

Co-Substituted Ni–Zn Ferrite Reinforced PVA Nanocomposites as High-Performance Electromagnetic Wave Absorbers in the X-Band Region

Ritu Ritu

Banasthali University

Sunil Kumar Dewanda

Banasthali University

P.K. Bhamu

Banasthali University

M.G. Siddiqui

Banasthali University

P.A. Alvi

Banasthali University

B.L. Choudhary

blcphysics@gmail.com

Banasthali University

Research Article

Keywords: Sol-gel, Ferrites, Rietveld, EMI, Nanocrystalline

Posted Date: August 26th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10701067/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Emergent Materials on October 13th, 2026. See the published version at <https://doi.org/10.1007/s42247-026-01556-8>.

Co-Substituted Ni–Zn Ferrite Reinforced PVA Nanocomposites as High-Performance Electromagnetic Wave Absorbers in the X-Band Region

Abstract

Cobalt-substituted nickel–zinc ferrites with the composition $\text{Co}_x\text{Ni}_{1-x-y}\text{Zn}_y\text{Fe}_2\text{O}_4$ ($x = 0.2, 0.4, 0.6, \text{ and } 0.8; y = 0.1$) were synthesized via the sol–gel method to investigate the influence of Co^{2+} substitution. XRD analysis confirmed the formation of a single-phase cubic spinel structure. Rietveld refinement further verified the crystallographic purity of the synthesized ferrites, while a systematic variation in lattice parameters was observed with increasing cobalt concentration. FESEM micrographs revealed nearly spherical nanoparticles with homogeneous grain distribution. FTIR and Raman spectroscopic studies confirmed the characteristic vibrational modes of the spinel ferrite structure, indicating the preservation of structural integrity after cobalt incorporation. UV–Visible spectroscopy showed a gradual reduction in the optical band gap from 1.45 to 1.07 eV, suggesting significant modification of the electronic structure. Electrical measurements exhibited frequency-dependent conductivity and impedance behavior, with enhanced conductivity for Co-substituted compositions. To evaluate their practical applicability, ferrite/PVA nanocomposite films were fabricated and investigated in the X-band frequency range relevant to 5G communication systems. The nanocomposites exhibited high dielectric properties and excellent electromagnetic interference shielding performance. The optimized composition demonstrated a reflection loss ranging from -19.86 to -45.33 dB, highlighting its strong potential for advanced microwave absorption and high-performance EMI shielding applications.

Keywords: Sol-gel, Ferrites, Rietveld, EMI, Nanocrystalline.

1. Introduction

In recent years, spinel ferrites have become among the most widely studied magnetic oxide materials because of their excellent structural stability, high electrical resistivity, and investigated for other technological applications[1]. These materials are generally represented by the formula MFe_2O_4 where M is a divalent metal ion including cobalt, nickel, zinc, and magnesium. Among the various ferrite systems, cobalt–nickel–zinc ferrites have captivated special consideration due to their useful combination of dielectric, and electrical properties[2], [3]. Because of these characteristics, they are considered suitable for applications like high-frequency devices, microwave absorbers, sensors, transformers, catalysts, and electromagnetic interference shielding. A key advantage of spinel ferrites is that their properties can be modified by changing the type and number of cations present at the tetrahedral and octahedral sites of the crystal structure. This makes them highly promising materials for multifunctional applications. Cobalt–nickel–zinc ferrites belong to the mixed spinel ferrite, in which the distribution of Co^{2+} , Ni^{2+} , Zn^{2+} , and Fe^{3+} ions between tetrahedral (A) and octahedral (B) sites strongly affects the overall structural and electrical behavior[4]. Cobalt ions usually increase magneto crystalline anisotropy and coercivity, while nickel ions improve magnetic permeability and structural stability. zinc ions are non-magnetic and generally prefer tetrahedral sites, where they alter the indirect exchange interactions between A and B sites, leading to changes in dielectric response. Due to the combined effect of these cations, cobalt substituted nickel zinc ferrites often show a desirable balance of high resistivity, moderate magnetization, low eddy current loss, and enhanced dielectric polarization. The properties of cobalt substituted nickel zinc ferrites are highly dependent on factors such as synthesis method, particle size, morphology, crystallinity, and chemical composition. Different preparation techniques, including sol – gel auto-combustion, co-precipitation, hydrothermal methods, solid-state reaction, and combustion synthesis, have been used to prepared ferrites with controlled microstructure and improved performance. In addition, the reduction in particle size

influences the domain structure and spin behavior, which directly affects the magnetic loss processes responsible for electromagnetic wave attenuation[5]. For this reason, nanostructured cobalt substitution nickel zinc ferrites are considered more suitable for shielding and absorbing applications. The incorporation of ferrite nanoparticles into polymer matrices results in polymer ferrite-based nanocomposites that combine the advantages of both components. The polymer provides flexibility, light weight, and easy processability, while the ferrite phase contributes magnetic loss, interfacial polarization, and dielectric relaxation, which improve the attenuation of electromagnetic waves. Such nanocomposites often exhibit synergistic effects, leading to enhanced shielding effectiveness through absorption, multiple reflections, and impedance matching. The performance of these materials depends on several factors, including filler concentration, particle size, morphology, dispersion within the polymer matrix, thickness of the shield, and the nature of interfacial interactions between polymer and ferrite. In particular, cobalt substitution of nickel zinc ferrites are of great interest because their structural and dielectric properties can be tuned by changing the cation composition, which directly influences EMI shielding behavior[6]. Among various fillers used in polymer matrices, ferrite nanoparticles have captivated extensive attention because of their unique structural and the electrical properties. In such nanocomposites, EMI shielding originates from a combination of reflection, absorption, and multiple internal reflections. The effectiveness of shielding mainly depends on several parameters, including ferrite loading, particle size, distribution of the nanoparticles in the polymer matrix, thickness of the composite, and the frequency range of operation. A homogeneous distribution of ferrite nanoparticles in the PVA matrix can create strong interfacial polarization and improved impedance matching, thereby enhancing the absorption of incident electromagnetic waves[6], [7], [8]. These features make PVA/cobalt–nickel–zinc ferrite nanocomposites highly promising for use in lightweight, flexible, and efficient EMI shielding materials for modern electronic applications. In the present study,

cobalt substituted nickel zinc spinel ferrites having the general composition $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$). were synthesized via the sol-gel technique. The effect of Co^{2+} substitution on the structural, morphological, optical, and electrical properties was examined in detail[4]. Various analytical techniques, such as X-ray diffraction, Field emission scanning electron microscopy, Fourier transform infrared spectroscopy, Raman spectroscopy, UV-Visible spectroscopy, and Electrical studies such as Ac conductivity, Impedance, Nyquist plot, and Dielectric studies, were employed to evaluate the changes in the properties of the synthesized ferrites as a function of composition dependent changes in the synthesized ferrites. In addition, the prepared materials were further explored for their potential use in electromagnetic interference (EMI) shielding application[9].

2. Experimental Procedure

2.1. Synthesis Process of Nano-Ferrites

In the present study, cobalt-substituted nickel–zinc ferrite nanoparticles were successfully synthesized using the sol–gel auto-combustion method. Analytical-grade chemicals were employed as precursor materials for the synthesis (figure 1). Metal nitrates served as the source of cations, while citric acid was used as a chelating agent to facilitate complex formation and improve the homogeneity and solubility of the precursor solution. The metal nitrates and citric acid were mixed in their respective stoichiometric ratios and dissolved in deionized (DI) water under continuous magnetic stirring for 4–5 h to obtain a homogeneous solution.

Subsequently, aqueous ammonia (NH_3) was added dropwise to adjust the pH of the solution to the range of 10–12. Upon ammonia addition, the solution gradually turned brown, indicating the formation of a stable sol. Continued stirring promoted gel formation through enhanced complexation among the metal ions and the chelating agent. The resulting gel underwent a self-sustained exothermic combustion reaction, yielding a fine ferrite powder. The obtained product was allowed to cool naturally to room temperature and was then thoroughly ground using an

agate mortar and pestle to obtain a uniform nanopowder suitable for further characterization[12], [13], [14].

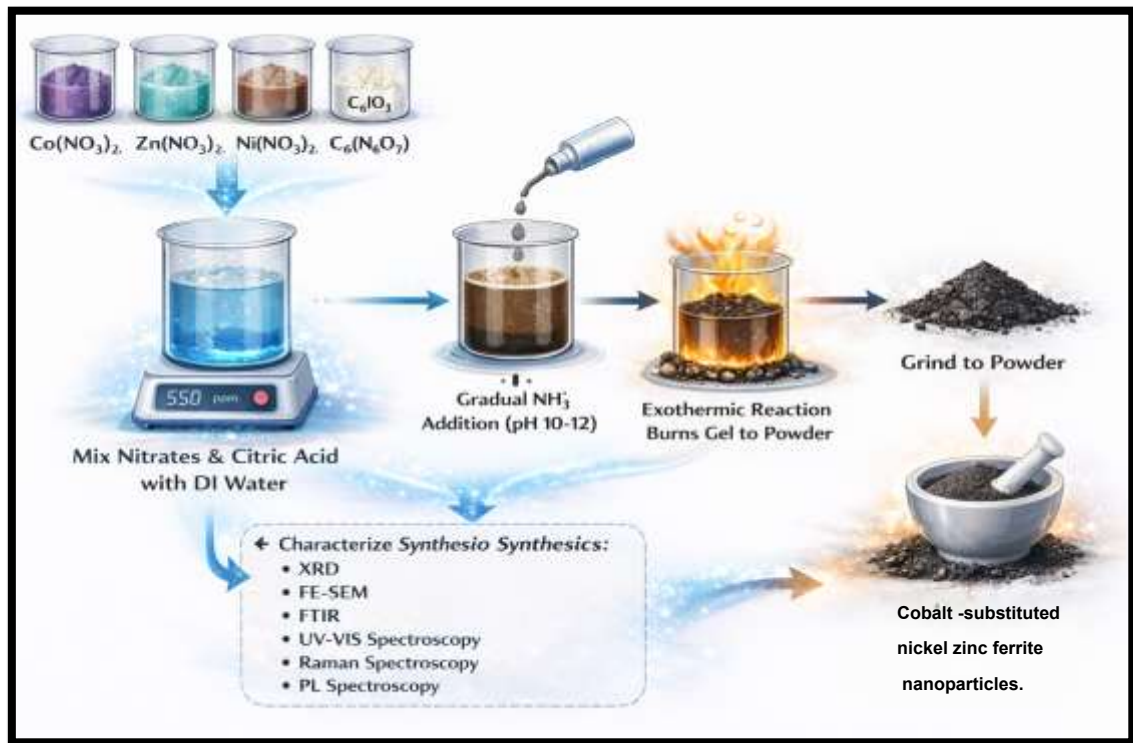


Figure1: Systematic diagram of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$) nano Ferrites.

2.2. Synthesis Process of Composite Film:

The PVA/nano-ferrite composite films were prepared using the solution-casting technique. Initially, the required amount of polyvinyl alcohol (PVA) was dissolved in distilled water and heated at 70–90 °C under continuous magnetic stirring until a clear and homogeneous solution was obtained (figure 2). Subsequently, the desired weight percentage of nano-ferrite powder was gradually added to the PVA solution and stirred continuously to ensure uniform dispersion of the nanoparticles throughout the polymer matrix. The resulting PVA/nano-ferrite suspension was then poured into a clean and leveled glass Petri dish to facilitate uniform film formation. The cast solution was dried in a hot-air oven at 40–60 °C for several hours to allow complete evaporation of the solvent. After thorough drying, the flexible composite film was carefully

peeled off from the casting surface and stored for further characterization and analysis[16], [17], [18].

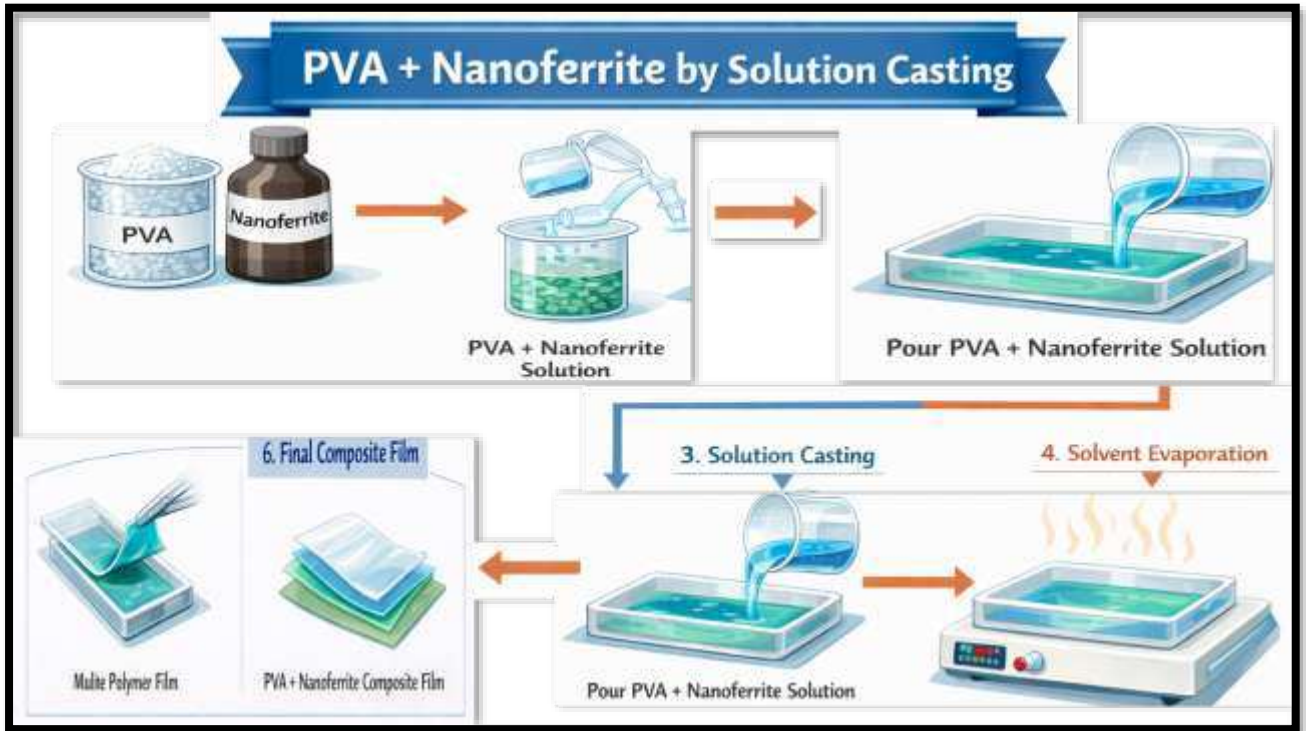


Figure 2: Systematic diagram of PVA/ $\text{Co}_x\text{Ni}_{(1-x-y)}\text{Zn}_y\text{Fe}_2\text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$) nanocomposite Film.

3. Result and Discussion

3.1. Structural Analysis

3.1.1 Rietveld refinement

The Rietveld refinement of the obtained XRD data were Evaluated to study the impact of Substitution of Cobalt (Co^{2+}) ions on Nickel Zinc ferrite. From the Rietveld refined XRD patterns, it is observed that the data is matching well with the experimentally determined data, showing differences between them[19], [20]. It is examined that, in the experimentally determined data, Bragg's reflection of XRD peaks is matching well with the determined data

Figure 3. Rietveld refinement of XRD patterns confirmed the single-phase cubic spinel structure with space group Fd-3 m. In the initial stage, global parameters like background and scale factors were refined. Afterwards, the refinement was carried out step by step for structural parameters, including lattice parameters, Goodness of fit (χ^2), Experimental factor (R_{EXP}), Profile factor (R_P), Weighted profile factor (R_{WP}) was determined, as shown in **Figure 3**, and presented in Table 1[21], [22], [23]. The quality of the fit between the experimental and calculated data is evaluated using parameters such as the goodness of fit (χ^2) and various R-factors, including the profile factor (R_P), weighted profile factor (R_{wp}), expected weighted profile factor (R_{exp})[22], [24], [25].

Table 1: The calculated structural refinement parameters, including R_P , R_{exp} , R_{wp} , and R_{GOF} , are listed.

