

Thermal Effect on Structural and Morphological Properties of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ Nanoparticles

Balbhim S. Maharnavar¹, Amol R. Pardeshi¹, Vaibhav D. Lohakare¹, Sahadev H. Kangude¹, Mahesh G. Bagal², Vishal K. Pandit³

¹ Rayat Shikshan Sanstha's, Dada Patil Mahavidyalaya, Karjat, Dist: Ahilyanagar, MH, India 414 402.

² Rayat Shikshan Sanstha's, S. M. Joshi College Hadapsar, Pune MH India 411 028.

³ Sakeshwar Gramin Vikas Seva Sanstha's, Adsul Technical Campus, Chas Ahilyanagar MH India 414005.

Corresponding Author: vishalpandit20[at]gmail.com, balbhim02[at]gmail.com

Abstract: $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ nanoparticles were synthesized by a co-precipitation method and annealed at 400 and 500 °C. X-ray diffraction confirmed the formation of a crystalline spinel ZnFe_2O_4 phase, along with a minor $\alpha\text{-Fe}_2\text{O}_3$ impurity phase. The crystallite size decreased from 19.5 nm at 400 °C (ZF1) to 15.0 nm at 500 °C (ZF2), indicating a reduction in the coherent diffraction domain size with increasing annealing temperature. FTIR spectra confirmed the characteristic tetrahedral and octahedral M-O vibrations of the spinel structure. SEM analysis showed irregular as well as some spherical agglomerated particles of ZF1, while the ZF2 sample exhibited more well-defined as well as compact spherical, short needle like and agglomerated particles with a uniform particle-size distribution. Overall, the ZF2 annealed sample demonstrated better crystallinity, structural perfection, and morphological development than the ZF1.

Keywords: Zinc Ferrite, Annealing Temperature, XRD and SEM

1. Introduction

Ferrite materials are technologically important magnetic oxides because of their high electrical resistivity, chemical and thermal stability, moderate magnetic response, and low eddy-current losses [1-4]. These properties make ferrites suitable for a wide range of applications, including transformers, inductors, filters, electromagnetic-interference suppression devices, microwave absorbers, antennas, sensors, magnetic recording, catalysis, water treatment, and biomedical technologies [5-8]. At the nanoscale, ferrites exhibit enhanced surface area and size-dependent structural, magnetic, optical, and electrical properties, allowing their performance to be tailored through particle size, morphology, crystallinity, cation distribution, and synthesis conditions [4-6].

ZnFe_2O_4 is an important cubic spinel ferrite with the general formula AB_2O_4 . In the ideal normal-spinel arrangement, Zn^{2+} ions occupy the tetrahedral sites, whereas Fe^{3+} ions occupy the octahedral sites. However, partial redistribution of Zn^{2+} and Fe^{3+} ions between these sites may occur depending on the synthesis route, annealing temperature, crystallite size, and defect concentration [9-11]. Such structural variations strongly influence the magnetic, optical, electrical, photocatalytic, and dielectric properties of ZnFe_2O_4 [12-15]. Due to its chemical stability, relatively low cost, low toxicity, semiconducting nature, and tenable physicochemical properties, ZnFe_2O_4 has attracted considerable attention for photocatalytic degradation of pollutants, wastewater treatment, hydrogen production, lithium-ion batteries, supercapacitors, microwave absorption, gas sensing, catalysis, and biomedical applications [16-22].

The properties of ZnFe_2O_4 nanoparticles are strongly dependent on the preparation method. Among the available techniques, co-precipitation is attractive because it is simple,

economical, chemically homogeneous, and suitable for large-scale production. Nevertheless, parameters such as pH, precursor concentration, precipitation conditions, drying, and annealing temperature affect the phase purity, crystallite size, lattice strain, morphology, and agglomeration of the final product [23,24]. Thermal annealing promotes crystallization and structural ordering but may also increase crystallite growth and particle agglomeration (25). Therefore, the present work investigates $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ nanoparticles synthesized by the co-precipitation method and annealed at 400 °C and 500 °C. The influence of annealing temperature was examined using X-ray diffraction, Fourier-transform infrared spectroscopy, scanning electron microscopy, and particle-size histogram analysis. The crystallite size and structural parameters were evaluated from the XRD data. The results showed that the sample ZF2 exhibited improved crystallinity and greater structural perfection compared with the ZF1. In addition to the ZnFe_2O_4 spinel phase, some diffraction peaks were assigned to a minor $\alpha\text{-Fe}_2\text{O}_3$ secondary phase. The study therefore clarifies the role of annealing temperature in controlling the structural and morphological characteristics of co-precipitated ZnFe_2O_4 nanoparticles.

