different concentrations and in various media (such as water and BSA) to prepare them for in vivo and in vitro applications.

CONCLUSION

Magnetic nanoparticles must possess certain properties to be used for biomedical purposes. Primarily, they should be monodispersed, hydrophilic, small in size (approximately <100 nm), and have functional surface properties. In applications where functional properties are important, such as magnetic hyperthermia therapy, the magnetic properties of nanoparticles become even more crucial. In this study, flower-shaped meghemite nanoparticles were prepared using the TEG: DEA polyol system. XRD was used to characterize the prepared particles for crystal structure, TEM for morphology, and VSM for magnetic properties. The results show that these nanoparticles, with a functional surface area and dimensions of 13.5 ± 3.6 nm, will be used in future planned magnetic hyperthermia and MRI imaging studies.

ACKNOWLEDGMENTS

This work was produced from the PhD thesis of Dr. Yeliz AKPINAR, and this study was supported by TÜBİTAK awarding grant (2211A) and ÖYP-DPT through Project BAP-08-11-DPT.2011K121010. We are grateful to Prof. Dr. Ayşen YILMAZ (METU, Department of Chemistry) for her support in the XRD measurements.

Artificial Intelligence Contribution Statement

The author(s) acknowledge and declare that AI tool (Grammarly) was used solely for auxiliary purposes such as grammar corrections; the entirety of original thought, commentary, and academic content belongs to the author(s).

REFERENCES

Atik, R., Islam, R., Ariza Gonzalez, M., Chinwangso, P., & Lee, T. R. (2025). Recent Advances in Polymer-Coated Metal and Metal Oxide Nanoparticles: From Design to Promising Applications. Nanomaterials, 15(22), 1744. https://doi.org/10.3390/nano15221744

Ayranpınar, İ., Duyar, A., Göçer, S., Kozak, M., Köroğlu, E. O., & Cırık, K. (2023). Demir (II, III) Oksit (Fe3O4) Nanopartiküller Kullanılarak Tekstil Atıksularının Arıtılması. Kahramanmaraş Sütçü İmam Üniversitesi Mühendislik Bilimleri Dergisi, 26(1), 1–7. https://doi.org/10.17780/ksujes.1142242

Baabu, P. R. S., Kumar, H. K., Gumpu, M. B., Babu K, J., Kulandaisamy, A. J., & Rayappan, J. B. B. (2022). Iron Oxide Nanoparticles: A Review on the Province of Its Compounds, Properties and Biological Applications. Materials, 16(1), 59. https://doi.org/10.3390/ma16010059

Caruntu, D., Caruntu, G., Chen, Y., O'Connor, C. J., Goloverda, G., & Kolesnichenko, V. L. (2004). Synthesis of Variable-Sized Nanocrystals of Fe3O4 with High Surface Reactivity. Chemistry of Materials, 16(25), 5527–5534. https://doi.org/10.1021/cm0487977

Coduri, M., Masala, P., Del Bianco, L., Spizzo, F., Ceresoli, D., Castellano, C., Cappelli, S., Oliva, C., Checchia, S., Allieta, M., Szabo, D.-V., Schlabach, S., Hagelstein, M., Ferrero, C., & Scavini, M. (2020). Local Structure and Magnetism of Fe2O3 Maghemite Nanocrystals: The Role of Crystal Dimension. Nanomaterials, 10(5), 867. https://doi.org/10.3390/nano10050867

Durmuş, H. O. (2024). Biomedical applications of nanomaterials: A short review. Nano and Medical Materials, 4(1), 2044. https://doi.org/10.59400/nmm2044

Gavilán, H., Simeonidis, K., Myrovali, E., Mazarío, E., Chubykalo-Fesenko, O., Chantrell, R., Balcells, Ll., Angelakeris, M., Morales, M. P., & Serantes, D. (2021). How size, shape and assembly of magnetic nanoparticles give rise to different hyperthermia scenarios. Nanoscale, 13(37), 15631–15646. https://doi.org/10.1039/D1NR03484G

Hachani, R., Lowdell, M., Birchall, M., Hervault, A., Mertz, D., Begin-Colin, S., & Thanh, N. T. K. (2016). Polyol synthesis, functionalisation, and biocompatibility studies of superparamagnetic iron oxide nanoparticles as potential MRI contrast agents. Nanoscale, 8(6), 3278–3287. https://doi.org/10.1039/C5NR03867G

