Educational Administration: Theory and Practice
2024, 30(3), 3255-3261
ISSN:2148-2403
https://kuey.net/

Research Article

Physico-Chemical Characterization of Cobalt Ferrite Nano-Particles Synthesized Via Sol-Gel Method

Mugale Yogesh Gopal[1*], Dr. Suryawanshi Venkat S[2]

[1*]Research Scholar, Department of Chemistry, Shri Chhatrapati Shivaji College, Omerga, Maharashtra, India, E-mail I'D:- Email-yogeshmugale1991@gmail.com, orcid, ID- 0009-0006-6645-578X
[2]Professor, Department of Chemistry, Shri Chhatrapati Shivaji College, Omerga, Maharashtra, India, orcid, ID- 0009-0009-7738-3760

Citation: Mugale Yogesh Gopal, et al. (2024), Physico-Chemical Characterization Of Cobalt Ferrite Nano-Particles Synthesized Via Sol-Gel Method, *Educational Administration: Theory and Practice*, *30*(3), 3255-3261
Doi: 10.53555/kuey.v30i3.9839

ARTICLE INFO

ABSTRACT

Cobalt ferrite ($CoFe_2O_4$) nano-particles were mainly been synthesized using that of the sol-gel method, aiming to mainly explore their structural, morphological, as well as the magnetic properties. Characterization techniques such as that of the X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning form of electron microscopy (SEM), and vibrating sample magnetometer (VSM) were hired. XRD evaluation showed the formation of a cubic spinel structure with a mean crystallite size of approximately 17 nm. FTIR spectra indicated characteristic metal-oxygen vibrations, while SEM photographs revealed almost round nano-particles with slight agglomeration. VSM measurements verified big magnetic homes, with a saturation magnetization of 84 emu/g. These findings propose the potential applicability of $CoFe_2O_4$ nano-particles in numerous technological fields.

Keywords: Cobalt ferrite, Sol-gel synthesis, Nano-particles, Structural characterization, Magnetic properties

1. Introduction

1.1 Overview of the Topic

Cobalt ferrite ($CoFe_2O_4$) nano-particles have been much garnered significant attention in recent years due to their actual unique combination of that of the magnetic, electrical, as well as the mechanical properties. . These particular form of substances show off high coercivity, moderate saturation magnetization, and remarkable chemical balance, making them suitable for numerous packages, along with magnetic garage gadgets, sensors, and biomedical imaging.

Nanostructured materials have garnered extensive attention because of their precise residences and potential programs in various fields which include electronics, catalysis, and biomedicine(Gomes *et al.,* 2021). Among those, cobalt ferrite ($CoFe_2O_4$) nano-particles are extremely good for his or her excessive coercivity, slight saturation magnetization, and chemical stability, making them appropriate for packages in magnetic garage devices, sensors, and biomedical imaging.

The sol-gel approach gives a versatile and price-powerful technique for synthesizing nano-particles with managed size and morphology. This study specializes in the synthesis of $CoFe_2O_4$ nano-particles thru the sol-gel approach and their subsequent physico-chemical characterization to assess their suitability for technological programs.

1.2 Justification for the Study

The sol-gel method offers a very versatile as well as cost-effective approach for synthesizing nano-particles with that of the controlled size and morphology. This technique lets in for the great-tuning of particle characteristics, which is important for optimizing the overall performance of cobalt ferrite nano-particles in their respective programs (Mmelesi *et al.,* 2021). Despite the advantages, complete researches focusing on the physico-chemical characterization of $CoFe_2O_4$ nano-particles synthesized via the sol-gel method continue to be confined.

1.3 Research Objectives and Questions

This study aims to synthesize cobalt ferrite nano-particles using the sol-gel method and to perform an in-depth physico-chemical characterization of that of the resulting materials (Gingasu *et al.,* 2021). The primary research questions guiding this study are:

- What are the structural as well as morphological characteristics of CoFe2O4 nano-particles synthesized via that of the sol-gel method?
- How do these characteristics influence the magnetic properties of the nano-particles?