2. Materials and Methods

2.1 Materials

Analytical reagent (AR) grade zinc chloride (ZnCl_2), ferric chloride (FeCl_3), and sodium hydroxide (NaOH) supplied by LOBA Chemie Pvt. Ltd. were used as starting materials for the synthesis of ZnFe_2O_4 nanoparticles. Whatman No. 42 filter paper was used for filtration and separation of the precipitate. Ethanol was used for washing the precipitate during the purification process. All chemicals were used as received without further purification (26).

2.2 Preparation of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ Nanoparticles

Appropriate amounts of the Zinc Chloride (0.1 M) and Iron Chloride (0.2) precursor salts were dissolved separately by volumetric ratio (1:1) in deionized water to obtain homogeneous solutions. The precursor solutions were mixed under continuous magnetic stirring heat up to 40 °C. The precipitating agent, NaOH, was added dropwise to the precursor solution under continuous stirring until the pH reached approximately 9. Subsequently, the temperature of the reaction mixture was increased to 80 °C, resulting in the formation of a visible precipitate. The suspension was maintained under continuous stirring at 80 °C to promote the precipitation and formation of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ precursor particles. Then the precipitate was several times filter DI water and Ethanol to remove soluble impurities and residual ions. The washed material was dried to obtain the precursor powder. The dried precursor was subsequently annealed at 400 °C and 500 °C for 3 h in a muffle furnace to obtain crystalline $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ nanoparticles these all steps illustrated in schematic of methodology in fig.1. Thus, the difference between the two samples was attributed primarily to the annealing temperature. The use of controlled heat treatment is important because thermal treatment can influence phase formation, crystallinity, crystallite growth and morphology in ZnFe_2O_4 (27)



Fig.1 Schematic of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ by nanoparticle synthesis by the co-precipitation method

3. Results and Discussion

3.1 XRD Structural Analysis

The phase composition and crystal structure of the synthesized ZnFe_2O_4 powders were investigated by X-ray diffraction (XRD) using $\text{Cu K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$). The diffraction patterns of ZF1 and ZF2 show the characteristic reflections of cubic spinel ZnFe_2O_4 , indexed to the (111), (220), (311), (222), (400), (422), (511), and (440) planes, respectively. The observed reflections are consistent with cubic ZnFe_2O_4 (JCPDS Ref. No. 22-1012). Weak additional reflections observed at approximately 2θ is 24, 33.49°, 41.15°, 49.79°, and 64.30° are attributed to $\alpha\text{-Fe}_2\text{O}_3$ (hematite), corresponding mainly to the (012), (104), (113), (024), and (300) planes. ZF1 were additional weak diffraction peak at 32.15°, is observed, which can be assigned to the (100) plane of hexagonal wurtzite ZnO, suggesting the presence of a minor ZnO secondary phase. The ZF2 were diffraction peaks become more prominent and the ZnO-related peak is significantly reduced, indicating improved phase formation and crystallinity of ZnFe_2O_4 at the higher annealing

temperature. The intense reflection of ZF1 at 35.58°(Fig.1-a), corresponding to the (311) plane, confirms the formation of cubic spinel ZnFe_2O_4 , therefore, this region requires careful consideration during peak-broadening analysis.