Composition	R_{EXP}	R_P	R_{wp}	χ^2
0.2	1.054	0.901	1.135	1.157
0.4	1.044	0.785	0.987	0.893
0.6	1.031	0.748	0.939	0.830
0.8	1.086	0.787	0.988	0.827

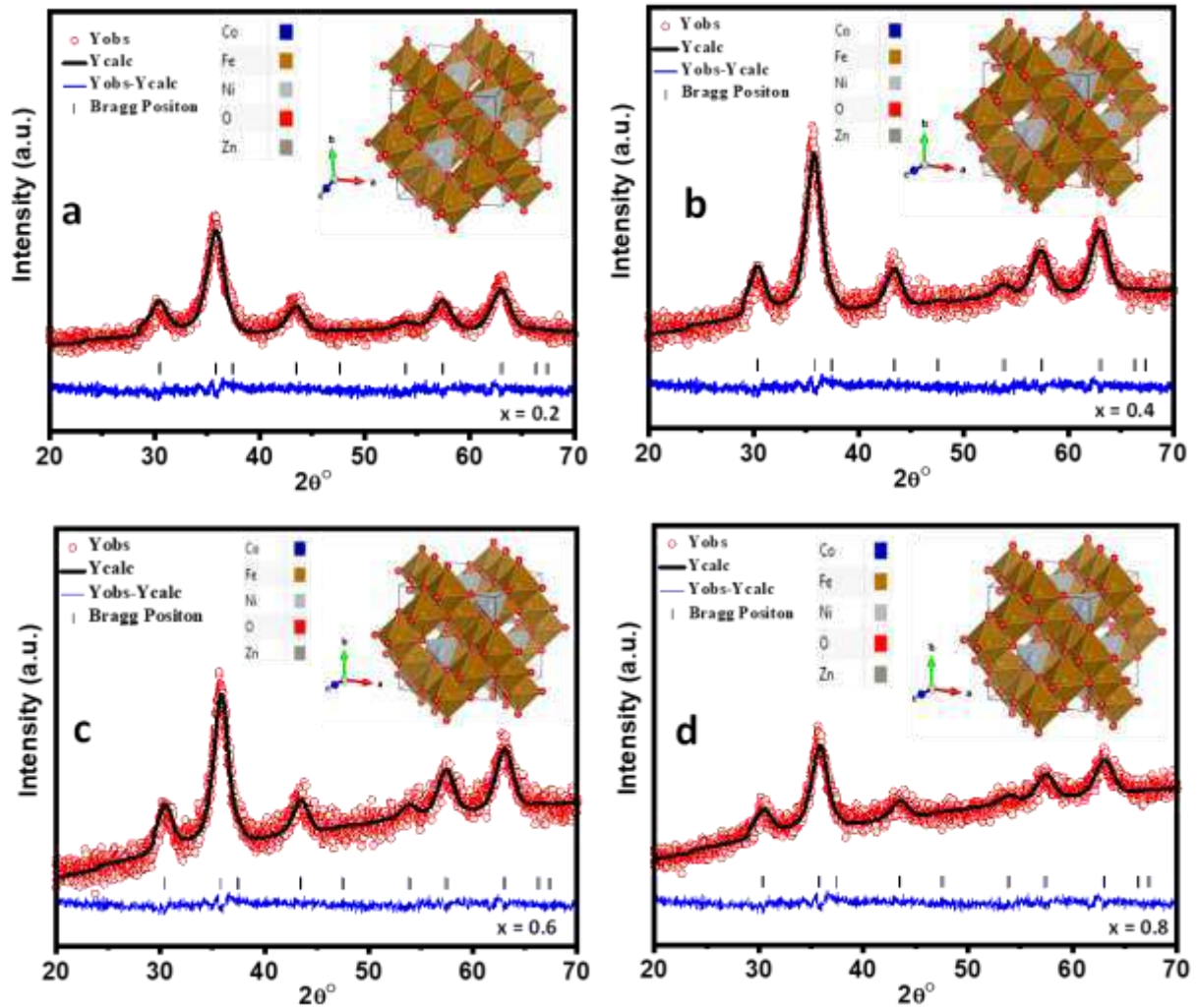


Figure 3: Rietveld refinement of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$).

3.1.2. X – Ray Diffraction

The XRD technique was used to determine both the crystal structure and phase composition of the nanomaterial. The study used XRD technique to examine the structural appearance of the fabricated nanoparticles[26]. The structural appearance of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$, (where $x = 0.2, 0.4, 0.6, 0.8$ and $y = 0.1$), and pure PVA and synthesized composite PVA/ $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ films for different ferrite composition is shown in **Figure 4**[27], [28]. was studied using a Cu-K α radiation source, and the X-ray diffractometer (XRD) was used. The range between 15° and 70° was used with 2θ degrees. All the diffraction peaks were found in the Fd-3m space group. The XRD patterns were obtained, and no additional peaks were found, signifying that the compounds were synthesized in a single phase. The broadening of XRD

peak reveal that the material is nano size. The XRD pattern for pure PVA reveal that it is semicrystalline in nature, showing two main peaks. The first broadening peak at $2\theta = 19.5^\circ$ correlates with the PVA crystalline phase, showing the peak at (101) due to strong intermolecular hydrogen bonding among PVA molecules[18], [29]. The substitution of Co^{2+} ions into nickel zinc ferrites resulted in an increase in peak intensity, encouraging the establishment of crystalline phases. Unlike the intensity of the planes, i.e., (220), (311), (400), (422), and (511) the intensity of the (101) plane is high are illustrated in figure 4.

The observed peak broadening in the X-ray diffraction (XRD) patterns indicates the presence of lattice strain along with a reduction in crystallite size within the synthesized samples. Among the various diffraction planes, the (311) reflection was selected for crystallite size determination due to its high intensity and well-defined nature in spinel ferrite structures. The average crystallite size of the samples was calculated using the Debye–Scherrer equation:

$$D = \frac{0.9\lambda}{\beta \cos \theta} \quad 1$$

where **D** represents the average crystallite size, λ is the wavelength of the incident X-ray radiation, β denotes the full width at half maximum (FWHM) of the diffraction peak expressed in radians, and θ corresponds to the Bragg diffraction angle associated with the selected (311) plane.

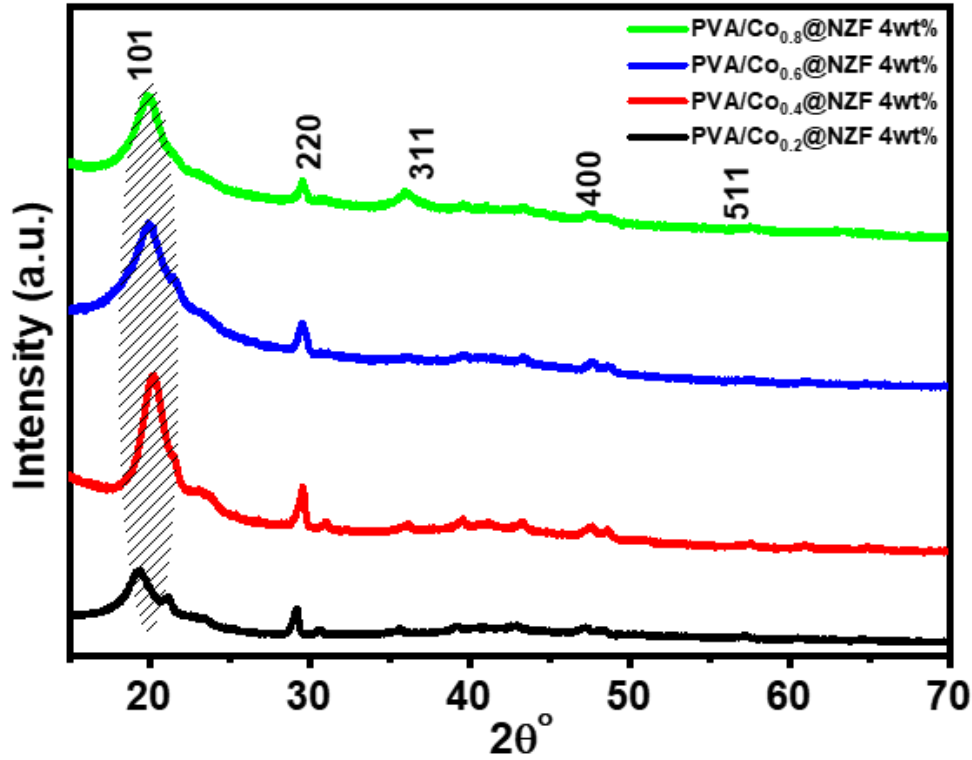


Figure 4: XRD Spectra of PVA/ $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$.

The table 2 indicates that the crystallite size varies from 6.2 to 6.9 nm, confirming the nanocrystalline nature of the samples, which is beneficial for EMI shielding applications. This behavior is accredited to the smaller ionic radius of nickel ions ($0.69 \text{ \AA}$) compared to cobalt and zinc ions ($0.74 \text{ \AA}$), which influences the lattice dimensions **Table 2**. Overall, the experimental results show a reduction in lattice parameter as the nickel concentration increases[30]. The X-ray density of Cobalt (Co^{2+}) substituted nickel – zinc ferrites was then evaluated using the appropriate formula.

$$\text{X-ray density} = \frac{ZM}{Na^3} \quad 2$$

Here M signifies the molecular weight and N signifies Avogadro's number of the prepared samples, and a is the lattice parameters. As the cobalt (Ni^{2+}) concentration increases

the X-ray density firstly decrease than increase[5], [30]. Other factors such as dislocation density are calculated by the following equation.

$$\sigma = \frac{1}{D^2} \quad 3$$

which confirms that the concentration of cobalt increasing, then dislocation density values were firstly decrease than increase progressively table 2.

Table 2: The structural parameters of synthesized $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$) evaluated for different Co^{2+} concentrations.

S.No.	Crystallite size(nm)	Dislocation Density	d-spacing Å	Lattice Parameters [Å]	Volume [Å] ³	Micro-Strain	X-ray density (g/cm ³)
0.2	6.2	0.0260	2.505	8.3065	573.148	1.743	5.45
0.4	6.7	0.0222	2.511	8.3264	577.2763	1.596	5.41
0.6	6.9	0.0210	2.505	8.3065	573.148	1.557	5.46
0.8	6.4	0.0244	2.505	8.3065	573.148	1.672	5.46

Several other parameters including specific surface area (S) can be evaluated using the equation given below:

$$S = \frac{6000}{\delta D} \quad 4$$

Various additional factors such as tetrahedral and octahedral bond length d_{AX} and d_{BX} , tetrahedral edge, shared, and unshared octahedral edges d_{AXE} , d_{BXE} , and d_{BXEU} can be described

$$d_{AX}(\text{Å}) = \sqrt[3]{3} \left(u - \frac{1}{4}\right) \quad 5$$

$$d_{BX}(\text{Å}) = \sqrt[3]{3} u^2 - 2u + 0.375 \quad 6$$

$$d_{AXE}(\text{Å}) = \sqrt[3]{2} \left(2u - \frac{1}{4}\right) \quad 7$$

$$d_{BXE}(\text{Å}) = \sqrt[3]{2} (1 - 2u) \quad 8$$

$$d_{\text{BXEU}}(\text{\AA}) = a(4u^2 - 3u + \frac{11}{16})^{1/2}$$

9

Based on literature reports, we take the oxygen positional parameter (u) as 0.375. Using this value, the aforementioned parameters were estimated, and the calculated results are presented in Table 3 [5], [31].

Table3: The structural parameters, including tetrahedral and octahedral bond lengths, tetrahedral edge length, and shared and unshared octahedral edge lengths, were evaluated.

S.No.	Lattice parameters [Å]	L _A [Å]	L _B [Å]	Specific Surface Area(m ² /g)	d _{AX} [Å]	d _{BX} [Å]	d _{AXE} [Å]	d _{BXE} [Å]	d _{BXEU} [Å]
0.2	8.3065	3.5964	2.9363	177.5673	1.7983	1.6481	5.8727	2.9363	0.5170
0.4	8.3264	3.6053	2.9434	165.5309	1.8026	1.6530	5.8868	2.9434	0.5183
0.6	8.3065	3.5967	2.9363	159.2610	1.7983	1.6481	5.8727	2.9363	0.5170
0.8	8.3065	3.596	2.9363	171.7032	1.7983	1.6481	5.8727	2.9363	0.5170

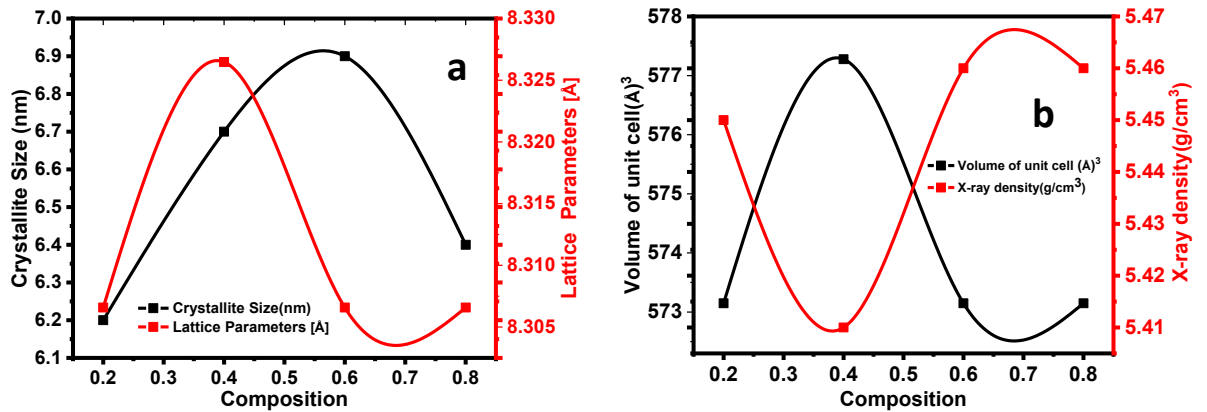


Figure 5: (a) Illustrates the deviations in crystallite size and lattice parameters. (b) Demonstrates the deviations in unit cell volume and X-ray density (g/cm³).

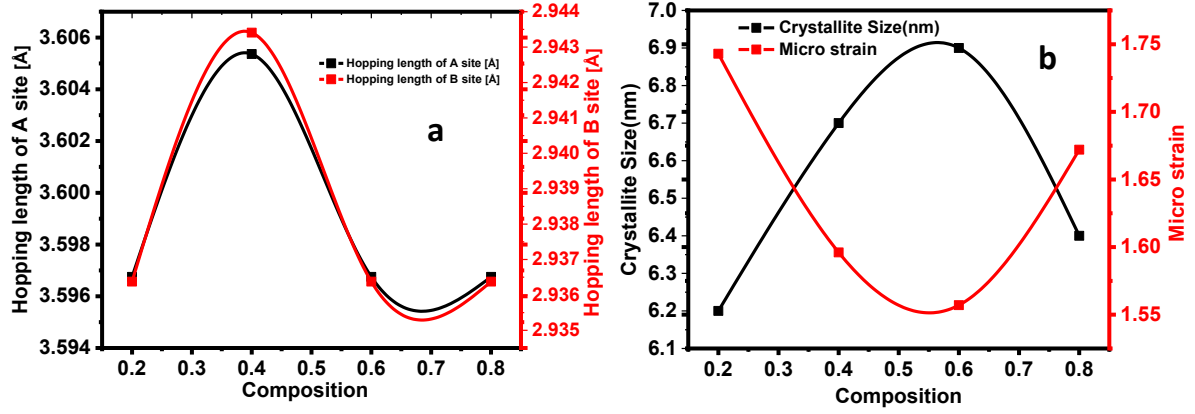


Figure 6: (a) Shows how the hopping lengths at A and B sites vary with cobalt composition. (b) Illustrates the variation in crystallite size and micro strain with increasing cobalt composition.

3.1.3 W-H Plot

The W-H plot used for estimating lattice strain in $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$) nano ferrite samples and for evaluating lattice strain and crystallite size using the equation provided below:

$$\beta \cos \theta = k\lambda/D + 4\epsilon \sin \theta \quad (10)$$

where β represents the FWHM, D denotes the crystallite size, λ is the wavelength of the X-ray, ϵ corresponds to the lattice strain, and θ is the Bragg angle. Figure 7 shows a plot in which $4\epsilon \sin \theta$ is plotted along the x-axis and $\beta \cos \theta$ along the y-axis to evaluate the lattice strain $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ nano ferrite samples.[32], [33]. The presence of tensile lattice strain is showed by a positive slope in this plot. But in this work, $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ nano ferrite samples are specified by positive slope in this plot[34], [35]. The lattice strain in Cobalt Nickel Zinc Ferrite samples is provided in **table 2** in the range of 1.557 to 1.743.