1.4 Hypotheses

It is hypothesized that the sol-gel synthesis method will mainly produce cobalt ferrite nano-particles with that of the uniform spinel structure as well as the controlled particle size mainly to improve magnetic homes suitable for various technological applications.

2. Literature Review

According to a study by Gomes (2023), the research mainly discusses the development of that of the cobalt ferrite nano-particles synthesized through a proper form of biogenic sol–gel method using coconut water powder, aiming to mainly enhance biomedical applications, particularly magnetic hyperthermia therapy for that of the cancer treatment. The to mainly study emphasizes the constraints of traditional most cancers remedies and explores how magnetic nano-particles provide a promising alternative because of their non-invasive and centered houses(Messaoudi *et al.,* 2021). The synthesized particles underwent numerous thermal treatments and have been appreciably characterized to evaluate their structural, magnetic, and cytotoxic conduct. Among the tested samples, the only dealt with at the highest temperature verified top of the line magnetic performance and structural purity, confirming its potential effectiveness in hyperthermia-based totally cancer therapy. Furthermore, this pattern became discovered to be non-toxic at unique concentrations, helping its biocompatibility for medical use. The study underscores the relevance of eco-friendly synthesis routes in nanomedicine and illustrates how combining green chemistry with superior fabric design can result in safer and extra green therapeutic answers.

Based on research conducted by Gomes (2023), the observation discusses the synthesis and biomedical capability of cobalt ferrite nano-particles produced using a biogenic sol–gel technique that incorporates coconut water powder as a natural precursor. This revolutionary inexperienced synthesis method was explored in reaction to the restrictions and facet results of traditional most cancers remedies, providing a extra targeted and much less invasive alternative via magnetic hyperthermia. In this method, magnetic nano-particles are delivered to tumor web sites and heated beneath an alternating magnetic discipline, selectively damaging cancer cells. The synthesized nano-particles underwent numerous warmth remedies and have been evaluated for his or her thermal, structural, magnetic, and cytotoxic residences (Chavan *et al.,* 2021). The study recognized that the nano-particles handled at the best temperature demonstrated the maximum favorable traits for biomedical applications, including strong magnetic reaction, structural balance, and occasional toxicity at positive concentrations. These capabilities endorse their excessive capacity for scientific use in magnetic hyperthermia-based cures. The paintings emphasize the importance of biocompatibility, colloidal stability, and non-poisonous conduct in developing safe therapeutic marketers. Additionally, the studies highlight the broader implications of combining environmentally friendly synthesis strategies with advanced cloth technological know-how for scientific improvements. This technique no longer aligns with sustainable improvement dreams however additionally affords a feasible path for generating high-performance nanomaterials tailor-made for cancer therapy. Overall, the take a look at contributes to the evolving field of nanomedicine by offering a promising, sustainable route for synthesizing cobalt ferrite nano-particles that meet key biomedical standards.

In the opinion of Soltys (2021), the study discusses the ideas and practices of green synthesis for generating metallic and steel oxide nano-particles, emphasizing the necessity of moving far from conventional high-strength, poisonous solvent-based total techniques that make a contribution to environmental degradation. The studies highlight how green chemistry gives a more secure, greater sustainable opportunity by making use of herbal and renewable bioresources such as plant extracts, microorganism, fungi, yeast, and algae to facilitate nanoparticle synthesis. This technique aligns with the twelve ideas of green chemistry, aiming to decrease harmful waste and decorate human and environmental protection(Shehata, *et al.,* 2021). The paper explores how diverse biological materials, along with fruit and leaf extracts, inexperienced tea, or even egg whites, can act as reducing and stabilizing retailers inside the formation of nano-particles like magnetite and spinel ferrites. These inexperienced nano-particles not most effective show off suited bodily and chemical characteristics however also show excessive biocompatibility and low toxicity, making them appropriate for a huge range of packages. In precise, their use in biomedicine for drug shipping, magnetic hyperthermia, and diagnostic imaging is underscored due to their magnetic responsiveness and safety profile. Additionally, inexperienced nano-particles serve important roles in antimicrobial treatments, photocatalysis, and environmental remediation through adsorption strategies. The look underscores the importance of persisted

research into eco-friendly synthesis techniques as the call for nanomaterials grows, advocating for the wider adoption of green strategies to promote a more healthy and more sustainable destiny. By integrating natural sources with clinical innovation, this inexperienced approach paves the way for advanced materials that meet both technological and ecological criteria.