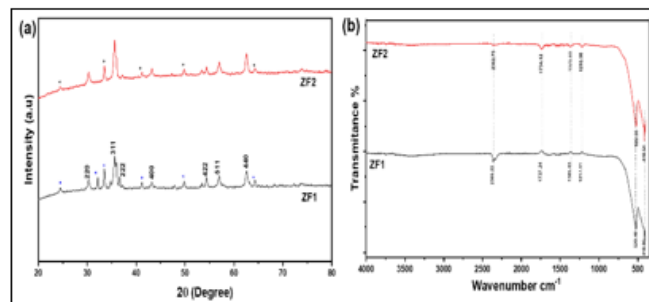


Fig.1. (a) XRD patterns of ZF1 and ZF2 with the corresponding crystallographic planes indexed, and (b) FTIR spectra of ZF1 and ZF2 recorded over the respective temperature range

The mean coherent crystallite size was determined from the broadening of the X-ray diffraction peaks using the Scherrer method (equation 1). The crystallite size represents the average size of coherently diffracting regions within the material. The micro strain indicates lattice distortion caused by structural defects, vacancies, substitutions, and other imperfections (Equation 2). The dislocation density represents the number of dislocations per unit volume and provides information about the defect concentration in the crystal (equation 3). Generally, smaller crystallite sizes are associated with higher micro strain and dislocation density shown in table 1(28).

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

$$\epsilon = \frac{\beta}{4 \tan \theta} \quad (2)$$

$$\delta = \frac{1}{D^2} \quad (3)$$

where D is the crystallite size, K is the shape factor, generally taken as 0.9, λ is the wavelength of the X-ray radiation, β is the corrected full width at half maximum (FWHM) in radians, and θ is the Bragg angle. The macrostrain (ϵ) is dimensionless, while the dislocation density (δ), is usually expressed in m^{-2} . Fig. 1a: reveals the structural analysis of ZnFe_2O_4 powder of ZF1 and ZF2

Table 1: Crystallite size (D), microstrain (ϵ), and dislocation density (δ) of ZF1 and ZF2 samples

Sample	Crystallite Size (D in nm)	micro strain (ϵ)	Dislocation Density δ (nm^{-2})
ZF 1	18.102	1.721×10^{-3}	3.051×10^{-3}
ZF 2	14.053	2.138×10^{-3}	5.063×10^{-3}

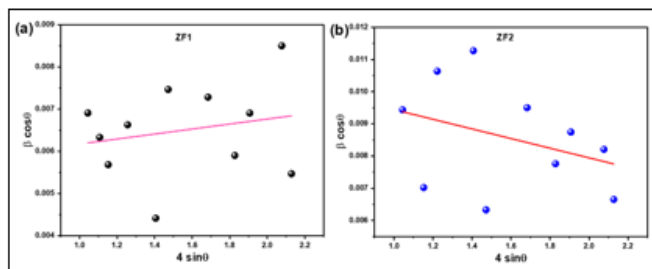


Fig. 2. W-H plots of the prepared ZnFe_2O_4 samples: (a) ZF1 and (b) ZF2

In fig. 2 (a) and (b) reveals the study of W-H plot for ZnFe_2O_4 powder material which show the Williamson–Hall (W–H) analysis was employed to distinguish the contributions of crystallite size and lattice microstrain to the broadening of the XRD diffraction peaks. The W–H plot of the ZnFe_2O_4 sample ZF1 exhibited a positive slope, indicating the presence of tensile microstrain in the crystallites. This tensile strain can be associated with residual lattice distortions, defects, vacancies, and surface/grain-boundary effects generated during the initial crystallization of the spinel phase. Similar positive W–H slopes have been reported for $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ and related ferrite nanoparticles and have been attributed to tensile microstrain. In contrast, the ZF2 exhibited a negative W–H slope, corresponding to compressive microstrain. The reversal in the sign of the W–H slope suggests a modification of the residual stress state during thermal treatment rather than a simple decrease in strain magnitude. The higher thermal energy at 500 °C promotes atomic diffusion, defect migration, grain-boundary rearrangement and crystallite growth, thereby allowing partial relaxation of the initially generated tensile strain. Simultaneously, redistribution of cations within the spinel lattice and rearrangement of lattice defects can generate local compressive distortions. Therefore, the transition from a positive slope at 400 °C to a negative slope at 500 °C can be attributed to thermally activated structural relaxation and reorganization of the defect/cation configuration in $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$. Such temperature-dependent changes in crystallite growth, grain-boundary migration and lattice strain are consistent with previously reported thermal-annealing studies of ZnFe_2O_4 .