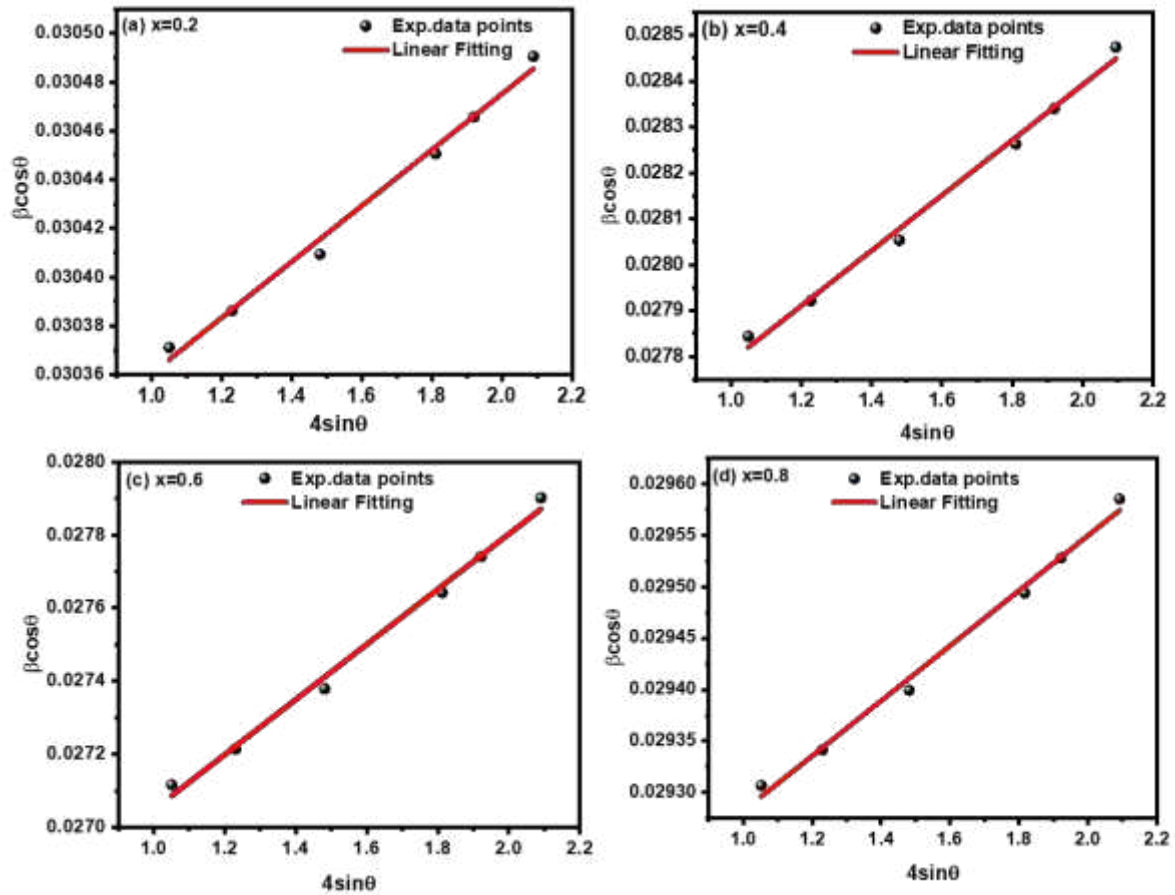


Figure7: W-H Plot of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

3.2. FESEM Analysis

The surface morphology of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$) powder samples was examined using Field emission scanning electron microscopy. To reduce charging and increase contrast, the samples were coated using a thin palladium layer[36]. The samples were then placed in the FE-SEM chamber. Once the required vacuum level and high voltage conditions were attained, images of the surface morphology of the samples were recorded. **Figure 8, 9** indicates that the FE-SEM images along with the particle size distribution of the samples $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x=0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$). The size of the particles was found to be **25.3, 29.0 and 37.2 nm** respectively. The increase in size of particles was verified using the FE-SEM images[37], [38]. Although it was found that higher concentrations result in lower agglomerations, the rate of growth of particles

and their microstructure are extremely sensitive to a number of factors, including sintering temperature, oxygen partial pressure, and stoichiometry.

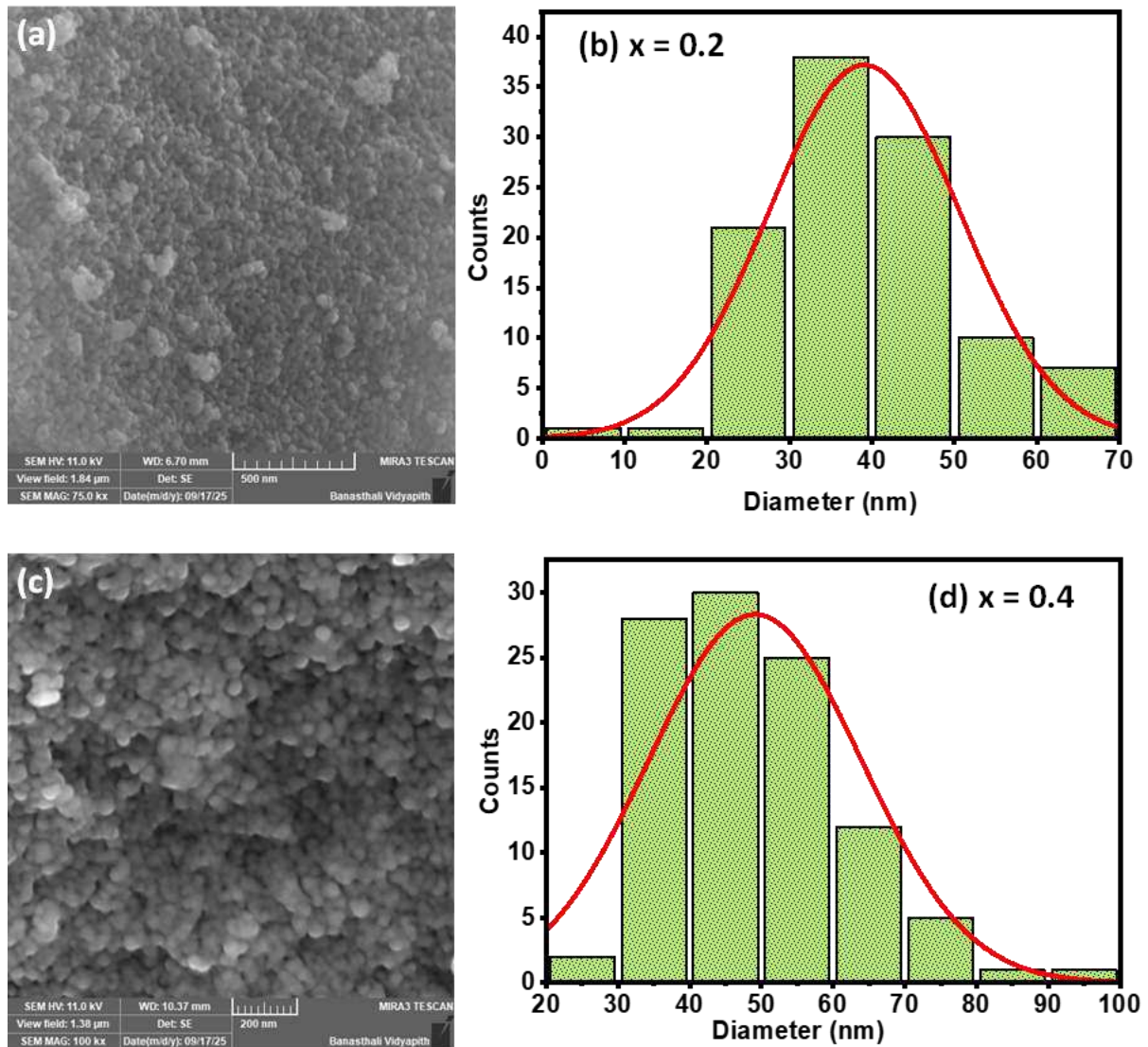


Figure 8: FE-SEM images of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.2, 0.4$ and $y = 0.1$.

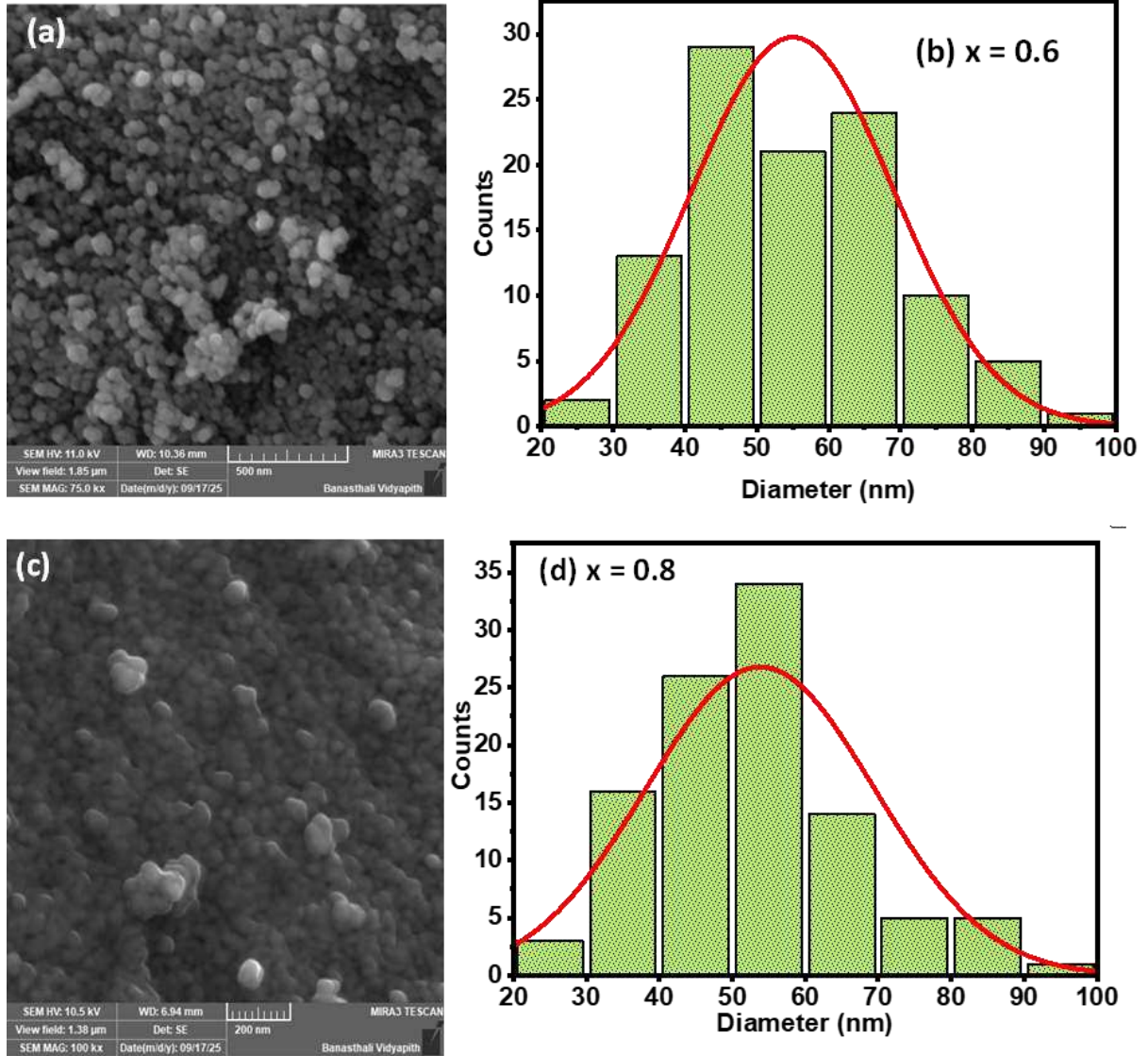


Figure 9: FE-SEM images of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.6, 0.8$ and $y = 0.1$.

3.2.1 EDAX

EDAX spectroscopy was performed to determine the elemental composition. EDAX was further applied to affirm the purity of the synthesized materials[39], [40]. The experimental results for the presence of C, O, Co, Ni, Zn, and Fe in the synthesized materials, represented as the weight and atomic percentages, are depicted in **figure 10, 11, 12, and 13** for the synthesized materials for $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$.

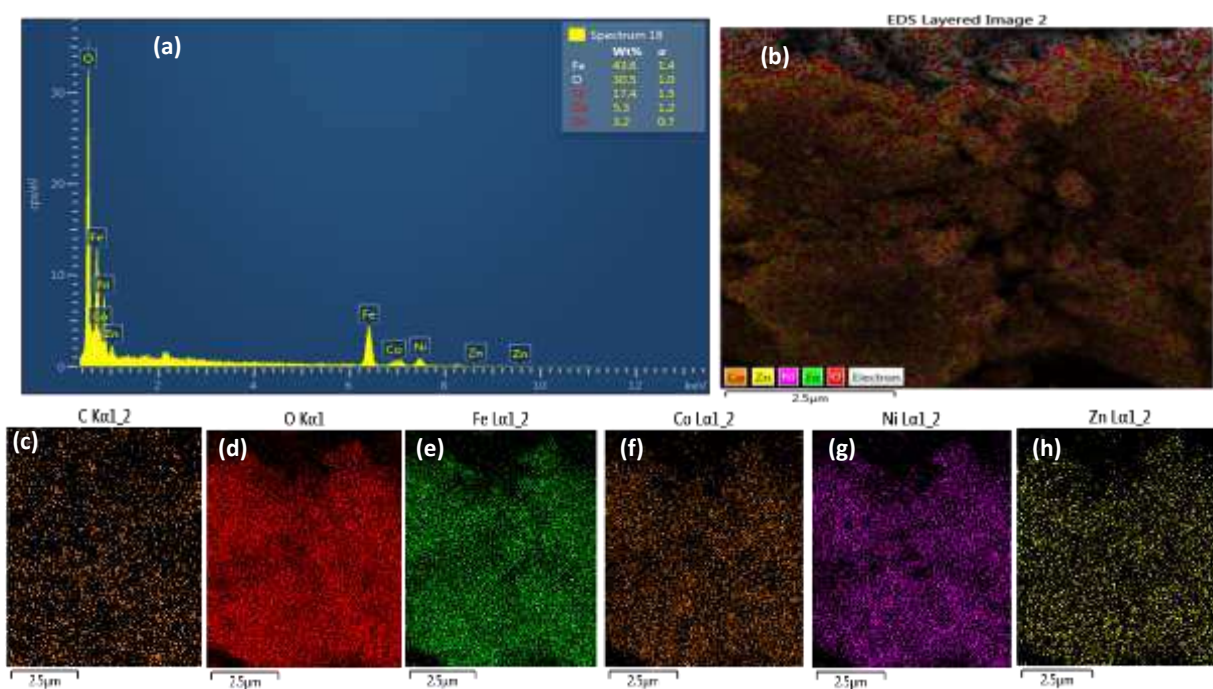


Figure 10: (a) EDAX spectrum, (b) Elemental mapping by using EDAX detector, (c) C, (d) O, (e) Fe, (f) Co, (g) Ni, (h) Zn distribution in the sample for $x=0.2$.

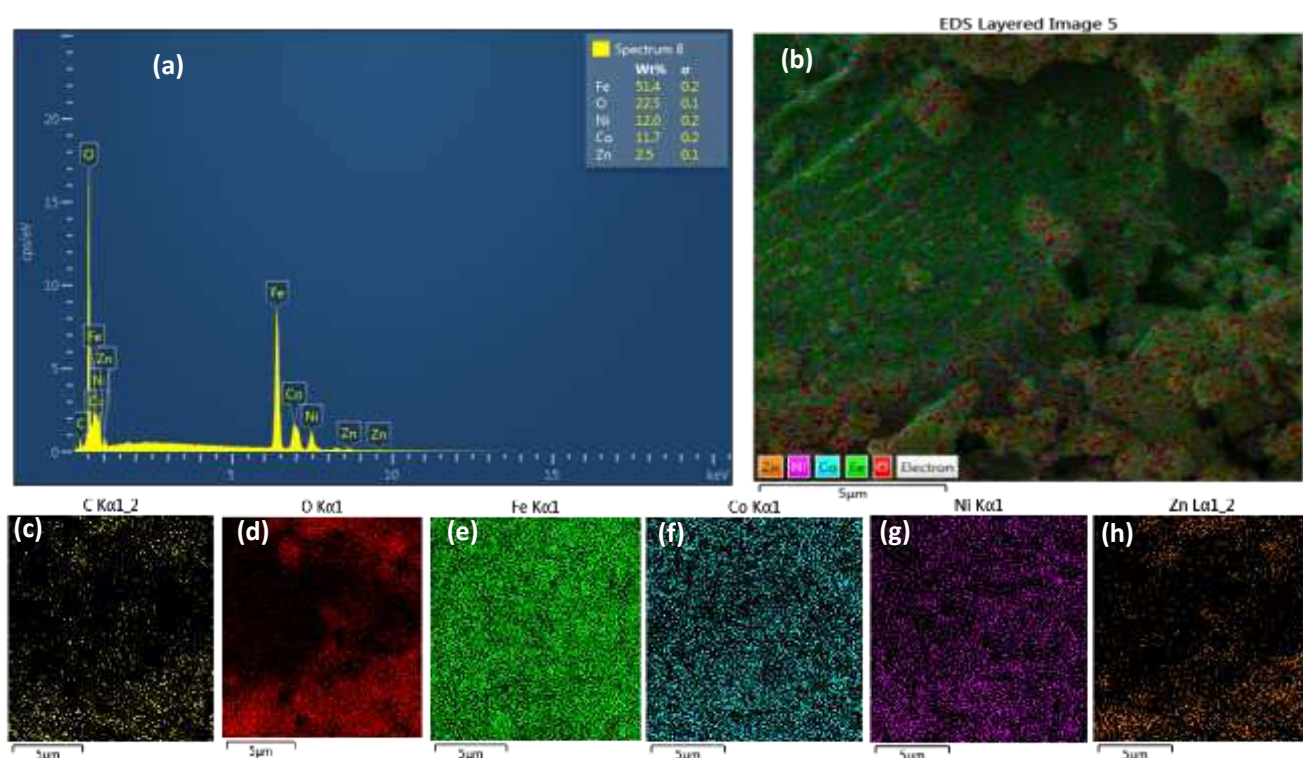


Figure 11: (a) EDAX spectrum, (b) Elemental mapping by using EDAX detector, (c) C, (d) O, (e) Fe, (f) Co, (g) Ni, (h) Zn distribution in the sample for $x=0.4$.