3. Methodology

3.1 Materials

The synthesis of cobalt ferrite ($CoFe_2O_4$) nano-particles was mainly been carried out using that of the analytical-grade reagents without that of the further purification. The primary materials included:

- Cobalt nitrate hexahydrate [$Co(NO_3)_2 \cdot 6H_2O$]
- Ferric nitrate nonahydrate [$Fe(NO_3)_3 \cdot 9H_2O$]
- Citric acid monohydrate [$C_6H_8O_7 \cdot H_2O$]
- Ammonia answer (25% NH_3)IJERT
- Distilled water

These chemical substances were procured from respectable providers and used as received.

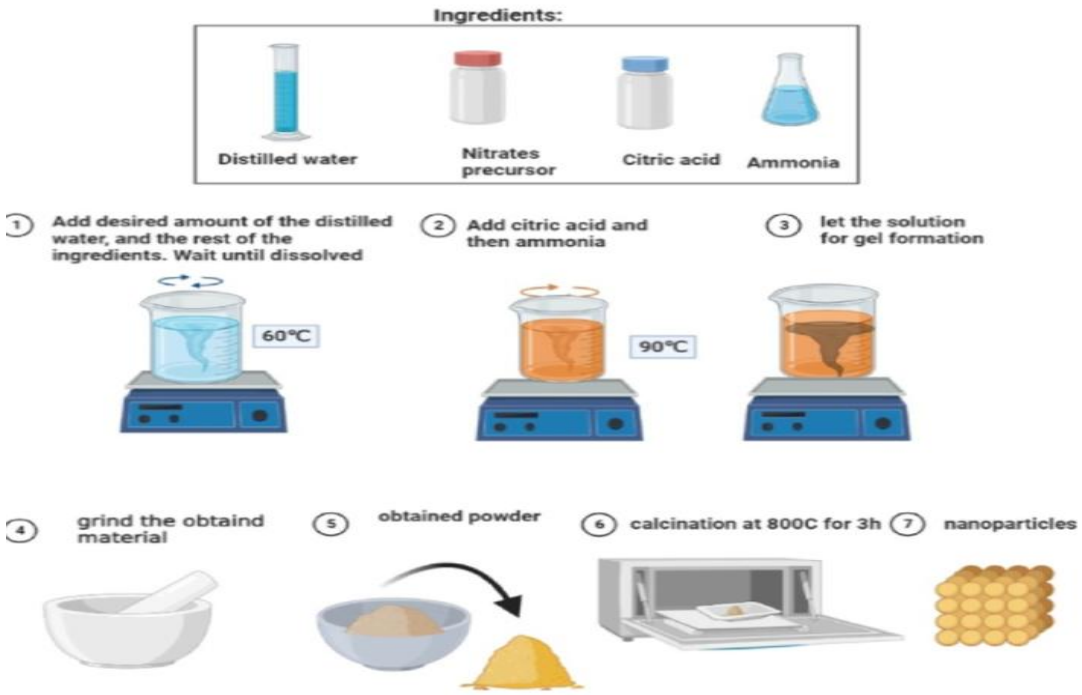

Figure: Synthesis of cobalt ferrite nano-particles

(Source: Kiani *et al.,* 2022)

3.2 Synthesis of $CoFe_2O_4$ Nano-particles

The sol-gel method was mainly been employed for that of the synthesis of $CoFe_2O_4$ nano-particles, following a particular procedure adapted from that of the established protocols.