3.2 FTIR Analysis

The FTIR spectra of ZF1 and ZF2 show in Fig.1(b) which exhibits the characteristic vibrational bands of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ with the main bands are observed at 418.80 and 418.54 cm^{-1} for ZF1 and ZF2, respectively. These bands are assigned to the metal–oxygen (M–O) vibrations at the tetrahedral and octahedral sites of the spinel $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ structure. The small shift in the band positions from ZF1 to ZF2 indicates a slight change in the local bonding environment with increasing annealing temperature. A weak band is observed at 1217 cm^{-1} for ZF1 and 1217 cm^{-1} for ZF2, while bands at 1737 and 1734 cm^{-1} are also observed for ZF1 and ZF2, respectively. These weak bands can be related to surface-adsorbed species or residual functional groups. The bands near 2366 cm^{-1} (ZF1) and 2363 cm^{-1} (ZF2) are associated mainly with atmospheric CO_2 .

The FTIR results are consistent with the XRD analysis, which confirms the formation of the cubic spinel ZnFe_2O_4 phase. The slight shifts in the M–O vibration bands after annealing

indicate changes in the local structural environment, while the basic spinel framework remains unchanged. Thus, the FTIR results support the structural information obtained from XRD

3.3 Morphological Study

The surface morphology of the $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ samples of ZF1 and ZF2 were examined using SEM. As shown in Fig. 3 (a) and (b). Both samples exhibit predominantly spherical particles with a relatively uniform morphology. The particles are distributed fairly uniformly, after annealing, the particles exhibit a finer and more well-defined morphology.

ZnFe_2O_4 nanoparticles prepared by different methods have been reported to exhibit spherical, quasi-spherical and agglomerated morphologies observed predominantly spherical ZnFe_2O_4 particles with agglomeration, while reported nanoscale particles together with larger aggregates (29). Annealing can modify particle morphology because higher temperature increases atomic mobility and can promote particle coalescence and grain growth. Temperature-dependent morphological evolution has been observed in several ZnFe_2O_4 studies (30).

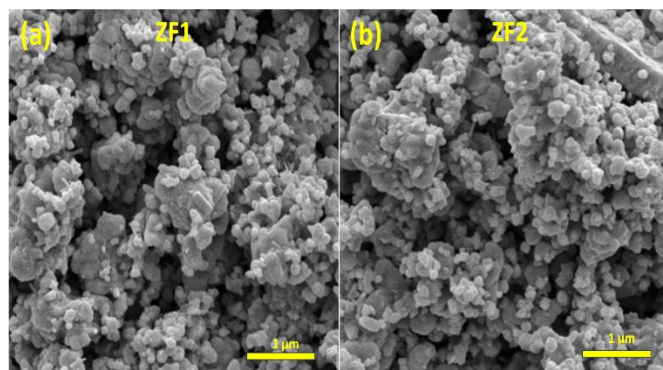


Figure 3: SEM for ZnFe_2O_4 for (a) ZF1 and (b) ZF2

3.4 Particle-Size Histogram Analysis

The particle-size distribution was evaluated from the SEM micrographs using a histogram of count % versus particle size (nm). Fig. 4(a-b) shows the particle-size distribution histograms of the prepared $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ samples, ZF1 and ZF2, obtained from the corresponding SEM images. The histogram provides the mean particle size, standard deviation, minimum particle size, maximum particle size, and total number of particles analysed. The average particle size was calculated using equation (4)

$$\bar{D} = \frac{\sum D_i}{N} \quad (4)$$

where D_i is the measured particle diameter and N is the total number of particles. The histogram comparison is particularly useful because XRD crystallite size and SEM particle size do not represent exactly the same physical quantity. XRD gives information about coherently diffracting crystalline domains, whereas SEM provides the apparent particle or aggregate dimensions visible in the micrograph. Recent $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ studies have used XRD together with electron microscopy to distinguish these structural and morphological scales (31). The average particle size was approximately 186.22 nm for ZF1 and 136.60 nm for ZF2. Thus, an increase in the annealing temperature from 400 to 500 °C resulted in a

decrease in the average particle size. This reduction may be associated with changes in the particle growth and structural rearrangement during annealing. The relatively uniform and spherical morphology observed for both samples indicates good control over the particle formation during the synthesis process.