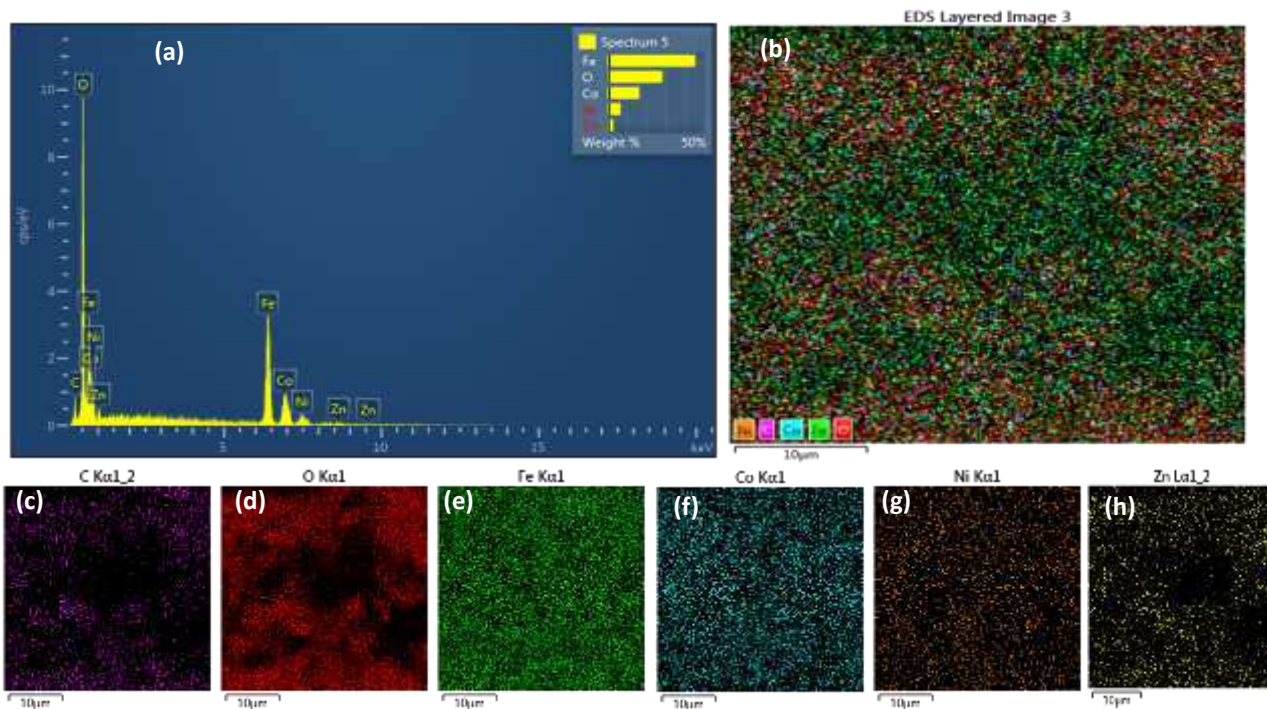


Figure 12: (a) EDAX spectrum, (b) Elemental mapping by using EDAX detector, (c) C, (d) O, (e) Fe, (f) Co, (g) Ni, (h) Zn distribution in the sample for $x=0.6$.

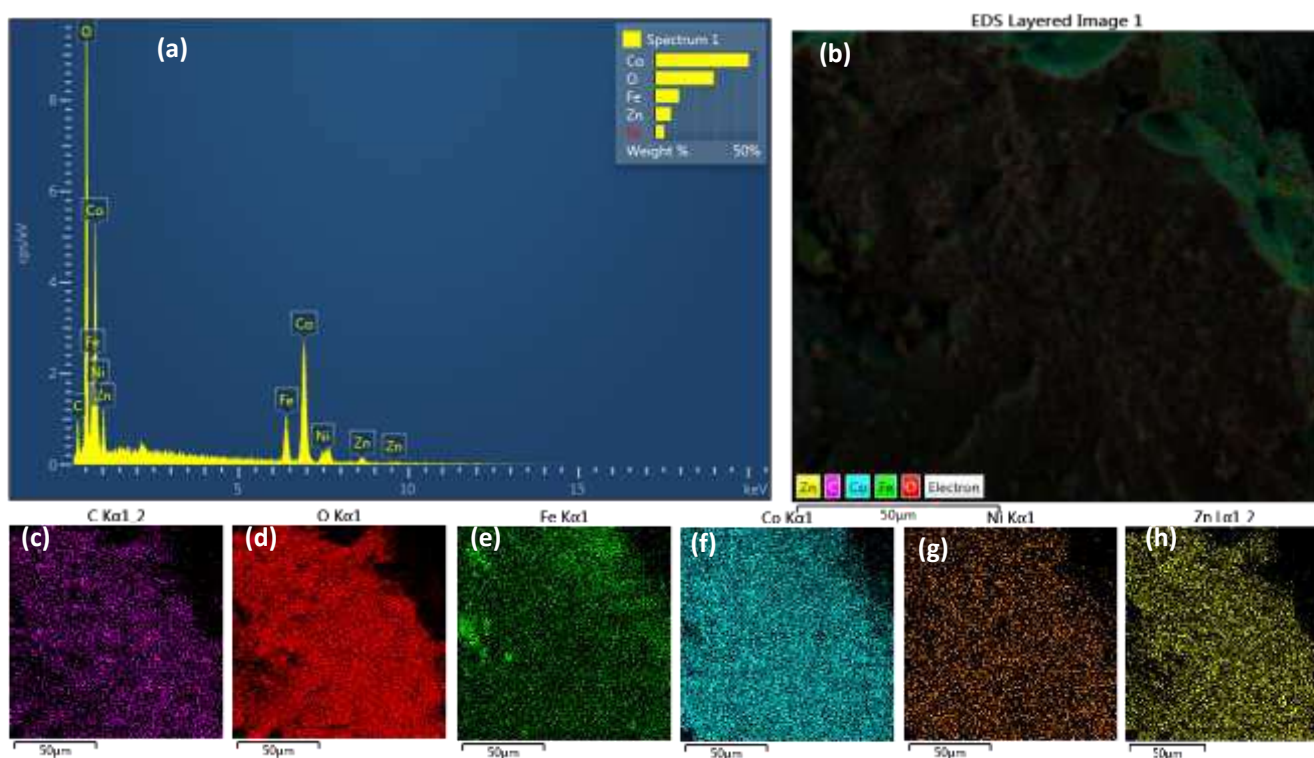


Figure 13: (a) EDAX spectrum, (b) Elemental mapping by using EDAX detector, (c) C, (d) O, (e) Fe, (f) Co, (g) Ni, (h) Zn distribution in the sample for $x=0.8$.

3.3 FTIR Analysis:

To investigate their structural properties of the prepared samples of $\text{Co}_x\text{Ni}_{(1-x-y)}\text{Zn}_y\text{Fe}_2\text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$). and ferrite-based polymer nanocomposite PVA/ $\text{Co}_x\text{Ni}_{(1-x-y)}\text{Zn}_y\text{Fe}_2\text{O}_4$ where ($x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$). FTIR spectra were acquired in the $400\text{--}4000\text{ cm}^{-1}$ range. The absorption bands at 3465 cm^{-1} and 1660 cm^{-1} correspond to O–H stretching and H–O–H bending vibrations, respectively, while the peaks at 2752 cm^{-1} indicate C–H stretching vibrations[41]. While the peak at 1344 cm^{-1} indicates the C–O stretching shown in **figure 14(a)** For the $\text{Co}_x\text{Ni}_{(1-x-y)}\text{Zn}_y\text{Fe}_2\text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$). nanocomposite, the FTIR spectrum shows features corresponding to both the polymer and ferrite components. The broad band at 3251 cm^{-1} indicates O–H stretching vibrations of PVA along with absorbed moisture, while the peak at 2904 cm^{-1} represents C–H stretching of $-\text{CH}_2$ groups. The band at 1644 cm^{-1} shows H–O–H bending vibrations (table 4). The absorption at 1402 cm^{-1} reflects C–H and O–H bending vibrations of the polymer backbone, whereas the prominent peak at 1073 cm^{-1} indicates C–O stretching in PVA[42], [43]. The band at 831 cm^{-1} corresponds to metal–oxygen vibrations, confirming the inclusion of ferrite nanoparticles within the polymer matrix shown in **Figure 14(b)**.

Table 4: FTIR bands and Debye temperature values.

Composition	$\nu_1(\text{cm}^{-1})$	$\nu_2(\text{cm}^{-1})$	$\nu_{12}(\text{cm}^{-1})$	$\theta_D(\text{K})$
0.2	587	707	647	932
0.4	589	690	639.5	921
0.6	591	600	595.5	857
0.8	582	663	622.5	896

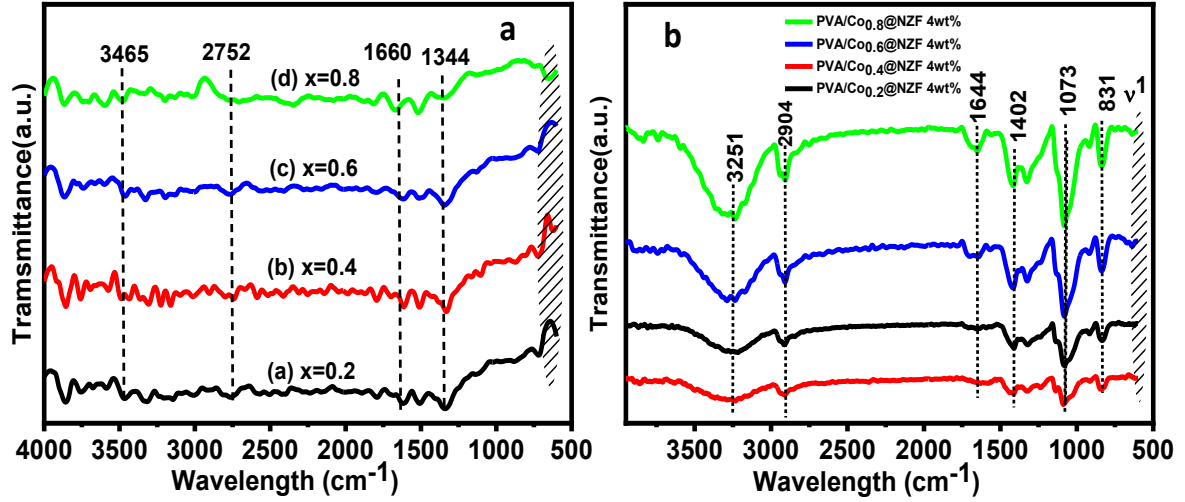


Figure 14:(a) FTIR Analysis of Co_x Ni_(1-x-y) Zn_yFe₂O₄ (where x = 0.2,0.4, 0.6 and 0.8 and y =0.1). (b) FTIR Analysis of PVA/Co_x Ni_(1-x-y) Zn_yFe₂O₄ (where x = 0.2,0.4, 0.6 and 0.8 and y =0.1).

The FTIR spectra exhibit two prominent absorption bands (ν_1 , ν_2), corresponding to the tetrahedral and octahedral metal–oxygen vibrations characteristic of the spinel ferrite structure[28]. The average vibrational frequency was calculated by:

$$\nu_{12} = \frac{\nu_1 + \nu_2}{2} \quad 11$$

The Debye temperature (θ_D), which indicates lattice stiffness and bond strength, was determined using

$$\theta_D = \frac{hc}{K} \nu_{12} \quad 12$$

The calculated values reveal that θ_D decreases initially with the composition and increases at higher concentration (table 4). The highest Debye temperature at composition 0.2 indicates stronger bonding and a more rigid lattice, while the lower values at intermediate composition suggests lattice distortion[41].

3.4 Raman Spectroscopy:

Raman spectroscopy was utilized to assess the crystallinity and microstructural characteristics of the nanoferrites. The obtained raman spectrum, shown in the **figure 15(a)**, validate the successful material preparation of cobalt substituted nickel zinc ferrite nanoparticles[44], [45]. For the low wavenumber region, three distinct peaks are measured at 301, 465, and 671 cm^{-1} , which are characteristic for ferrite spinel structures. The two peaks at 301 and 465 cm^{-1} are assigned to T_{2g} vibrations for metal oxygen bonds in octahedral (B) sites in ferrite spinel structures. The dominant peak at 671 cm^{-1} is accredited to the A_{1g} vibrational mode of the ferrite spinel structures, The A_{1g} mode corresponds to metal oxygen bonds in tetrahedral (A) sites in ferrite spinel structures. The peaks at high wavenumber values of 2921, 1423, and 831 cm^{-1} are associated to the stretching and bending vibrations for PVA[46], [47]. The peak observed at 2921 cm^{-1} is attributed to the stretching vibrations of $-\text{CH}$ groups in PVA, while the peak at 1423 cm^{-1} corresponds to the bending vibrations of $-\text{CH}_2$ groups in PVA. Additionally, the peak at 831 cm^{-1} is associated with the stretching and bending vibrations of C–C and C–H groups in PVA[48]. The occurrence of these peaks thus confirms the integrity of PVA in the composite material shown in **figure 15(b)**.

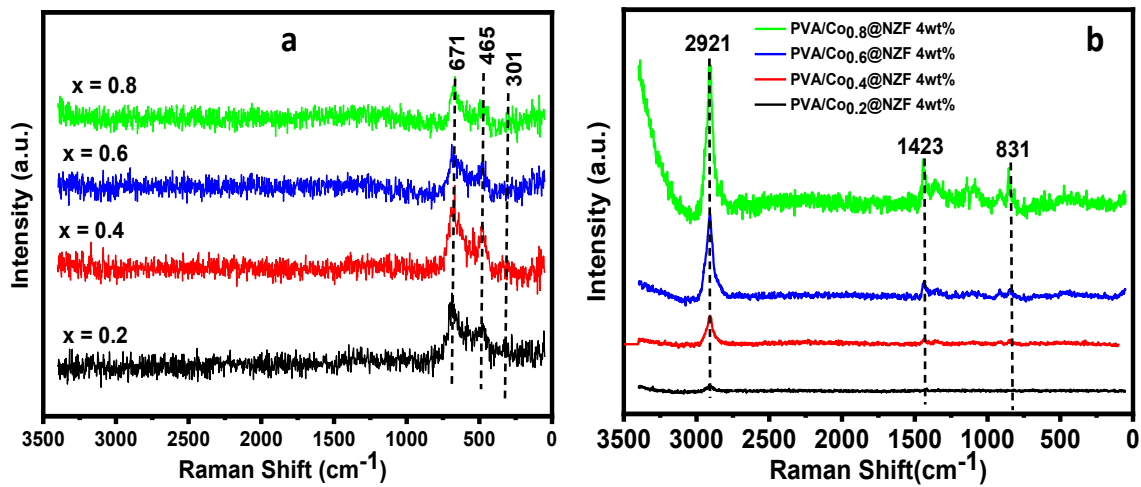


Figure15: (a) Raman Spectra of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where, $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$). (b) Raman Spectra of PVA/ $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$).

The Factor Group Analysis predicted three vibrational modes in the $MFeO_4$ spinel structure, i.e., E_g , $T_{2g}(3)$, A_{1g} , which are attributes of spinel ferrites[28]. The A_{1g} mode corresponds to the symmetric stretching vibrations of oxygen atoms surrounding the metal ions at the tetrahedral A sites, and it typically appears as the most intense peak in the Raman spectra of ferrites. Thus, the presence of this mode is strong evidence of the formation of a well-ordered spinel ferrite structure[49]. The $T_{2g}(3)$ mode is associated with asymmetric stretching vibrations involving metal–oxygen interactions at the tetrahedral A sites, while the E_g mode corresponds to the bending vibrations of oxygen atoms surrounding the octahedral metal ions. The presence of all these distinct Raman active modes in **figure 16** verified the formation of homogenous cubic spinel phases. Thus, no additional peaks were observed, indicating high phase purity and crystallinity of the ferrite samples[50], [51].