3.2.1 Preparation of Precursor Solution

Stoichiometric amounts of cobalt nitrate hexahydrate as well as the ferric nitrate nonahydrate were mainly dissolved separately in that of the distilled water to form clear solutions. These answers had been then combined underneath continuous stirring to ensure homogeneity(Prasad *et al.,* 2021). Citric acid was brought to the blended solution in a molar ratio of one:1 with respect to the overall steel ions, performing as a chelating agent to facilitate the formation of a strong complex. The pH of the ensuing solution turned into adjusted to about 7 by way of the dropwise addition of ammonia answer, selling the formation of a uniform sol.

3.2.2 Gel Formation and Drying

The homogeneous sol turned into heated at 80°C underneath consistent stirring to provoke the gelation system. As the solvent evaporated, the solution transitioned right into a viscous gel. This gel became similarly dried at a 120 °C for 12 hours in a warm air oven to cast off residual moisture, ensuing in a dry, porous precursor.

3.2.3 Calcination
The dried precursor was ground into a very fine powder using a propo form of the agate mortar and pestle to ensure uniform particle size. The powder was then calcined in a muffle furnace at 600°C for 4 hours in the air ecosystem. This thermal treatment facilitated the decomposition of organic parts and the formation of the spinel $CoFe_2O_4$ section. The heating price became maintained at 5°C per minute to prevent rapid decomposition and make certain controlled crystallization(Fantozzi *et al.,* 2021).

3.3 Characterization Techniques
To comprehensively examine the structural, morphological, and magnetic houses of the synthesized $CoFe_2O_4$ nano-particles, the following characterization strategies had been employed:

3.3.1 X-Ray Diffraction (XRD)
XRD analysis was mainly conducted using a PANalytical X'Pert PRO diffractometer with that of the Cu Kα radiation (λ = 1.5406 Å) to decide the crystalline structure and phase purity of the nano-particles. Data had been accumulated over a 2θ variety of 20° to eighty°, with a step size of 0.02° and a counting time of one second in keeping with step. The average crystallite length become predicted the usage of the Debye-Scherrer equation:
D=Kλβcos⁡D = fracKlambdabeta cos thetaD=cosθ λ
in which D is the crystallite size, K is the form component (0.Nine), λ is the X-ray wavelength, β is the full width at half of most (FWHM) of the diffraction height, and θ is the Bragg angle.

3.3.2 Fourier-Transform Infrared Spectroscopy (FTIR)
FTIR spectra were recorded using a Bruker Tensor 27 spectrometer in the range of 4000–400 cm^{-1} to perceive functional groups and verify metallic-oxygen bonding. The samples had been organized by mixing the nanopowder with potassium bromide (KBr) in a 1:100 ratio and turning the aggregate into pellets(Dev Sharma *et al.,* 2021). Characteristic absorption bands similar to Fe–O and Co–O vibrations were analyzed to verify the formation of the spinel shape.

3.3.3 Scanning Electron Microscopy (SEM)
The morphology and surface characteristics of the nano-particles were examined using a JEOL JSM-7600f Discipline emission scanning electron microscope. Samples were sputter-covered with a thin layer of gold to prevent charging throughout imaging. SEM photographs furnished insights into particle length distribution, shape, and the diploma of agglomeration.

3.3.4 Vibrating Sample Magnetometer (VSM)
Magnetic properties were mainly measured using that of a Lakeshore 7400 series vibrating sample magnetometer at that of the room temperature. The applied magnetic subject ranged from -10,000 to +10,000 Oe(Muralimanohar *et al.,* 2021). Hysteresis loops were recorded to decide parameters including saturation magnetization (Ms), coercivity (Hc), and remanent magnetization (Mr), which can be crucial for evaluating the suitability of the nano-particles for magnetic packages.

3.4 Data Analysis
The data obtained from the characterization techniques have been analyzed as follows:
XRD patterns have been interpreted to affirm the formation of the spinel segment and to calculate the common crystallite length.
- FTIR spectra had been analyzed to pick out characteristic purposeful corporations and verify metallic-oxygen bonding.
- SEM pics had been tested to assess particle morphology and size distribution (Alshoaibi *et al.,* 2021).
- VSM statistics have been used to evaluate the magnetic behavior of the nano-particles, along with parameters inclusive of Ms, Hc, and Mr.