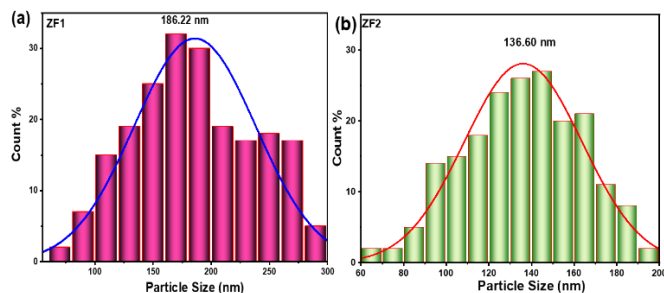


Figure 4: Histogram of analyzed SEM images which shows the nature of the materials

4. Conclusion

$\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ nanoparticles were successfully synthesized by the co-precipitation method, and the effect of annealing temperature was investigated using XRD, FTIR, and SEM analyses. The XRD results confirmed the formation of the cubic spinel $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ structure. The crystallite size decreased from approximately 18 nm for ZF1 to 14 nm for ZF2, indicating a change in the structural characteristics with increasing annealing temperature. The FTIR spectra showed the characteristic M-O vibrational bands of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$, confirming the ferrite structure. SEM analysis revealed predominantly spherical particles, with the average particle size decreasing from ZF1 to ZF2. The particle-size histograms further supported the observed morphological refinement at higher annealing temperature. Overall, the results demonstrate that annealing temperature significantly influences the structural and morphological properties of $\text{ZnFe}_2\text{O}_4/\alpha\text{-Fe}_2\text{O}_3$ nanoparticles, with ZF2 exhibiting finer particle morphology compared with ZF1.