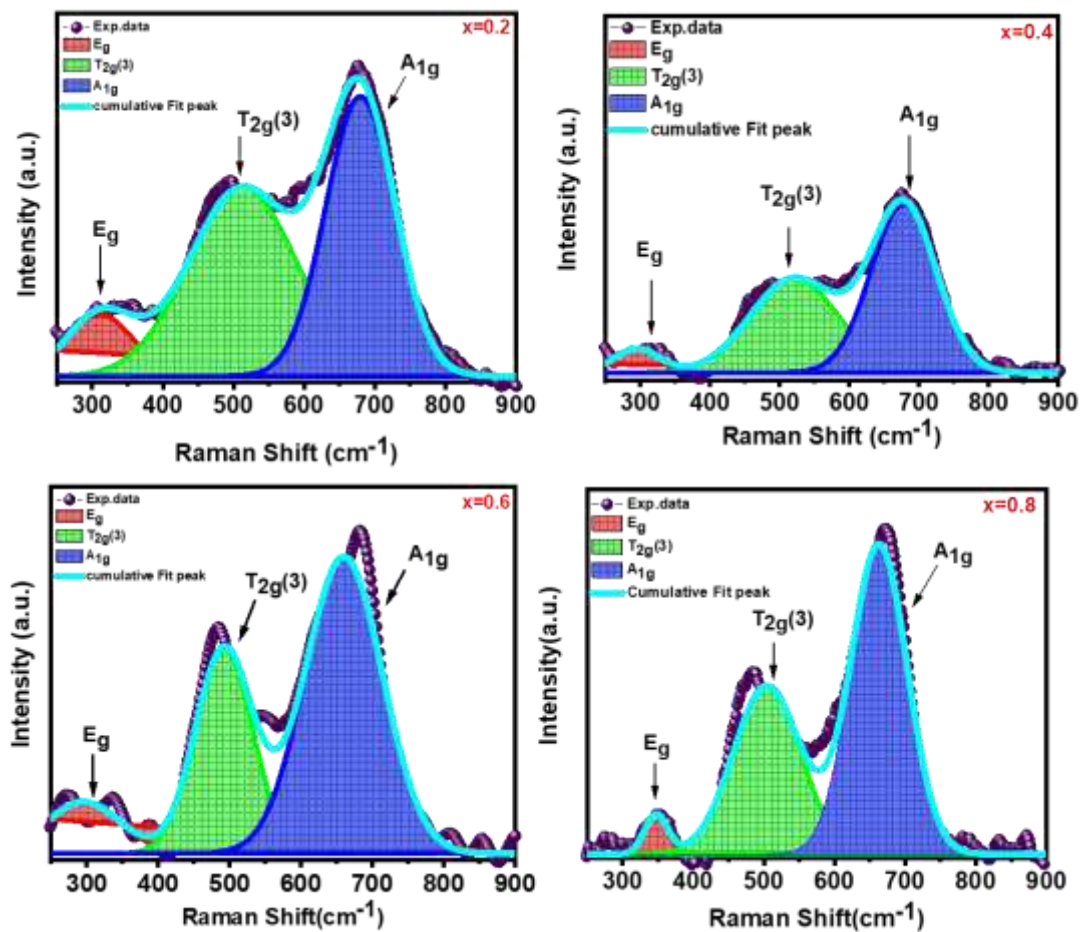


Figure 16: Deconvoluted Raman spectra of $Co_x Ni_{(1-x-y)} Zn_y Fe_2 O_4$ (where, $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$).

3.5 UV-VIS Spectroscopy:

The optical properties and electronic transitions are investigated via UV-VIS spectroscopy[52]. The obtained absorption spectra confirm the formation of Cobalt (Co^{2+}) substituted Nickel Zinc ferrite nanoparticles, with absorption observed in the UV-Vis range of 200 to 800nm, as illustrated in **Figure 17(a)**. The Tauc's relation is used to determined the energy band gap.

$$\alpha h\nu = A(h\nu - E_g)^n \quad 13$$

where α is defined as the absorption coefficient and $h\nu$ is the photonic energy, A is the absorbance, E_g is the band gap, and n depends on the nature of electronics transition[53], [54]. For the direct band gap n is 2 and for the indirect band gap n is $\frac{1}{2}$. By using the Tauc's plot of cobalt (Co^{2+}) substituted nickel zinc ferrite nanoparticle is varying form 1.07eV to 1.45eV are listed in **the table 5**.

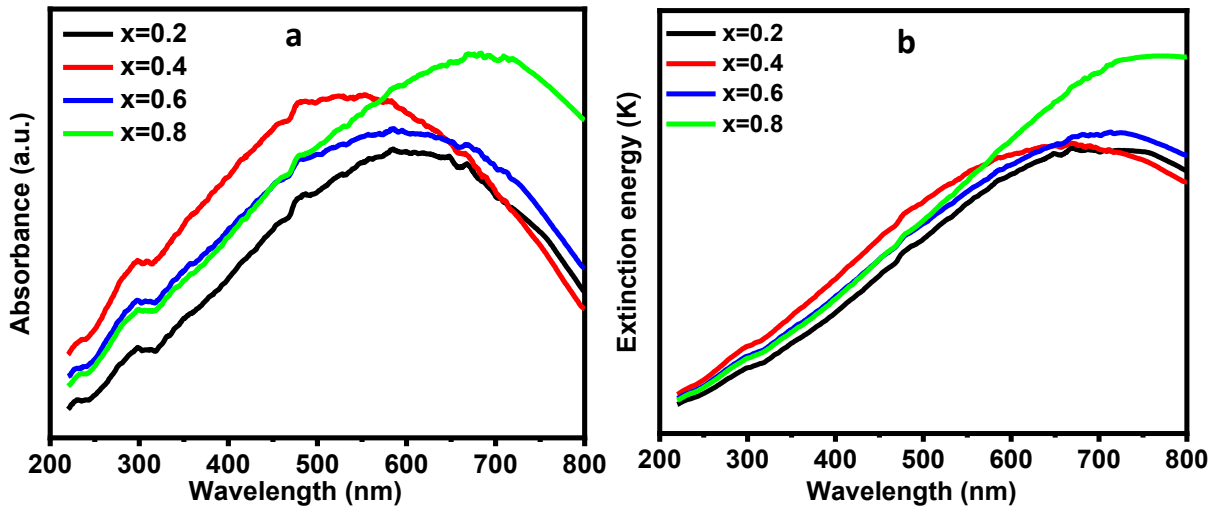


Figure 17: (a) Absorbance spectra of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$. (b) Extinction energy spectra of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.2, 0.4, 0.6$ and 0.8 and $y = 0.1$.

The absorption coefficient (α) was calculated from the absorption data, which describes the interaction of electromagnetic radiation with the material[28]. The extinction coefficient (k), representing the attenuation of light within the material, was determined using the relation:

$$k = \frac{\alpha\lambda}{4\pi} \quad 14$$

where α is defined as the absorption coefficient and λ is the wavelength. The extinction coefficient was found to increase significantly in the ultraviolet region due to strong charge transfer transitions between O^{2-} and Fe^{3+} ions. In the visible region, lower values of k indicate reduced absorption, consistent with the semiconducting nature of ferrite nanoparticles shown in figure 17(b) and the values of extinction coefficient are mentioned in table 5[30], [55].

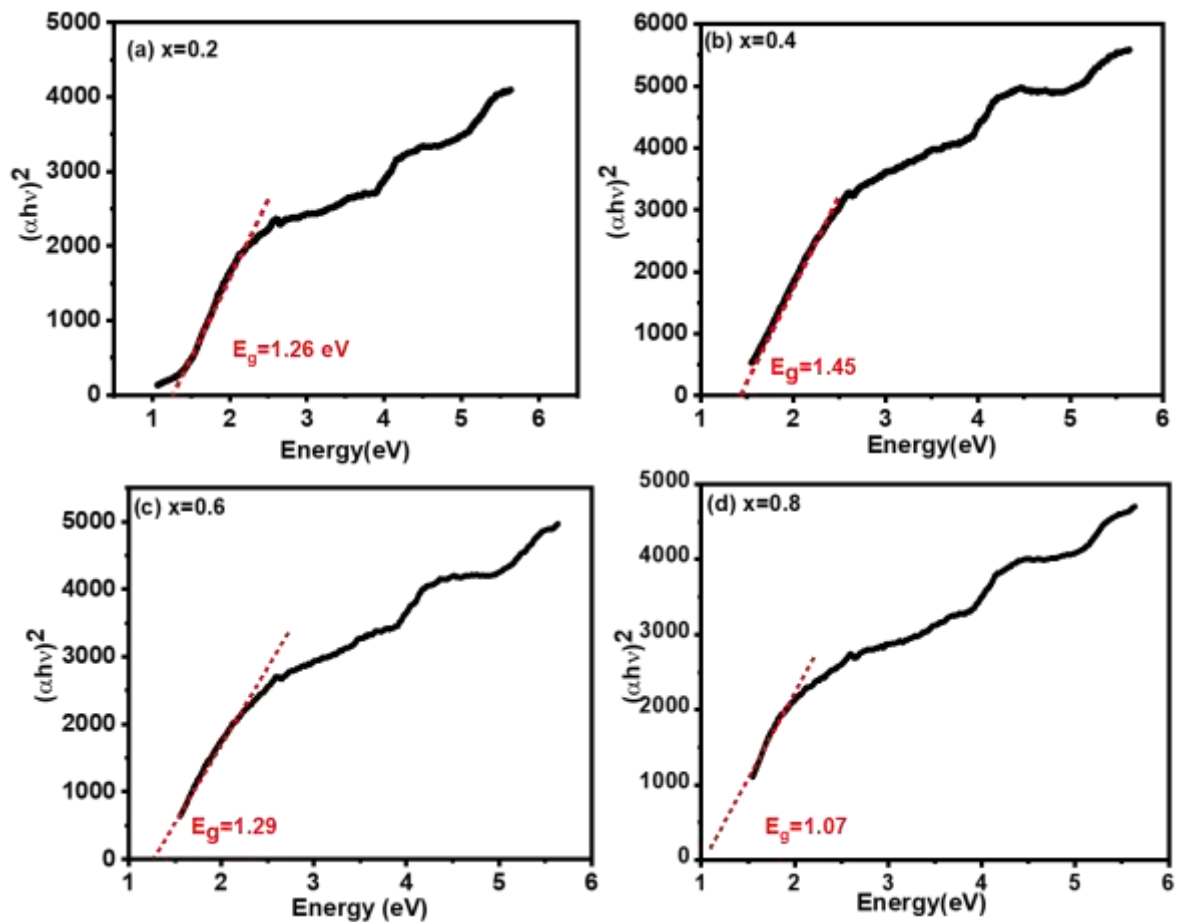


Figure18: Tauc's plot of $Co_x Ni_{(1-x-y)} Zn_y Fe_2 O_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

Table 5: Calculated values of wavelength, band gap, Extinction coefficient and Urbach energy of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ where $x = 0.2, 0.4, 0.6$ and 0.8 .

Composition	Wavelength(nm)	Band gap(eV)	Extinction coefficient(K)	Urbach Energy(eV)
0.2	632	1.26	1.96	2.1
0.4	550	1.45	2.25	2.2
0.6	581	1.29	2.13	2.6
0.8	669	1.07	1.85	4.3

3.6 Dielectric Analysis:

3.6.1 Ac Conductivity:

The figure 19 shows the variation of AC conductivity with frequency for the prepared samples. All the samples exhibit frequency-dependent conductivity, which is a typical characteristic of ferrite materials.[56], [57]. It can be seen that the conductivity remains almost unchanged in the lower frequency region and increases noticeably as the frequency increases. This type of behavior is commonly observed in nano ferrite materials and indicates that the conduction process is strongly dependent on frequency[51], [58]. The variation in AC conductivity with cobalt concentration reveals that $\text{Co}_{0.4}\text{Ni}_{0.5}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ exhibits the highest conductivity among the investigated compositions. This behavior can be attributed to the existence of an optimum cobalt substitution level that promotes the hopping conduction mechanism in the spinel ferrite system. In ferrites, AC electrical conduction mainly originates from the hopping of charge carriers between ions of the same element present in different valence states, predominantly Fe^{2+} and Fe^{3+} at the octahedral (B) sites[59]. For the composition $\text{Co}_{0.4}\text{Ni}_{0.5}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$, the cation distribution appears to be most favorable for this electron exchange process, thereby enhancing the probability of hopping and resulting in higher conductivity. At lower cobalt concentration, such as $\text{Co}_{0.2}\text{Ni}_{0.7}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ the substitution level is insufficient to significantly modify the cation arrangement and create a large number of effective hopping centres. Consequently, the charge carrier mobility remains comparatively lower, which leads to reduced

AC conductivity. However, when the cobalt content is increased beyond the optimum value, as in $\text{Co}_{0.6}\text{Ni}_{0.3}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ and $\text{Co}_{0.8}\text{Ni}_{0.1}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ the electrical conductivity decreases. This reduction may be associated with increased lattice distortion, enhanced grain boundary resistance, and possible suppression of the $\text{Fe}^{2+}/\text{Fe}^{3+}$ hopping pathways due to excessive cobalt incorporation. The higher cobalt content can alter the structural symmetry and impede charge transport, thereby lowering the conductivity[60], [61].

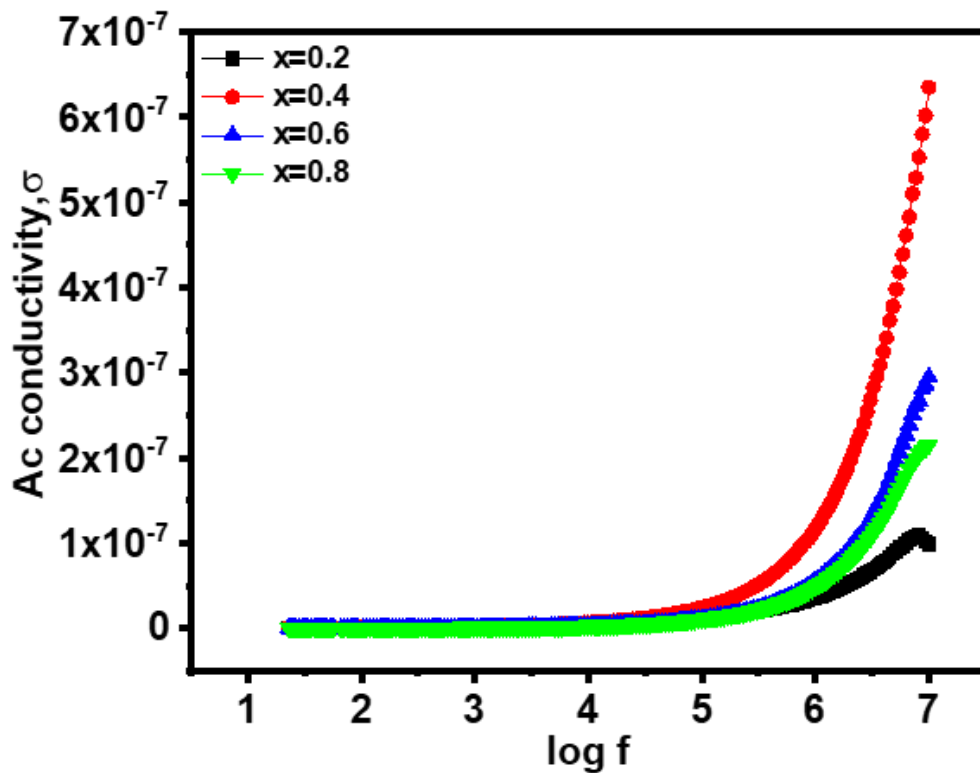


Figure 19: AC conductivity of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

3.6.2 Impedance:

Figure 20 illustrates the variation of impedance with frequency for cobalt (Co^{2+}) substituted nickel–zinc ferrite samples. For all compositions, the impedance decreases with increasing frequency, which may be attributed to the diminishing contribution of space charge polarization at higher frequencies[61]. At low frequencies, grain boundary resistance dominates the electrical response, resulting in higher impedance values. A continuous decrease in impedance

with increasing frequency is observed due to the inability of charge carriers to follow the alternating field. Among the studied samples, $\text{Co}_{0.4}\text{Ni}_{0.5}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ exhibits the lowest impedance, indicating the least resistance to charge transport. This may be due to the optimum cobalt substitution, which favors electron hopping between Fe^{2+} and Fe^{3+} ions at the octahedral sites and reduces grain boundary contribution[62]. In contrast, lower and higher cobalt concentrations lead to comparatively higher impedance, possibly due to insufficient hopping centres at low Co^{2+} content and structural distortion or enhanced grain boundary effects at higher Co content. Hence, $\text{Co}_{0.4}\text{Ni}_{0.5}\text{Zn}_{0.1}\text{Fe}_2\text{O}_4$ demonstrates the most favorable electrical conduction behavior among the investigated compositions. The complex impedance plots (Nyquist plots) and the frequency dependent impedance characteristics illustrated in **figure 21** offers valuable insights into the mechanisms of electrical relaxation and conduction[63], [64]

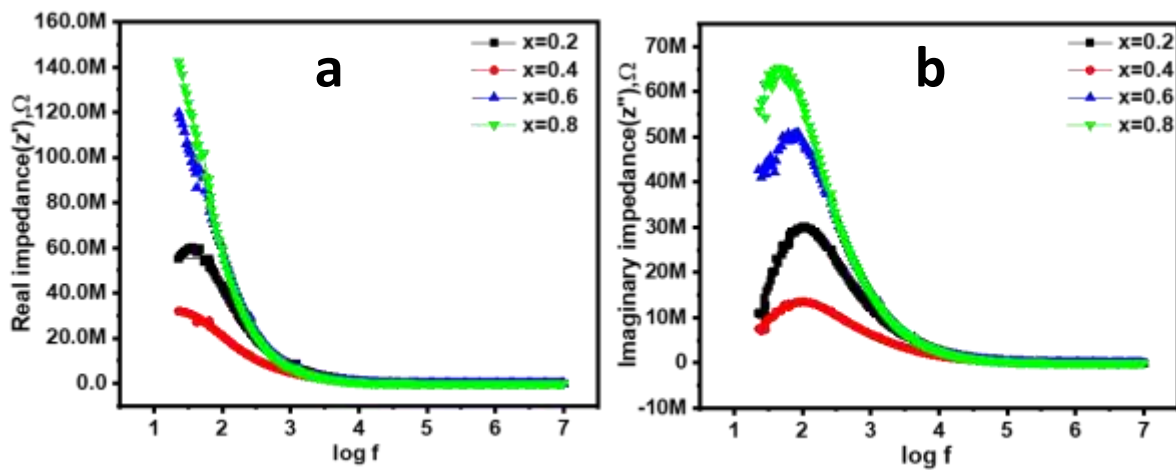


Figure20: (a) Frequency-dependent variation of real impedance (Z') and (b) imaginary impedance (Z'') as a function of logarithmic frequency ($\log f$) for different compositions.