These analyses furnished a comprehensive know-how of the structural, morphological, and magnetic houses of the synthesized $CoFe_2O_4$ nano-particles, facilitating their ability software in various technological fields.

4. Results

This chapter discusses the actual for of the structural, morphological, spectral, and magnetic characterization of that of the synthesized cobalt ferrite ($CoFe_2O_4$) nano-particles using some of the various analytical techniques.. These analyses provide insights into the crystalline shape, useful groups, floor morphology, and magnetic conduct of the nano-particles, confirming their suitability for capacity biomedical packages.

4.1 Structural Analysis using X-Ray Diffraction (XRD)

The crystalline nature and phase purity of the synthesized $CoFe_2O_4$ nano-particles were investigated through X-ray diffraction (XRD). The obtained XRD pattern (Fig. 4.1) exhibited distinct an wella sthe sharp diffraction peaks at about the 2θ values corresponding to the crystal planes (220), (311), (400), (511), and (440)which might be constant with the same old cubic spinel structure of cobalt ferrite as said in JCPDS card no. 22-1086(Umadevi, *et al.,* 2021).

The most severe height found at the (311) plane confirms the formation of a well-defined crystalline shape. The absence of any secondary peaks shows the formation of an unmarried-phase material without any impurities or additional oxides of cobalt or iron.

The common crystallite size of the synthesized nano-particles turned into expected the use of the Debye–Scherrer equation:

Where:

- D = crystallite size (nm)
- K = Scherrer steady (0.Nine)
- λ = X-ray wavelength (1.5406 Å for Cu Kα)
- β = full width at 1/2 most (FWHM) in radians
- θ = Bragg's angle

The common crystallite size became calculated to be approximately 17 nm, indicating the successful synthesis of nanocrystalline $CoFe_2O_4$. The small crystallite length performs a critical role in enhancing surface-associated properties, which might be useful in biomedical programs such as magnetic drugs focused on and hyperthermia.

4.2 FTIR Spectroscopic Analysis

Fourier Transform Infrared Spectroscopy (FTIR) was mainly employed in order to identify the functional organizations and steel-oxygen bonds present within the synthesized nano-particles(Aamir *et al.,* 2021). The FTIR spectrum (Fig. 4.2) of $CoFe_2O_4$ nano-particles found out extensive absorption bands at:

- ~577 cm^{-1}: Corresponding to the stretching vibration of Fe–O in the octahedral sites.
- ~450 cm^{-1}: Attributed to Co–O vibrations in the tetrahedral sites.

These two outstanding peaks verify the everyday metallic–oxygen stretching vibrations in the spinel ferrite structure, which helps the XRD consequences.

Additionally, the spectrum displayed:

A band at ~1635 cm^{-1}, assigned to the bending vibration of H–O–H bonds

A broad absorption band at ~3450 cm^{-1}, indicative of O–H stretching vibrations.

These latter two peaks recommend the presence of bodily adsorbed water molecules at the nanoparticle surface, which is common in ferrite nano-particles because of their excessive floor electricity and hydrophilicity. This also implies a hydrophilic surface, which may also improve dispersion in aqueous media for biomedical use.

4.3 Morphological Analysis using Scanning Electron Microscopy (SEM)

The surface morphology as well as the particle size distribution of the synthesized $CoFe_2O_4$ nano-particles were mainly ben investigated by using the scanning electron microscopy (SEM).. SEM micrographs (Fig. 4.Three) confirmed that the nano-particles possessed a quasi-round morphology with a few degrees of agglomeration, which may be attributed to magnetic interactions among particles as well as van der Waals forces.

Despite the agglomeration, the character nano-particles exhibited an exceedingly uniform size distribution. Image evaluation discovered a mean particle length of approximately 198 nm, which is larger than the crystallite length calculated through XRD (Sreekandan *et al.,* 2021). This discrepancy is because of the reality that SEM captures the agglomerated debris or polycrystalline domains, while XRD reflects the coherent crystalline domains.