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References

- Valenzuela, R. (2012). Novel applications of ferrites. *Physics Research International*, 2012, Article 591839. <https://doi.org/10.1155/2012/591839>
- Pullar, R. C. (2012). Hexagonal ferrites: A review of the synthesis, properties and applications of hexaferrite ceramics. *Progress in Materials Science*, 57(7), 1191–1334. <https://doi.org/10.1016/j.pmatsci.2012.04.001>
- Vedrtam, A., Kalauni, K., Dubey, S., & Kumar, A. (2020). A comprehensive study on structure, properties, synthesis and characterization of ferrites. *AIMS Materials Science*, 7(6), 800–835. <https://doi.org/10.3934/matricsci.2020.6.800>
- Salih, S. J., & Mahmood, W. M. (2023). Review on magnetic spinel ferrite (MFe_2O_4) nanoparticles: From synthesis to application. *Heliyon*, 9(6), e16601. <https://doi.org/10.1016/j.heliyon.2023.e16601>
- Soufi, A., Hajjaoui, H., Elmoubark, R., Abdennouri, M., Qourzal, S., & Barka, N. (2021). Spinel ferrite nanoparticles: Synthesis methods and application in heterogeneous Fenton oxidation of organic pollutants—A review. *Applied Surface Science Advances*, 6, 100145. <https://doi.org/10.1016/j.apsadv.2021.100145>
- Dippong, T., Levei, E. A., & Cadar, O. (2021). Recent advances in synthesis and applications of MFe_2O_4 ($\text{M} = \text{Co}, \text{Cu}, \text{Mn}, \text{Ni}, \text{Zn}$) nanoparticles. *Nanomaterials*, 11(6), 1560. <https://doi.org/10.3390/nano11061560>
- Kefeni, K. K., Mamba, B. B., & Msagati, T. A. M. (2017). Application of spinel ferrite nanoparticles in water and wastewater treatment: A review. *Separation and Purification Technology*, 188, 399–422. <https://doi.org/10.1016/j.seppur.2017.07.015>
- Kharisov, B. I., Rasika Dias, H. V., & Kharissova, O. V. (2019). Mini-review: Ferrite nanoparticles in the catalysis. *Arabian Journal of Chemistry*, 12(7), 1234–1246. <https://doi.org/10.1016/j.arabjc.2014.10.049>
- O'Neill, H. St. C. (1992). Temperature dependence of the cation distribution in zinc ferrite (ZnFe_2O_4) from powder XRD structural refinements. *European Journal of Mineralogy*, 4(3), 571–580. <https://doi.org/10.1127/ejm/4/3/0571>
- Braestrup, F. R., Hauback, B. C., & Kammer Hansen, K. (2008). Temperature dependence of the cation distribution in ZnFe_2O_4 measured with high-temperature neutron diffraction. *Journal of Solid-State Chemistry*, 181(9), 2364–2369. <https://doi.org/10.1016/j.jssc.2008.05.028>
- Sandemann, J. R., Stöckler, K. A. H., Wang, X., Chakoumakos, B. C., & Iversen, B. B. (2023). Benchmark crystal structure of defect-free spinel ZnFe_2O_4 . *Journal of the American Chemical Society*, 145(38), 21053–21065. <https://doi.org/10.1021/jacs.3c07334>
- Blanco-Gutiérrez, V., Torralvo-Fernández, M. J., & Sáez-Puche, R. (2010). Magnetic behavior of ZnFe_2O_4 nanoparticles: Effects of a solid matrix and the particle size. *The Journal of Physical Chemistry C*, 114(4), 1789–1795. <https://doi.org/10.1021/jp908395v>
- Wang, Y., Li, G., Zhang, Y., & Li, L. (2021). Zinc ferrite nanoparticles: Unusual growth mechanism for size-dependent properties. *ChemistrySelect*, 6(8), 1862–1869. <https://doi.org/10.1002/slct.202004562>
- Lemine, O. M., Bououdina, M., Sajieddine, M., Al-Saie, A. M., Shafi, M., Khatab, A., Al-Hilali, M., & Henini, M. (2011). Synthesis, structural, magnetic and optical properties of nanocrystalline ZnFe_2O_4 . *Physica B: Condensed Matter*, 406(10), 1989–1994. <https://doi.org/10.1016/j.physb.2011.02.072>
- Sapna, Budhiraja, N., Kumar, V., & Singh, S. K. (2019). Shape-controlled synthesis of superparamagnetic ZnFe_2O_4 hierarchical structures and their comparative structural, optical and magnetic properties. *Ceramics International*, 45(1), 1067–1076. <https://doi.org/10.1016/j.ceramint.2018.09.286>
- Zhu, J., Zhu, Y., Chen, Z., Wu, S., Fang, X., & Yao, Y. (2022). Progress in the preparation and modification of zinc ferrites used for the photocatalytic degradation of organic pollutants. *International Journal of*