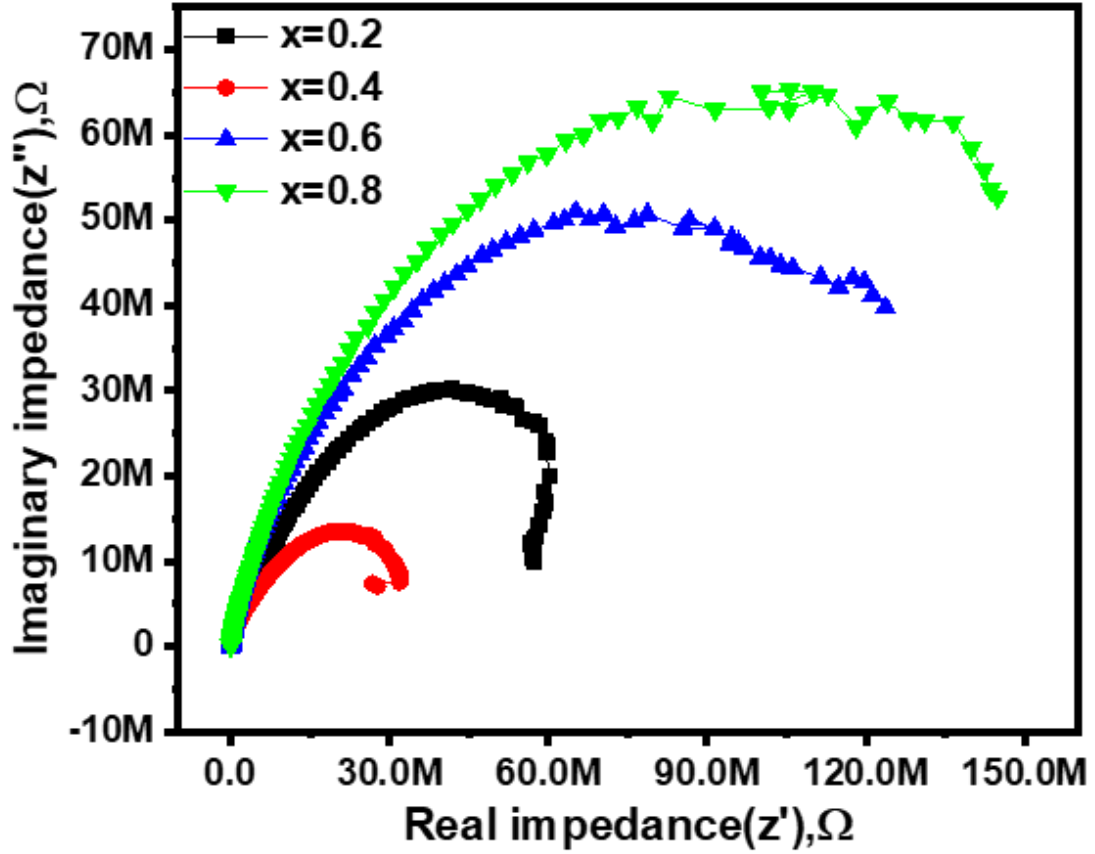


Figure 21: Nyquist Plot of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

3.6.3 Cole-Cole Plot

According to Koop's hypothesis dielectric structures consist of conductive grains which create insulating boundaries between their grain materials. The dielectric properties of polycrystalline nanomaterials depend on two factors which are their conductive grain components and their grain boundary components which resist electrical flow[51], [65], [66]. The lattice plane defects known as grain boundaries serve an important function within the system. Researchers use the Cole-Cole plot for their research work because it helps them identify different dielectric material sources in a nanomaterial study. The plot depicts the connection between imaginary (z'') and real (z') components of the dielectric modulus which creates a semicircular shape that scientists use as the Cole - Cole plot for dielectric materials. Figure 22 displays all the Cole-

Cole plots which researchers obtained from their experiments using cobalt as a substitute for nickel zinc nano-ferrite materials[54].

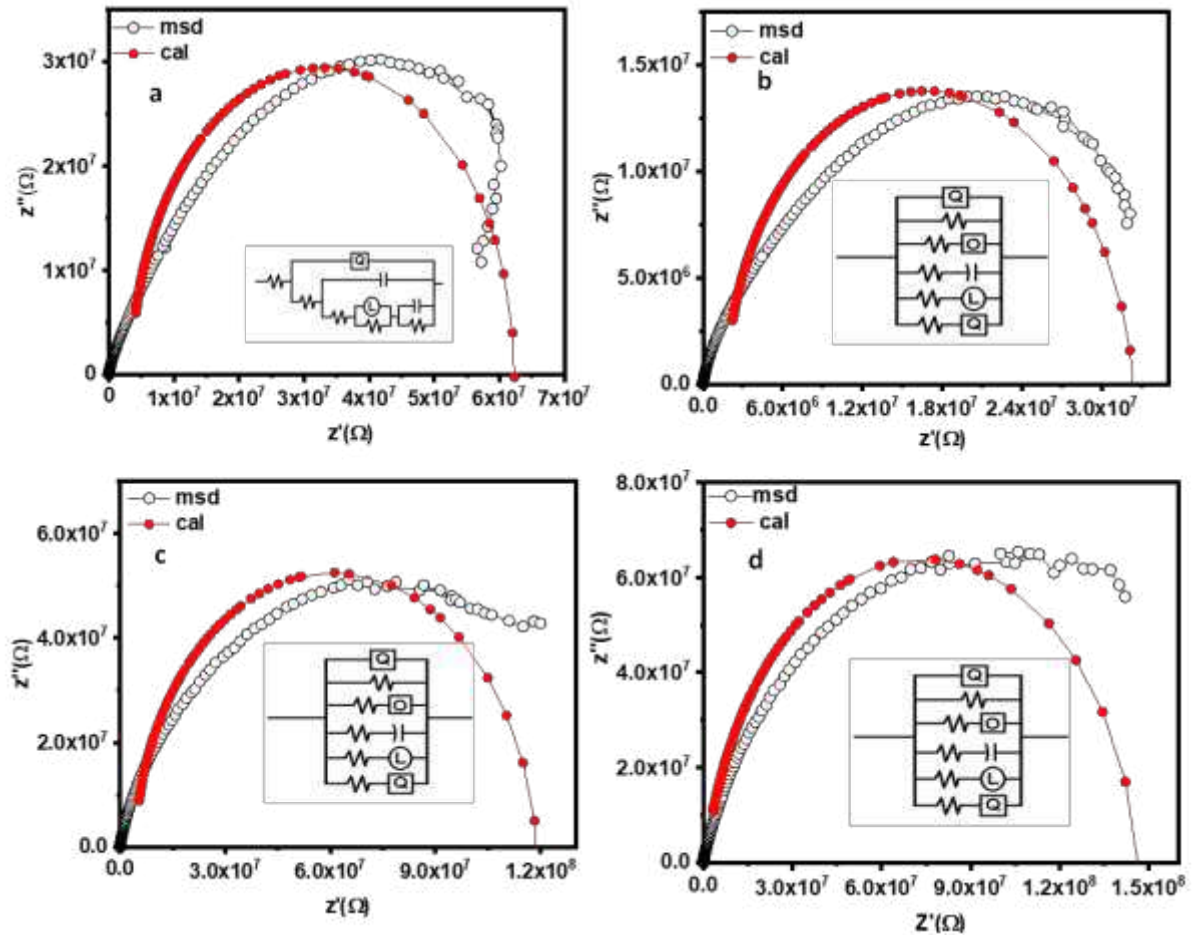


Figure 22: Cole-Cole Plot of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

3.6.4 Dielectric constant:

Figure 23 illustrates the variation of the dielectric constant (ϵ') as a function of frequency for different compositions ($x = 0.2, 0.4, 0.6$, and 0.8). For all compositions, the dielectric constant was found to decrease with increasing frequency, showing a typical dielectric dispersion behavior. Higher ϵ' values at low frequencies were attributed to interfacial polarization arising from space charge accumulation at the grain boundaries[67]. In this region, charge carriers and dipoles are able to follow the slowly varying applied electric field, resulting in enhanced polarization and hence a larger dielectric constant. As the frequency increases, the dielectric

constant decreases sharply and eventually attain an approximately constant value in the high-frequency region. This behavior occurs because dipoles and charge carriers fail to respond to the quickly alternating electric field, thereby reducing the overall polarization[68]The observed trend follows the Maxwell-Wagner interfacial polarization model and Koop's phenomenological theory. The sample with $x = 0.4$ shows the highest dielectric constant across all measurement frequencies. The enhancement results from three factors: increased space charge polarization, improved grain boundary contribution, and higher charge carrier mobility. The dielectric constant decreases in the order [69].

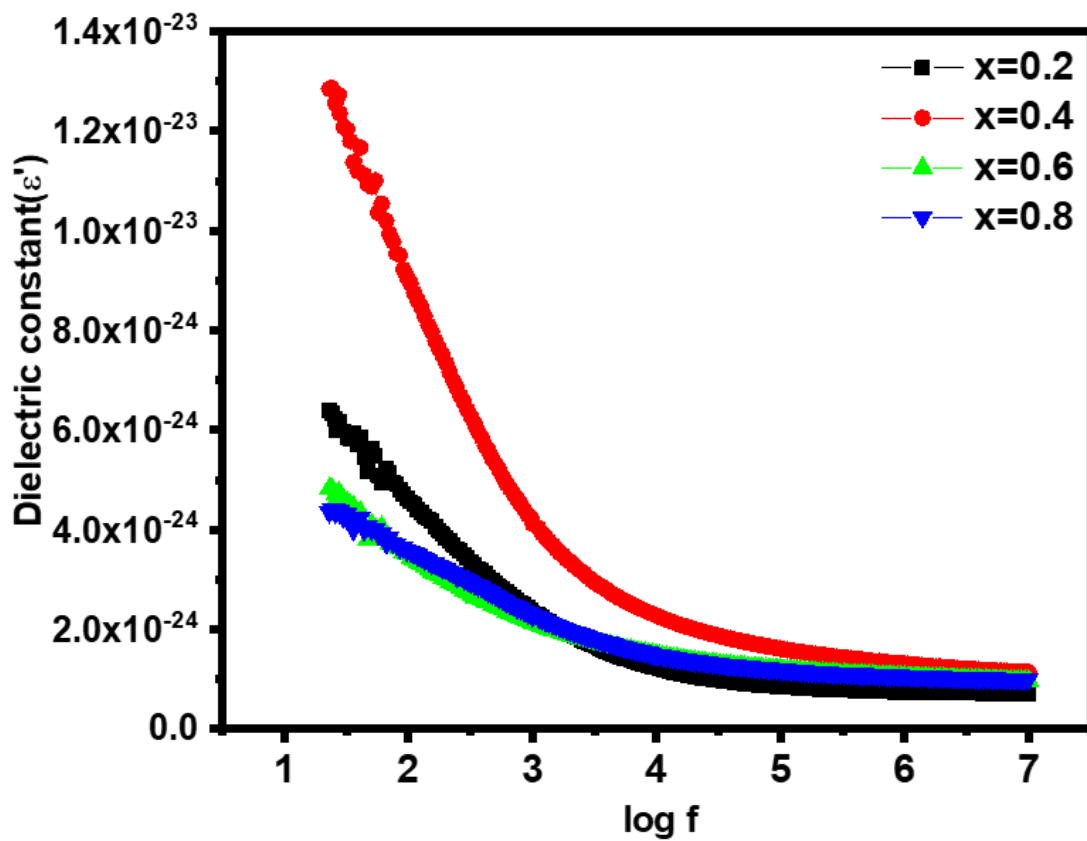


Figure 23: Dielectric constant of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

3.6.5 Dielectric loss:

Figure 24 shows how dielectric loss ($\tan \delta$) changes with different frequencies for the various compositions ($x = 0.2, 0.4, 0.6$, and 0.8) used in the study. The dielectric loss for all compositions shows a continuous decrease as the frequency of the signal's increases [69], [70], [71]. At low frequencies, relatively high values of $\tan \delta$ are observed, which are attributed to space charge polarization and charge carrier hopping at grain boundaries. In this region, charge carriers accumulate at interfaces and gradually follows the variation in external electric field, resulting in significant energy dissipation and hence higher dielectric loss. With increasing frequency, the dielectric loss decreases sharply and becomes nearly constant in the high-frequency region. This behavior occurs because charge carriers and dipoles are unable to respond to the rapidly alternating electric field, thereby reducing polarization losses and energy dissipation. The shown trend with the Maxwell-Wagner interfacial polarization may be considered as consistent with Koop's phenomenological theory. The highest dielectric loss in the low-frequency region is exhibited by the $x = 0.8$ sample, while the lowest dielectric loss over the entire measured frequency range is shown by the $x = 0.6$ sample. Enhanced dielectric stability and reduced energy dissipation in the material are indicated by the lower dielectric loss at higher frequencies[68], [72], [73].

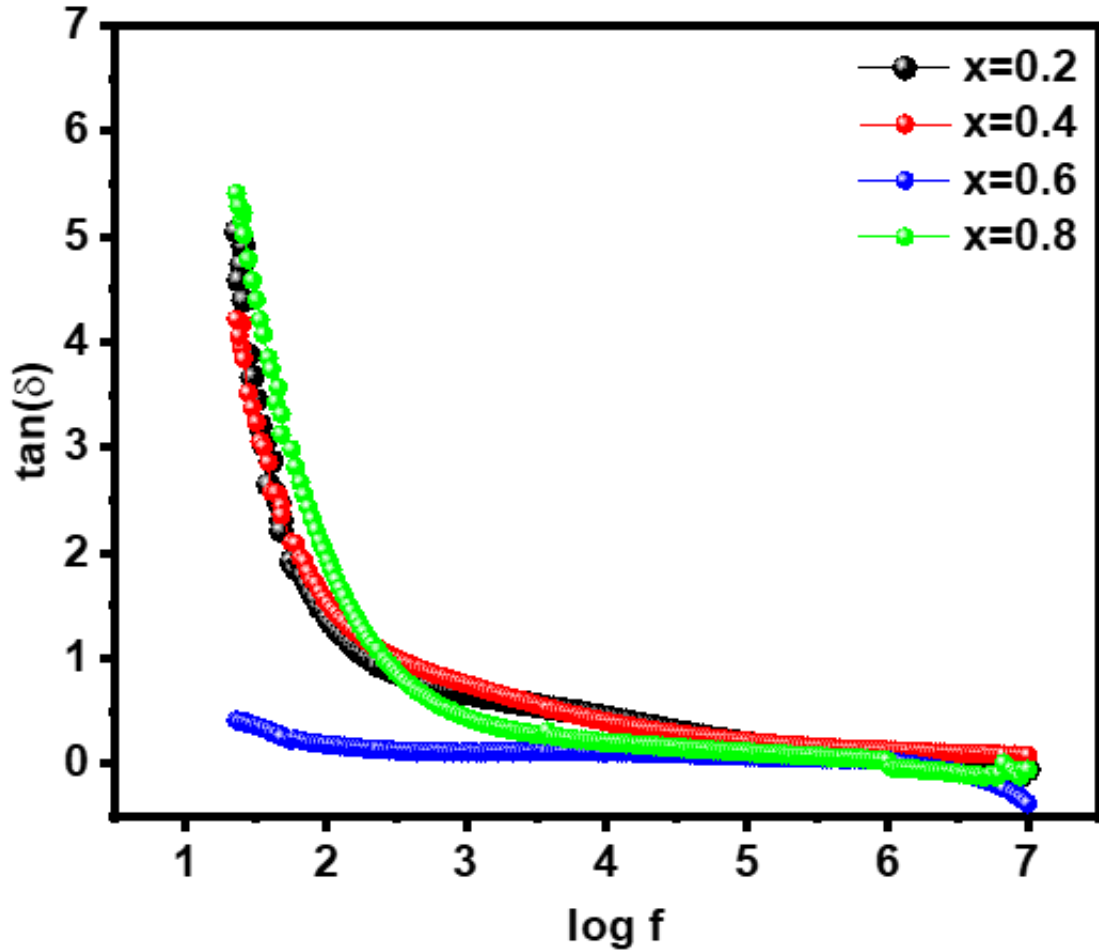


Figure24: Dielectric loss of $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$).