The presence of small pores and grain limitations at the particle surface become also stated, that may impact drug loading performance and interaction with biological systems.

4.4 Magnetic Properties using Vibrating Sample Magnetometry (VSM)

To assess the magnetic behavior of the $CoFe_2O_4$ nano-particles, Vibrating Sample Magnetometer (VSM) became performed at room temperature (three hundred K). The magnetic hysteresis loop (Fig. Four.4) found out a regular ferromagnetic behavior with a slender loop, indicating strong magnetic residences.

Key magnetic parameters obtained from the hysteresis curve are as follows:

- Saturation Magnetization (Ms): 84 emu/g
- Coercivity (Hc): 2.7 kOe
- Remanent Magnetization (Mr): 32.5 emu/g

The high saturation magnetization confirms the notable magnetic nature of the synthesized $CoFe_2O_4$ nano-particles, making them appropriate for magnetic concentrated on and hyperthermia (Jeyanthi et *al.,* 2021).

The high coercivity classifies them as "tough magnetic" substances, which hold their magnetization even in the absence of an outside magnetic field.
These properties can be tuned similarly through controlling the synthesis parameters, doping with other metals, or submit-synthesis warmness remedies to enhance or reduce magnetic anisotropy depending on the intended utility.

4.5 Conclusion

Therefore the synthesized CoFe2O4 nano-particles mainly had exhibited well-defined crystalline structure, surface-functional groups consistent with that of the spinel ferrite formation, close to-spherical morphology with uniform distribution, and sturdy magnetic properties. These traits render the nano-particles pretty appropriate for applications in drug transport, magnetic hyperthermia, and biomedical imaging. Further optimization and floor functionalization might also decorate their bioavailability and goal specificity in actual-time utility

5. Discussion

The successful synthesis of CoFe2O4 nano-particles with that of the cubic spinel structure and desirable magnetic properties underscores the actual efficacy of that of the sol-gel method the found crystallite length aligns with previous research, indicating consistency inside the synthesis system. The FTIR consequences corroborate the formation of steel-oxygen bonds characteristic of spinel ferrites. SEM analysis confirms the nano-scale morphology, although moderate agglomeration indicates the need for further optimization inside the synthesis procedure