- Environmental Research and Public Health, 19(17), 10710. <https://doi.org/10.3390/ijerph191710710>
- [17] Kefeni, K. K., & Mamba, B. B. (2020). Photocatalytic application of spinel ferrite nanoparticles and nanocomposites in wastewater treatment: Review. *Sustainable Materials and Technologies*, 23, e00140. <https://doi.org/10.1016/j.susmat.2019.e00140>
- [18] Chandrasekaran, S., Bowen, C., Zhang, P., Li, Z., Yuan, Q., Ren, X., & Deng, L. (2018). Spinel photocatalysts for environmental remediation, hydrogen generation, CO₂ reduction and photoelectrochemical water splitting. *Journal of Materials Chemistry A*, 6(24), 11078–11104. <https://doi.org/10.1039/C8TA03669A>
- [19] Zhu, C.-C., Jiang, T., Yang, H.-C., Li, Y.-Y., Li, Z.-J., & Yao, H.-C. (2023). ZnFe₂O₄ nanoparticles with iron-rich surfaces for enhanced photocatalytic water vapor splitting. *Applied Surface Science*, 636, 157842. <https://doi.org/10.1016/j.apsusc.2023.157842>
- [20] Bini, M., Ambrosetti, M., & Spada, D. (2021). ZnFe₂O₄, a green and high-capacity anode material for lithium-ion batteries: A review. *Applied Sciences*, 11(24), 11713. <https://doi.org/10.3390/app112411713>
- [21] Wang, C., Li, Y., Ruan, Y., Jiang, J., & Wu, Q.-H. (2017). ZnFe₂O₄-nanocrystal-assembled microcages as an anode material for high-performance lithium-ion batteries. *Materials Today Energy*, 3, 1–8. <https://doi.org/10.1016/j.mtener.2016.12.001>
- [22] Zhou, J., Wei, B., Wang, M., Yao, Z., Chen, P., Zhou, C., & Li, Z. (2021). Three-dimensional flower-like ZnFe₂O₄ ferrite-loaded graphene: Enhancing microwave absorption performance by constructing microcircuits. *Journal of Alloys and Compounds*, 889, 161734. <https://doi.org/10.1016/j.jallcom.2021.161734>
- [23] Hoque, S. M., Hossain, M. S., Choudhury, S., Akhter, S., & Hyder, F. (2016). Synthesis and characterization of ZnFe₂O₄ nanoparticles and its biomedical applications. *Materials Letters*, 162, 60–63. <https://doi.org/10.1016/j.matlet.2015.09.066>
- [24] Sugi, S., Radhika, S., & Padma, C. M. (2022). Co-precipitation of zinc ferrite nanoparticles in the presence and absence of polyvinyl alcohol with other constant parameters and the analysis of polyvinyl alcohol-mediated zinc ferrite nanoparticles. *Materials Chemistry and Physics*, 292, 126799. <https://doi.org/10.1016/j.matchemphys.2022.126799>
- [25] Islam, S., Rahman, M. L., Moni, M. R., Biswas, B., Ahmed, M. F., & Sharmin, N. (2023). Impacts of annealing temperature on microstructure, optical and electromagnetic properties of zinc ferrite nanoparticles synthesized by polymer-assisted sol–gel method. *Arabian Journal of Chemistry*, 16(10), 105186. <https://doi.org/10.1016/j.arabjc.2023.105186>
- [26] Andhare, D. D., Jadhav, S. A., Khedkar, M. V., Somvanshi, S. B., More, S. D., & Jadhav, K. M. (2020). Structural and chemical properties of ZnFe₂O₄ nanoparticles synthesised by chemical co-precipitation technique. *Journal of Physics: Conference Series*, 1644(1), 012014. <https://doi.org/10.1088/1742-6596/1644/1/012014>
- [27] Kumar, V., Kumar, N., Das, S. B., Singh, R. K., Sarkar, K., & Kumar, M. G. (2021). Sol-gel assisted synthesis and tuning of structural, photoluminescence, magnetic and multiferroic properties by annealing temperature in nanostructured zinc ferrite. *Materials Today: Proceedings*, 47, 6242–6248. <https://doi.org/10.1016/j.matpr.2021.05.215>
- [28] Franklin, J. B., Anand, G. T., Sujitha, G. M., Sundaram, S. J., Raj, A. D., & Kaviyarasu, K. (2022). Synthesis and characterization of zinc ferrite nanoparticles using *Prunus dulcis* (almond gum) for antibacterial applications. *Materials Today: Proceedings*, 68(3), 593–601. <https://doi.org/10.1016/j.matpr.2022.08.429>
- [29] Abdulhamid, Z. M., Dabbawala, A. A., Delclos, T., Straubinger, R., Rueping, M., Polychronopoulou, K., & Anjum, D. H. (2023). Synthesis, characterization, and preliminary insights of ZnFe₂O₄ nanoparticles into potential applications, with a focus on gas sensing. *Scientific Reports*, 13, 19705. <https://doi.org/10.1038/s41598-023-46960-w>
- [30] adhav, S. S., Salunke, V. Y., Jadhav, C. H., Mujawar, S. H., & Bhongale, S. R. (2021). Preparation of zinc ferrite by solid state method and its characterizations. *Macromolecular Symposia*, 400(1), 2100070. <https://doi.org/10.1002/masy.202100070>
- [31] Gharibshahian, M., et al. (2025). Magnetic properties of ZnFe₂O₄ ferrite nanoparticles prepared by sol-gel auto combustion method: Study under Mössbauer, field cooling and VSM techniques. *Ceramics International*, 51(24), 41272–41279. <https://doi.org/10.1016/j.ceramint.2025.06.351>