Hemery, G., Keyes, A. C., Garaio, E., Rodrigo, I., Garcia, J. A., Plazaola, F., Garanger, E., & Sandre, O. (2017). Tuning Sizes, Morphologies, and Magnetic Properties of Monocore Versus Multicore Iron Oxide Nanoparticles through the Controlled Addition of Water in the Polyol Synthesis. Inorganic Chemistry, 56(14), 8232–8243. https://doi.org/10.1021/acs.inorgchem.7b00956

Hugounenq, P., Levy, M., Alloyeau, D., Dubois, E., Ricolleau, C., Wilhelm, C., Gazeau, F., & Bazzi, R. (2012). Iron Oxide Monocrystalline Nano flowers for Highly Efficient Magnetic Hyperthermia. *The Journal of Physical Chemistry C*, *116* (29), 15702-15712. https://doi.org/ 10.1021/jp3025478

Jyoti Rajput, & Kashish Saroj. (2025). Nanotechnology in Modern Physics: Materials, Devices, and Applications. International Journal of Advanced Research and Interdisciplinary Scientific Endeavours, 3(6), 1119–1129. https://doi.org/10.61359/11.2206-2564

Khulbe, R., Kandpal, A., Prasad, J., Chandra, B., & Kandpal, N. D. (2023). Polyol Synthesis of Nanoparticles: A Decade of Advancements and Insights. Asian Journal of Chemistry, 35(11), 2618–2630. https://doi.org/10.14233/ajchem.2023.30223

Kucheryavy, P., He, J., John, V. T., Maharjan, P., Spinu, L., Goloverda, G. Z., & Kolesnichenko, V. L. (2013). Superparamagnetic Iron Oxide Nanoparticles with Variable Size and an Iron Oxidation State as Prospective Imaging Agents. Langmuir, 29(2), 710–716. https://doi.org/10.1021/la3037007

Labbi, A., Benhaoua, B., Ahmouda, K., Meftah, Y., & Benhaoua, Kh. (2021). Effect of iron chlorine concentration on type of green synthezed iron oxides nanoparticles using pheonixdactylifera l leaves extract. Digest Journal of Nanomaterials and Biostructures, 16(4), 1627–1634. https://doi.org/10.15251/DJNB.2021.164.1627

Qu, J., Cheah, P., Adams, D., Collen, C., & Zhao, Y. (2024). The influence of the polyol solvents on the continuous growth of water-dispersible iron oxide nanoparticles. Journal of Materials Research, 39(1), 165–175. https://doi.org/10.1557/s43578-023-01236-x

Rajput, S., Singh, L. P., Pittman, C. U., & Mohan, D. (2017). Lead (Pb 2+) and copper (Cu 2+) remediation from water using superparamagnetic maghemite (γ-Fe2O3) nanoparticles synthesized by Flame Spray Pyrolysis (FSP). Journal of Colloid and Interface Science, 492, 176–190. https://doi.org/10.1016/j.jcis.2016.11.095

Salunkhe, A. B., Khot, V. M., & Pawar, S. H. (2014). Magnetic Hyperthermia with Magnetic Nanoparticles: A Status Review. Current Topics in Medicinal Chemistry, 14(5), 572–594. https://doi.org/10.2174/1568026614666140118203550

Singh, V., Yadav, S. S., Chauhan, V., Shukla, S., & Vishnolia, K. K. (2021). Applications of Nanoparticles in Various Fields (pp. 221–236). https://doi.org/10.4018/978-1-7998-6527-8.ch011

Teja, A. S., & Koh, P.-Y. (2009). Synthesis, properties, and applications of magnetic iron oxide nanoparticles. Progress in Crystal Growth and Characterization of Materials, 55(1–2), 22–45. https://doi.org/10.1016/j.pcrysgrow.2008.08.003

Vollath, D., Szabó, D. V., Taylor, R. D., Willis, J. O., & Sickafus, K. E. (1995). Synthesis and properties of nanocrystalline superparamagnetic γ-Fe2O3. Nanostructured Materials, 6(5–8), 941–944. https://doi.org/10.1016/0965-9773(95)00215-4

Yousif, N., Al-Jawad, S., Taha, A., & Stamatis, H. (2023). A review of Structure, Properties, and Chemical Synthesis of Magnetite Nanoparticles. Journal of Applied Sciences and Nanotechnology, 3(2), 18–31. https://doi.org/10.53293/jasn.2022.5179.1178