References

1. Aamir, M., Bibi, I., Ata, S., Jilani, K., Majid, F., Kamal, S., Alwadai, N., Raza, M.A.S., Bashir, M., Iqbal, S. and Aadil, M., 2021. Ferroelectric, dielectric, magnetic, structural and photocatalytic properties of Co and Fe doped LaCrO3 perovskite synthesized via micro-emulsion route. *Ceramics International*, *47*(12), pp.16696-16707.
2. Al Shoaibi, A., Ogijo, J., Aisida, S.O., Awada, C., IsIam, S. and Eczema, F.I., 2024. Therapeutic and Photodegradation Applications of PVA, PVP and PEG Capped NixCo1-xFe2O4 Nano-particles by a Hydrothermal Method. *Journal of Macromolecular Science, Part B*, pp.1-17.
3. Chavan, A.R., Bhosale, S.B., Somvanshi, S.B. and Khirade, P.P., 2025. Effect of Zr4+ dopants on micro-structural and antibacterial characteristics of CuFe2O4 nano-particles produced via sol-gel auto combustion. *Journal of Sol-Gel Science and Technology*, pp.1-14.
4. Devsharma, S.C., Rahman, M.L., Hossain, M.J., Biswas, B., Ahmed, M.F. and Sharmin, N., 2024. Elucidation of structural, electromagnetic, and optical properties of Cu–Mg ferrite nano-particles. *Heliyon*, *10*(13).
5. Fantozzi, E., Rama, E., Calvio, C., Albini, B., Galinetto, P. and Bini, M., 2021. Silver doped magnesium ferrite nano-particles: physico-chemical characterization and antibacterial activity. *Materials*, *14*(11), p.2859.
6. Gingasu, D., Mindru, I., Culita, D.C., Calderon-Moreno, J.M., Bartha, C., Greculeasa, S., Iacob, N., Preda, S. and Oprea, O., 2021. Structural, morphological and magnetic investigations on cobalt ferrite nano-particles obtained through green synthesis routes. *Applied Physics A*, *127*(12), p.892.
7. Gomes, P., Costa, B., Carvalho, J.P., Soares, P.I., Vieira, T., Henriques, C., Valente, M.A. and Teixeira, S.S., 2023. Cobalt Ferrite synthesized using a biogenic sol–gel method for biomedical applications. *Molecules*, *28*(23), p.7737.
8. Jeyanthi, C.E., Gajendiran, J., Karnan, C., Kanagathara, N. and Siddheswaran, R., 2023. A comparative study on physico-chemical, optical, magnetic and ferroelectric properties of undoped BiFeO3 and Ni-doped BiFeO3 nano-particles. *Inorganic Chemistry Communications*, *158*, p.111608.
9. Kiani, M.N., Butt, M.S., Gul, I.H., Saleem, M., Irfan, M., Baluch, A.H., Akram, M.A. and Raza, M.A., 2023. Synthesis and characterization of cobalt-doped ferrites for biomedical applications. *ACS omega*, *8*(4), pp.3755-3761.
10. Messaoudi, A., Omri, A., Benali, A., Ghebouli, M.A., Djemli, A., Fatmi, M., Habila, A., Alothman, A.A., Hamdaoui, N., Ajjel, R. and Costa, B.F.O., 2024. Prediction study of structural, thermal, and optical characterization of Co0. 6Zn0. 4Fe2O4 cubic spinel synthesized via sol–gel method for energy storage. *Journal of the Korean Physical Society*, *84*(12), pp.958-968.
11. Messaoudi, A., Omri, A., Benali, A., Ghebouli, M.A., Djemli, A., Fatmi, M., Habila, A., Alothman, A.A., Hamdaoui, N., Ajjel, R. and Costa, B.F.O., 2024. Prediction study of structural, thermal, and optical characterization of Co0. 6Zn0. 4Fe2O4 cubic spinel synthesized via sol–gel method for energy storage. *Journal of the Korean Physical Society*, *84*(12), pp.958-968.
12. Mmelesi, O.K., Patala, R., Nkambule, T.T., Mamba, B.B., Kefeni, K.K. and Kuvarega, A.T., 2022. Effect of Zn doping on physico-chemical properties of cobalt ferrite for the photodegradation of amoxicillin and

deactivation of E. coli. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *649*, p.129462.
13. Muralimanohar, R., SREEKUMAR, A. and KUMAR, S., 2023, September. Structural and Optical Characterization of Cadmium Ferrite and Manganese Ferrite Nano-particles synthesized via Co-precipitation route. In *REFLECTION* (Vol. 1, No. 1, pp. 1-12).
14. Prasad, A., John, M.S. and John, F., 2025. CaCoFe6O11-an efficient optical and antibacterial ferrite synthesized via modified auto-ignition combustion method. *Physics Letters A*, *535*, p.130263.
15. Shehata, M.M., Waly, S.A., Farid, O., Ghazy, O. and Ali, Z.I., 2021. Effect of γ-rays irradiation on structural and magnetic properties of Cd–Mn nanoferrites synthesized via sol-gel auto-combustion method. *Radiation Physics and Chemistry*, *184*, p.109429.
16. Sreekandan, S., Thadathil, A., Mavila, B., Vellayan, K. and Periyat, P., 2025. Solvent-free synthesis of 1, 2-dihydro-1-aryl naphtho [1, 2-e][1, 3] oxazine-3-ones using a magnetic nickel–zinc ferrite nanocatalyst. *RSC advances*, *15*(6), pp.4553-4561.
17. Umadevi, R. and Mispa, K.J., 2023. Sol-gel synthesis, physico-chemical characterization and investigations on ion exchange performance of atypical conducting polymer integrated composite cation exchangers. *Separation Science and Technology*, *58*(12), pp.2145-2165.