3.6.6 EMI Shielding application:

To examine the EMI shielding performance of the flexible PVA/ $\text{Co}_x \text{Ni}_{(1-x-y)} \text{Zn}_y \text{Fe}_2 \text{O}_4$ (where $x = 0.2, 0.4, 0.6$ and 0.8 and $y=0.1$) nanocomposites, a Vector Network Analyzer (ROHDE & SCHWARZ ZNB 40 VNA 100 kHz – 40 GHz) was used in the 7 - 13 GHz X-band range through a waveguide-based method[6]. The flexible film samples were positioned between two copper holders of a rectangular X-band waveguide for their measurement. The two-port setup enables measurement of reflected and transmitted signals through complex scattering parameters which describe the signals as reflection and transmission. In particular, S-parameters S_{11} (S_{22}) and S_{21} (S_{12}) were obtained from the VNA to determine the total shielding effect (expressed in dB), where S_{11} (S_{22}) and the S_{21} (S_{12}) parameters denote the reflectance and

transmittance, respectively. Using these S-parameters, the reflectivity ($R = |S_{11}|^2 = |S_{22}|^2$) and the transmittivity ($T = |S_{21}|^2 = |S_{12}|^2$) can be evaluated, and the absorptivity A can be determined using the equation $A + R + T = 1$ [9]. The three elements - R , T , and A - are utilized to determine the shielding effect. The net EMI shielding effectiveness (SE_{total}) is represented by the combined effectiveness of absorption (SEA), reflection (SER), and other attenuating components. In this study, the EMI shielding effectiveness of PVA/ $Co_x Ni_{(1-x-y)} Zn_y Fe_2O_4$ (where $x = 0.2, 0.4, 0.6$, and 0.8) nanocomposites was evaluated using a Vector Network Analyzer (VNA). Figures 25 and 26 illustrate the reflection loss as a function of frequency for composites with different weight proportions of PVA/ $Co_x Ni_{(1-x-y)} Zn_y Fe_2O_4$. The EMI shielding graphs reveal that the shielding effectiveness of the samples varies with frequency, confirming the frequency-dependent nature of electromagnetic attenuation. Among the all samples, the PVA/ $Co_{0.4}$ @NZF 4wt% shows comparatively lower shielding values in the range of about **-19.86 to -27.05 dB**, indicating moderate shielding behavior. In contrast, PVA/ $Co_{0.6}$ @NZF 4wt% and PVA/ $Co_{0.8}$ @NZF 4wt% show much deeper minima, reaching about **-45.33 dB** and **-43.89 dB**, respectively, which confirms their superior shielding performance [74]. The enhanced attenuation in these samples may be due to better impedance matching, stronger dielectric and magnetic losses, interfacial polarization, and multiple internal reflections. Overall, the results demonstrate that the PVA/ $Co_{0.6}$ @NZF 4wt% sample exhibits the highest EMI shielding effectiveness, followed by the PVA/ $Co_{0.8}$ @NZF 4wt% sample, while the PVA/ $Co_{0.4}$ @NZF 4wt% sample shows the lowest shielding among the investigated materials [74], [75].

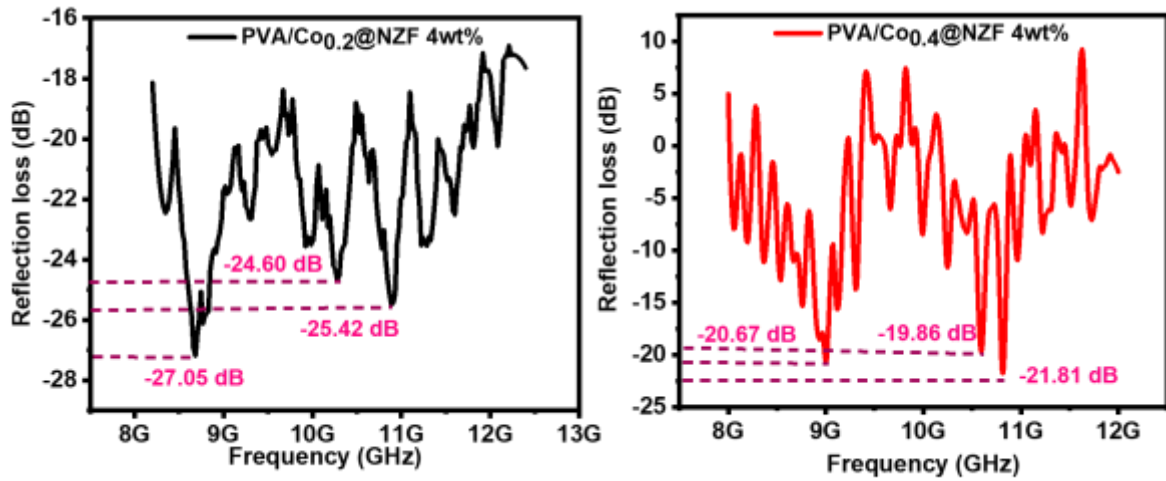


Figure 25: EMI Shielding of PVA/Co_{0.2}Ni_{0.7}Zn_{0.1}Fe₂O₄ and PVA/Co_{0.4}Ni_{0.5}Zn_{0.1}Fe₂O₄ nanocomposites filler concentration.

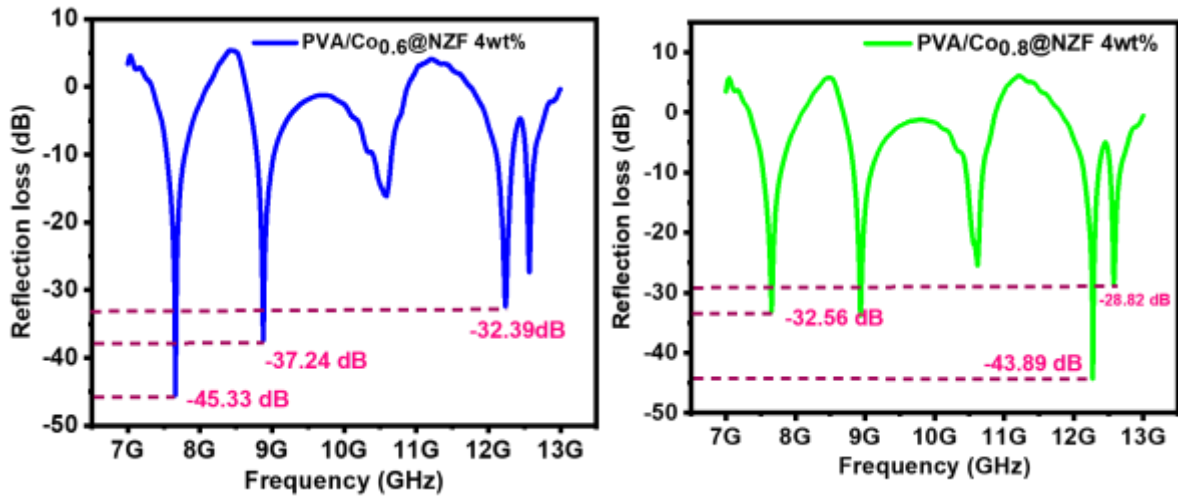


Figure 26: EMI Shielding of PVA/Co_{0.6}Ni_{0.3}Zn_{0.1}Fe₂O₄ and PVA/Co_{0.8}Ni_{0.1}Zn_{0.1}Fe₂O₄ nanocomposites filler concentration.

4. Conclusions

Cobalt-substituted Ni–Zn ferrite nanoparticles were successfully synthesized using the sol–gel method, and X-ray diffraction along with Rietveld refinement confirmed the formation of a single-phase cubic spinel structure with good crystallographic agreement. The calculated crystallite size ranged from about 6.2 to 6.9 nm, confirming the nanocrystalline nature of the synthesized samples, which is favorable for electrical and shielding-related applications. FESEM analysis revealed uniformly distributed nanograins, while EDAX confirmed the presence of the expected elemental composition

without detectable impurity phases, indicating successful synthesis of the desired materials. FTIR and Raman spectroscopic studies exhibited characteristic tetrahedral and octahedral metal–oxygen vibrational modes, confirming the structural stability of the spinel ferrite phase and the effective incorporation of ferrite nanoparticles into the PVA polymer matrix. Optical analysis using UV–Visible spectroscopy showed a gradual decrease in optical band gap from 1.45 to 1.07 eV with increasing cobalt concentration, indicating modification in the electronic structure due to cation substitution. Electrical studies demonstrated typical frequency-dependent AC conductivity and impedance behavior, mainly governed by electron hopping between Fe^{2+} and Fe^{3+} ions at octahedral sites, with the composition around $x = 0.4$ showing comparatively enhanced electrical performance. Dielectric studies indicated a decrease in dielectric constant and dielectric loss with increasing frequency, consistent with Maxwell–Wagner interfacial polarization and Koop’s theory, confirming the dielectric stability of the materials. The prepared PVA/ferrite nanocomposite films exhibited significant EMI shielding effectiveness in the X-band frequency range, with the $\text{Co}_{0.6}$ composition demonstrating the highest reflection loss of approximately -45 dB, indicating strong electromagnetic wave absorption capability. Overall, cobalt substitution effectively modified the structural, optical, electrical, and dielectric properties of Ni–Zn ferrites, and the flexible PVA/ferrite nanocomposites demonstrated strong potential as lightweight, flexible, and efficient materials for advanced electromagnetic interference shielding applications.

References

- [1] H. Cheema, S. Kumar, P. A. Alvi, B. L. Choudhary, and U. Kumar, “Synthesis and physical properties of nanopowder and electrical properties of bulk samples of $\text{ZnFe}_{2-x}\text{Ni}_x\text{O}_4$ (x : 0, 0.05, 0.10),” *Advanced Powder Technology*, vol. 31, no. 10, pp. 4241–4252, 2020, doi: <https://doi.org/10.1016/j.ap.2020.09.001>.

- [2] G. Lal, K. Punia, S. N. Dolia, P. A. Alvi, B. L. Choudhary, and S. Kumar, "Structural, cation distribution, optical and magnetic properties of quaternary $\text{Co}_{0.4+x}\text{Zn}_{0.6-x}\text{Fe}_2\text{O}_4$ ($x = 0.0, 0.1$ and 0.2) and Li doped quinary $\text{Co}_{0.4+x}\text{Zn}_{0.5-x}\text{Li}_{0.1}\text{Fe}_2\text{O}_4$ ($x = 0.0, 0.05$ and 0.1) nanoferrites," *J. Alloys Compd.*, vol. 828, p. 154388, 2020, doi: <https://doi.org/10.1016/j.jallcom.2020.154388>.
- [3] Monika, S. Pachori, R. Agrawal, B. L. B. L. Choudhary, and A. S. A. S. Verma, "An efficient and stable lead-free organic–inorganic tin iodide perovskite for photovoltaic device: Progress and challenges," *Energy Reports*, vol. 8, pp. 5753–5763, 2022, doi: <https://doi.org/10.1016/j.egyr.2022.03.183>.
- [4] Ritu, S. R. Choudhary, P. A. Alvi, and B. L. Choudhary, "Structural, Optical and Vibrational analysis of Co^{2+} Substitution of $\text{Co}_y\text{Ni}_x\text{Zn}_{(1-y-x)}\text{Fe}_2\text{O}_4$ Nanoferrites," *EPJ Web Conf.*, vol. 356, 2026, [Online]. Available: <https://doi.org/10.1051/epjconf/202635601002>
- [5] A. Anchal *et al.*, "Characterization and synthesis of nanocrystalline CoFe_2O_4 ferrites prepared by sol-gel method with citric acid variation," in *AIP Conference Proceedings*, AIP Publishing, 2024.
- [6] P. Raju, T. Ramesh, and S. R. Murthy, "Ferrite + Polymer nanocomposites for EMI applications," 2014.
- [7] H. Gupta, B. L. Choudhary, S. Ahmad, K. P. Tewari, and P. A. Alvi, "Performance analysis of AlGaIn -led for D-UV emission," in *AIP Conference Proceedings*, 2020. doi: 10.1063/5.0001131.
- [8] M. F. Shakir *et al.*, "Effect of Nickel-spinal-Ferrites on EMI shielding properties of polystyrene/polyaniline blend," *SN Appl. Sci.*, vol. 2, no. 4, Apr. 2020, doi: 10.1007/s42452-020-2535-4.
- [9] P. Raju, J. Shankar, J. Anjaiah, and S. R. Murthy, "Shielding effectiveness studies of NiCuZn ferrite-polyaniline nanocomposites for EMI suppression applications," in *AIP Conference Proceedings*, American Institute of Physics Inc., Oct. 2019. doi: 10.1063/1.5130237.
- [10] S. S. Teixeira, F. Amaral, M. P. F. Graça, and L. C. Costa, "Comparison of lithium ferrite powders prepared by sol-gel and solid state reaction methods," *Materials Science and Engineering: B*, vol. 255, p. 114529, 2020, doi: <https://doi.org/10.1016/j.mseb.2020.114529>.
- [11] A. Chatterjee, D. Das, S. K. Pradhan, and D. Chakravorty, "Synthesis of nanocrystalline nickel-zinc ferrite by the sol-gel method," *J. Magn. Magn. Mater.*, vol. 127, no. 1–2, pp. 214–218, 1993.
- [12] N. Sanpo, J. Wang, and C. C. Berndt, "Sol-Gel Synthesized Copper-Substituted Cobalt Ferrite Nanoparticles for Biomedical Applications," *Journal of Nano Research*, vol. 25, pp. 110–121, 2013, doi: 10.4028/www.scientific.net/JNanoR.25.110.

- [13] P. Gupta *et al.*, “A comparative study of the sol-gel synthesized nanostructured SnO₂ powders,” in *AIP Conference Proceedings*, 2013, pp. 159–160. doi: 10.1063/1.4810149.
- [14] N. Hamdi, L. Bessais, and W. Belam, “Sol-gel autocombustion elaboration and physiochemical characterizations of Cu²⁺ substituted cobalt ferrite nanoparticles,” *Open Chemistry Journal*, vol. 7, no. 1, 2020.
- [15] G. Srivastava, S. Dalela, S. Kumar, B. L. Choudhary, and P. A. Alvi, “Structural and Raman studies of MnO₂ and Mn₂O₃ nano-particles,” *Mater. Today Proc.*, 2022, doi: <https://doi.org/10.1016/j.matpr.2022.08.515>.
- [16] Garima *et al.*, “Tailoring the structural and dielectric properties of ZnFe₂O₄ through annealing temperature,” *Physica B Condens. Matter*, vol. 674, 2024, doi: 10.1016/j.physb.2023.415574.
- [17] Garima *et al.*, “Unraveling the structural and magnetic characteristics of Mg doped CoCr₂O₄,” *Mater. Lett.*, vol. 377, 2024, doi: 10.1016/j.matlet.2024.137550.
- [18] Ravina *et al.*, “Synthesis and investigations of structural, surface morphology, electrochemical, and electrical properties of NiFe₂O₄ nanoparticles for usage in supercapacitors,” *Journal of Materials Science: Materials in Electronics*, vol. 34, no. 10, p. 868, 2023, doi: 10.1007/s10854-023-10312-1.
- [19] N. B. Mahmood, F. R. Saeed, K. R. Gbashi, A. Hamodi, and Z. M. Jaffar, “Structural properties of Co_xCu_{1-x}Fe₂O₄ solid solution,” *J. Mech. Behav. Mater.*, vol. 30, no. 1, pp. 220–227, 2021.
- [20] A. Samariya *et al.*, “Size dependent structural and magnetic behaviour of CaFe₂O₄,” *Current Applied Physics*, vol. 13, no. 5, pp. 830–835, 2013.
- [21] S. M. Mane *et al.*, “Correlative structural refinement-magnetic tunability, and enhanced magnetostriction in low-temperature, microwave-annealed, Ni-substituted CoFe₂O₄ nanoparticles,” *J. Alloys Compd.*, vol. 895, p. 162627, 2022, doi: <https://doi.org/10.1016/j.jallcom.2021.162627>.
- [22] S. E. Shirsath, S. Patange, R. Kadam, M. Mane, and K. Jadhav, “Structure refinement, cation site location, spectral and elastic properties of Zn²⁺ substituted NiFe₂O₄,” *J. Mol. Struct.*, vol. 1024, pp. 77–83, 2012, doi: 10.1016/j.molstruc.2012.05.014.
- [23] Ritu, S. R. Choudhary, S. K. Dewanda, Y. Choudhary, P. A. Alvi, and B. L. Choudhary, “Enhanced Functional Performance of Co-Ni-Zn Ferrites: Structural Stability, Bandgap Reduction, and Electrical Conductivity,” *Int. J. Mod. Phys. B*, Feb. 2026, doi: 10.1142/S0217979226501067.
- [24] A. Kumar, M. K. Gora, S. Kumar, B. L. Choudhary, P. K. Maheshwari, and S. N. Dolia, “Reitveld refinement, structural, optical band gap and low-temperature magnetic characterization of Gd³⁺ doped spinel cubic CoFe₂O₄ nanoparticles,”

Bangladesh Journal of Scientific and Industrial Research, vol. 57, no. 3 SE-Articles, pp. 173–186, 2022, doi: 10.3329/bjsir.v57i3.62019.

- [25] V. K. Mande, R. B. Borade, V. B. Raut, and R. P. Pawar, “Rietveld refinement and cation distribution of Zn-Al substituted NiFe₂O₄ ferrite nanoparticles,” *J. Magn. Magn. Mater.*, vol. 596, p. 171908, 2024.
- [26] R. Kumar, R. R. Singh, and P. B. Barman, “COBALT DOPED NICKEL ZINC FERRITE NANOPARTICLES – XRD ANALYSES AN INSIGHT,” *Int. J. Sci. Eng. Res.*, vol. 5, no. 5, 2014, [Online]. Available: <http://www.ijser.org>
- [27] B. L. Choudhary, A. Krishnamurthy, and B. K. Srivastava, “Size dependence of magneto-resistive behaviour of nano-particle magnetite,” *Indian Journal of Pure and Applied Physics*, vol. 49, no. 3, pp. 190–194, 2011.
- [28] Sarita *et al.*, “Studies of Structural, Optical, and Raman Analysis of Ni-Substituted CoFe₂O₄,” *Physica Status Solidi (A) Applications and Materials Science*, vol. 221, no. 18, pp. 1–11, 2024, doi: 10.1002/pssa.202400083.
- [29] G. Srivastava *et al.*, “Exploration of Optical, Structural, and Electrochemical Properties of MnO₂/Mn₂O₃ Nanocomposite as Anode Material for Energy Storage Applications,” *Phys. Status Solidi B Basic Res.*, vol. 262, no. 2, 2025, doi: 10.1002/pssb.202400370.
- [30] B. L. Choudhary, N. Kumari, J. Kumari, A. Kumar, and S. N. Dolia, “Relaxation mechanism in Ni_{0.5}Zn_{0.5}Fe₂O₄ nanocrystalline ferrite at a lower temperature,” *Mater. Lett.*, vol. 304, p. 130731, 2021, doi: <https://doi.org/10.1016/j.matlet.2021.130731>.
- [31] Anchal, Sarita, N. Jakhar, P. A. Alvi, and B. L. Choudhary, “Exploring superparamagnetic behavior in Mn_xCo_{1-x}Fe₂O₄ quantum dots: A structural and spectroscopic investigation,” *Inorg. Chem. Commun.*, vol. 174, p. 114058, 2025, doi: <https://doi.org/10.1016/j.inoche.2025.114058>.
- [32] F. Hamed, T. Ramachandran, and V. Kurapati, “The effect of induced strains on the optical band gaps in lanthanum-doped zinc ferrite nanocrystalline powders,” *Modern Physics Letters B*, vol. 30, no. 18, p. 1650230, 2016.
- [33] V. D. Mote, Y. Purushotham, and B. N. Dole, “Williamson-Hall analysis in estimation of lattice strain in nanometer-sized ZnO particles,” *Journal of Theoretical and Applied Physics*, vol. 6, no. 1, p. 6, 2012, doi: 10.1186/2251-7235-6-6.
- [34] N. Kumar, K. P. Misra, S. K. Jain, and B. L. Choudhary, “Structural and morphological properties of Ce doped ZnO,” in *AIP Conference Proceedings*, 2013, pp. 605–606. doi: 10.1063/1.4810372.
- [35] A. V. Ravindra, M. Chandrika, C. Rajesh, P. Kollu, S. Ju, and S. D. Ramarao, “Simple synthesis, structural and optical properties of cobalt ferrite nanoparticles,” *Eur. Phys. J. Plus*, vol. 134, no. 6, Jun. 2019, doi: 10.1140/epjp/i2019-12690-2.

- [36] N. A. Amaran, N. Ibrahim, and Z. Mohamed, "Structural and Morphology Changes in PrMnO₃ Manganite Induced by Ba (x= 0.33) Doping," *Journal of Advanced Research in Applied Sciences and Engineering Technology*, vol. 29, no. 3, pp. 160–167, 2023.
- [37] B. L. Choudhary, A. Krishnamurthy, and B. K. Srivastava, "Magnetic behaviour of bismuth substituted perovskites La_{1-x}BixMn_{0.8}Co_{0.2}O₃," in *AIP Conference Proceedings*, 2010, pp. 307–309. doi: 10.1063/1.3530526.
- [38] B. L. Choudhary, A. Krishnamurthy, and B. K. Srivastava, "Size dependence of magneto-resistive behaviour of nano-particle magnetite," *Indian Journal of Pure and Applied Physics*, vol. 49, no. 3, pp. 190–194, 2011.
- [39] B. L. Choudhary *et al.*, "Exploring Magnetic Behaviour in La_{0.70}Pr_{0.30}Mn_{0.8}Co_{0.2}O₃ Perovskite," *J. Supercond. Nov. Magn.*, vol. 35, no. 5, pp. 1183–1193, 2022, doi: 10.1007/s10948-022-06173-0.
- [40] R. Sahu, S. K. Jain, B. Tripathi, and B. L. Choudhary, "X-ray Diffraction Analysis of Zinc Sulfide Nanocrystal with Different Microstructural Parameters," in *8th International Conference on Advanced Computing and Communication Systems, ICACCS 2022*, 2022, pp. 480–484. doi: 10.1109/ICACCS54159.2022.9785031.
- [41] M. Deepty *et al.*, "XRD, EDX, FTIR and ESR spectroscopic studies of co-precipitated Mn-substituted Zn-ferrite nanoparticles," *Ceram. Int.*, vol. 45, no. 6, pp. 8037–8044, 2019, doi: <https://doi.org/10.1016/j.ceramint.2019.01.029>.
- [42] A. Elahi, N. A. Niaz, M. S. Awan, A. Shakoar, K. Mahmood, and Y. Khan, "Structural, electrical, and magnetic properties of polypyrrole–Zn_{0.5}Ni_{0.45}Mn_{0.05}Fe₂O₄ nanocomposites prepared by in situ chemical polymerization," *Polymer Science - Series B*, vol. 57, no. 6, pp. 738–749, Nov. 2015, doi: 10.1134/S1560090415060044.
- [43] V. Dhayal *et al.*, "Optical and electrical properties of biocompatible and novel (CS–GO) polymer nanocomposites," *Opt. Quantum Electron.*, vol. 53, no. 1, 2021, doi: 10.1007/s11082-020-02723-9.
- [44] F. Nekvapil, A. Bunge, T. Radu, S. Cinta Pinzaru, and R. Turcu, "Raman spectra tell us so much more: Raman features and saturation magnetization for efficient analysis of manganese zinc ferrite nanoparticles," *Journal of Raman Spectroscopy*, vol. 51, no. 6, pp. 959–968, 2020, doi: <https://doi.org/10.1002/jrs.5852>.
- [45] A. Ahlawat and V. G. Sathe, "Raman study of NiFe₂O₄ nanoparticles, bulk and films: effect of laser power," *Journal of Raman Spectroscopy*, vol. 42, no. 5, pp. 1087–1094, 2011, doi: <https://doi.org/10.1002/jrs.2791>.
- [46] P. R. Graves, C. Johnston, and J. J. Campaniello, "Raman scattering in spinel structure ferrites," *Mater. Res. Bull.*, vol. 23, no. 11, pp. 1651–1660, 1988, doi: [https://doi.org/10.1016/0025-5408\(88\)90255-3](https://doi.org/10.1016/0025-5408(88)90255-3).

- [47] Ravina, S. Dalela, S. Kumar, B. L. Choudhary, and P. A. Alvi, "Structural, optical and Raman studies of Co₃O₄ nano-particles," *Mater. Today Proc.*, 2022, doi: <https://doi.org/10.1016/j.matpr.2022.08.513>.
- [48] G. Srivastava, S. Dalela, S. Kumar, B. L. Choudhary, and P. A. Alvi, "Structural and Raman studies of MnO₂ and Mn₂O₃ nano-particles," in *Materials Today: Proceedings*, 2023, pp. 169–171. doi: 10.1016/j.matpr.2022.08.515.
- [49] A. Kumar, M. A. Dar, P. Sharma, and D. Varshney, "Structural and Raman scattering study of Ni-doped CoFe₂O₄," in *AIP Conference Proceedings*, American Institute of Physics, 2014, pp. 1148–1150.
- [50] K. B. Modi *et al.*, "Raman and mossbauer spectroscopy and x-ray diffractometry studies on quenched copper–ferri–aluminates," *Inorg. Chem.*, vol. 54, pp. 1543–1555, 2015, doi: 10.1021/ic502497a.
- [51] Ritu, S. R. Choudhary, S. K. Dewanda, Y. Choudhary, P. A. Alvi, and B. L. Choudhary, "Enhanced Functional Performance of Co-Ni-Zn Ferrites: Structural Stability, Bandgap Reduction, and Electrical Conductivity," *Int. J. Mod. Phys. B*, Feb. 2026, doi: 10.1142/S0217979226501067.
- [52] N. Y. Elamin, A. Modwi, W. Abd El-Fattah, and A. Rajeh, "Synthesis and structural of Fe₃O₄ magnetic nanoparticles and its effect on the structural optical, and magnetic properties of novel Poly (methyl methacrylate)/Polyaniline composite for electromagnetic and optical applications," *Opt. Mater. (Amst.)*, vol. 135, p. 113323, 2023.
- [53] T. Tatarchuk *et al.*, "Structural, optical, and magnetic properties of Zn-doped CoFe₂O₄ nanoparticles," *Nanoscale Res. Lett.*, vol. 12, pp. 1–11, 2017, doi: 10.1186/s11671-017-1899-x.
- [54] A. M. Moustafa, S. A. Gad, and H. M. Hashem, "Mg²⁺ Doped ZCF AO Spinel Ferrite: Structural, Optical, Dielectric and Magnetic Explorations," *J. Inorg. Organomet. Polym. Mater.*, pp. 1–14, 2024.
- [55] B. L. Choudhary, S. Kumar, A. Krishnamurthy, and B. K. Srivastava, "Preparation and magnetic studies of Mn substituted analogues of BiFeO₃," in *AIP Conference Proceedings*, 2011, pp. 83–86. doi: 10.1063/1.3644422.
- [56] S. K. Jain, S. N. Dolia, B. L. Choudhary, and B. L. Prashant, "Structural and morphological study of Zn_{0.9}Mn_{0.05}Fe_{0.05}O synthesized by sol-gel wet chemical precipitation route," in *IOP Conference Series: Materials Science and Engineering*, 2018. doi: 10.1088/1757-899X/348/1/012004.
- [57] H. Cheema, S. Kumar, P. A. Alvi, B. L. Choudhary, and U. Kumar, "Synthesis and physical properties of nanopowder and electrical properties of bulk samples of ZnFe₂-xNi_xO₄ (x: 0, 0.05, 0.10)," *Advanced Powder Technology*, vol. 31, no. 10, pp. 4241–4252, 2020, doi: 10.1016/j.apr.2020.09.001.

- [58] N. M. Yousif, N. Makram, and L. A. Wahab, "Structural, dielectric, and magnetic properties of $\text{LaCo}_{0.2}\text{Mn}_{0.8}\text{O}_3$ and $\text{La}_2\text{CoMnO}_6$ perovskite materials," *J. Solgel Sci. Technol.*, vol. 98, no. 1, pp. 238–251, 2021, doi: 10.1007/s10971-021-05502-4.
- [59] M.-R. Syue, F.-J. Wei, C.-S. Chou, and C.-M. Fu, "Magnetic, dielectric, and complex impedance properties of nanocrystalline Mn–Zn ferrites prepared by novel combustion method," *Thin Solid Films*, vol. 519, pp. 8303–8306, 2011, doi: 10.1016/j.tsf.2011.04.003.
- [60] D. K. Pradhan *et al.*, "Correlation of dielectric, electrical and magnetic properties near the magnetic phase transition temperature of cobalt zinc ferrite," *Physical Chemistry Chemical Physics*, vol. 19, no. 1, pp. 210–218, 2017, doi: 10.1039/C6CP06133H.
- [61] N. Jahan, M. N. I. Khan, and J. I. Khandaker, "Exploration through Structural, Electrical, and Magnetic Properties of Al^{3+} Doped Ni–Zn–Co Nanospinel Ferrites," *ACS Omega*, vol. 6, no. 48, pp. 32852–32862, 2021, doi: 10.1021/acsomega.1c04832.
- [62] S. B. B. Dangi *et al.*, "Exploration of spectroscopic, surface morphological, structural, electrical, optical and mechanical properties of biocompatible PVA-GO PNCs," *Diam. Relat. Mater.*, vol. 127, p. 109158, 2022, doi: <https://doi.org/10.1016/j.diamond.2022.109158>.
- [63] S. B. Dangi *et al.*, "Exploration of spectroscopic, surface morphological, structural, electrical, optical and mechanical properties of biocompatible PVA-GO PNCs," *Diam. Relat. Mater.*, vol. 127, 2022, doi: 10.1016/j.diamond.2022.109158.
- [64] S. Saleem *et al.*, "Investigating the impact of Cu^{2+} doping on the morphological, structural, optical, and electrical properties of CoFe_2O_4 nanoparticles for use in electrical devices," *Materials*, vol. 15, no. 10, p. 3502, 2022.
- [65] Garima *et al.*, "Tailoring the structural and dielectric properties of ZnFe_2O_4 through annealing temperature," *Physica B Condens. Matter*, vol. 674, p. 415574, 2024, doi: <https://doi.org/10.1016/j.physb.2023.415574>.
- [66] G. A. Lone and M. Ikram, "Investigating the structural and dielectric properties of $\text{CoFe}_{2-x}\text{Ni}_x\text{O}_4$ spinel ferrite," *J. Alloys Compd.*, vol. 908, p. 164589, 2022, doi: <https://doi.org/10.1016/j.jallcom.2022.164589>.
- [67] A. A. Ansari *et al.*, "Microstructure, optical and dielectric properties of cobalt-doped zinc ferrite nanostructures," *Journal of Materials Science: Materials in Electronics*, vol. 32, no. 17, pp. 21988–22002, Sep. 2021, doi: 10.1007/s10854-021-06647-2.
- [68] Aakash, M. P. Ghosh, and S. Mukherjee, "Dielectric and electrical characterizations of transition metal ions-doped nanocrystalline nickel ferrites," *Applied Physics A*, vol. 125, no. 12, p. 853, 2019, doi: 10.1007/s00339-019-3155-y.
- [69] S. Kumari, N. Dhanda, A. Thakur, S. Singh, and P. Thakur, "Investigation of calcium substitution on magnetic and dielectric properties of Mg–Zn nano ferrites," *Mater. Chem. Phys.*, vol. 297, p. 127394, 2023.

- [70] A. Kumar, M. K. Gora, S. Kumar, B. L. Choudhary, R. K. Singhal, and S. N. Dolia, "Study of electronic structure and dielectric properties of Gd-doped cobalt nanoferrites," *Journal of the Korean Physical Society*, vol. 81, no. 9, pp. 894–902, 2022, doi: 10.1007/s40042-022-00612-w.
- [71] S. Kumari, N. Dhanda, A. Thakur, S. Singh, and P. Thakur, "Investigation of calcium substitution on magnetic and dielectric properties of Mg–Zn nano ferrites," *Mater. Chem. Phys.*, vol. 297, p. 127394, 2023.
- [72] M. Gurusiddesh, B. J. Madhu, G. J. Shankaramurthy, and B. Shruthi, "Structural, dielectric and magnetic studies on polyaniline-decorated Ni_{0.5}Cu_{0.5}Fe₂O₄ nanoferrites for electromagnetic interference shielding applications," *Appl. Phys. A Mater. Sci. Process.*, vol. 126, no. 2, Feb. 2020, doi: 10.1007/s00339-019-3268-3.
- [73] J. S. Kounsalye, P. B. Kharat, D. N. Bhoyar, and K. M. Jadhav, "Radiation-induced modifications in structural, electrical and dielectric properties of Ti⁴⁺ ions substituted Li_{0.5}Fe_{2.5}O₄ nanoparticles," *Journal of Materials Science: Materials in Electronics*, vol. 29, no. 10, pp. 8601–8609, 2018, doi: 10.1007/s10854-018-8874-x.
- [74] N. Sharma *et al.*, "Exploring and tailoring the characteristics of biocompatible next-generation soft materials: PCG and PCPtG polymer nanocomposites," *Diam. Relat. Mater.*, vol. 164, p. 113454, 2026, doi: <https://doi.org/10.1016/j.diamond.2026.113454>.
- [75] N. K. Gautam *et al.*, "Novel method of synthesis for MXene/LIG nanocomposites via laser fabrication technique for enhanced performance in energy storage applications," *J. Alloys Compd.*, vol. 1057, p. 186827, 2026, doi: <https://doi.org/10.1016/j.jallcom.2026.186827>.