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Impact of Copper substituted cobalt ferrite nano particles structural, morphological Optical and microbial studies

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Abstract

The sol-gel auto-combustion procedure was used to synthesize copper doped cobalt nano ferrites nano ferrites. X-ray diffraction measurements validated the mono-phase formation and nanocrystalline character of the produced samples. It possesses a monophasic cubic-spinel lattice structure with an average crystallite size ranging from 24.10 nm to 43.50nm. The morphological characteristics were shown using SEM analysis, which revealed the almost spherical form of grains with sizes ranging from 24.10 nm to 43.50nm its good agreements for the TEM analysis. SEM images revealed that the nanoparticles were nearly spherical with a uniform size distribution around 20-30 nm. Nano-sized ferrites often display a larger band gap compared to their bulk counterparts due to quantum confinement effects and also shows the good microbial agents.Nano ferrites have distinct advantages over their bulk counterparts, including enhanced surface area, quantum size effects, and tunable optical properties. The influence of synthesis techniques on particle size, morphology, and cation distribution is also discussed, highlighting the critical role these factors play in determining the material's properties. This paper aims to provide a $CuCoFe_2O_4$ nano ferrites, focusing on their synthesis, properties, and applications.

Key words: Co–doped Cu-Co ferrite, Sol-gel, XRD, SEM, Energy band gap.

1. Introduction

Nano ferrites are a class of ferrites that have been engineered at the nanometer scale, typically with particle sizes less than 100 nanometers. These materials exhibit unique magnetic, electrical, and structural properties that differ significantly from their bulk counterparts due to the increased surface area and quantum effects at the nanoscale. Enhanced Magnetic Properties: Nano ferrites often show higher saturation magnetization and coercivity compared to bulk ferrites. This makes them useful in applications requiring strong and stable magnetic fields. Increased Surface Area: The high surface-to-volume ratio in nano ferrites leads to improved catalytic activity and better performance in applications like sensors and environmental remediation. Tailorable Electrical Properties: By adjusting the composition and size of the nanoparticles, it's possible to fine-tune the electrical properties for specific uses, such as in high-frequency devices[1-2]. Applications are in Medical Field: Nano ferrites are used in targeted drug delivery, magnetic resonance imaging (MRI) contrast agents, and hyperthermia treatment for cancer. Electronics: They are used in high-density data storage, advanced electronics, and as components in microwave devices. Environmental: Nano ferrites are employed in wastewater treatment and as catalysts in various chemical reactions.

Nanoparticles have received significant attention in various engineering fields due to their diverse applications [8]. These nanostructures are composed of a range of materials, including ferrite nanoparticles. They have drawn considerable attention in photoluminescence, photocatalysis, humidity sensors, corrosion protection, biosensors, catalysis, magnetic drug delivery, permanent magnets, magnetic refrigeration, microwave absorbers, water decontamination, ceramic pigments, magnetic liquids, antimicrobial agents, biomedicine (hyperthermia), high-density data storage materials, converters, and antenna frames, etc. [9]. “Ferrite” is a common term applied various ceramic ferromagnetic materials. They are structurally more stable than iron oxide and possess integrated properties of magnetic materials and insulators. Ferrite can be produced by combining large amounts of iron (III) oxide Fe_2O_3, with smaller amounts of metallic elements, such as cobalt, magnesium, bismuth, strontium, barium, manganese, nickel, copper, zinc, silver, and non-metal elements such as carbon, sulfur, and nitrogen, in varying ratios to obtain different desirable effects [10]. These nanoparticles are essential because of their excellent chemical and physical properties. Their exceptional optical, thermal, magnetic, dielectric, electronic, catalytic, mechanical, and electrical properties have significant impact in various sectors of human interest [9]. The most important and widespread applications of ferrites include optics, electronics, mechanics, and other technical fields [1-2]. Ferrites particularly, spinel ferrite nanoparticles have emerged as frontrunners in nanoscience and nanobiotechnology, demonstrating a wide range of promising applications. Spinel ferrite is a ferromagnetic compound comprising iron oxide and various transition metals. Examples include $ZnFe_2O_4$, $NiFe_2O_4$, $CuFe_2O_4$, $CoFe_2O_4$, $MnFe_2O_4$, and $MgFe_2O_4$. Recently, researchers have focussed on the extensive use of ferrite nanoparticles and their composites in various applications. Both doped and undoped transition-metal ferrites are attractive candidates for catalysis, sustainable hydrogen production, sensors, electronic devices, and magnetic devices.

According to their magnetic properties and crystal structures, ferrites are classified into four distinct groups based on the iron and metal oxides used as their primary constituents: garnet (MIIIFe5O12), spinel (MIIFe2O4), magneto-plumbite (MIIFe12O19), and ortho (MIIIFeO3). Ferrites possess distinct crystal forms [18]. The ions influence their magnetic properties, categorized as soft or hard ferrites based on their magnetic coercivity and resistance to demagnetization. Soft ferrites are ferrimagnetic materials with low hysteresis losses, low coercivity, and high saturation magnetization. These soft ferrites contain iron oxide and divalent metal oxides, have cubic spinel crystalline structures, and do not exhibit magnetism after being magnetized. In terms of applications, the most critical soft ferrites are Mn–Zn ferrites (MnZnFe2O4), Ni–Zn ferrites (NiZnFe2O4), and Mg–Mn–Zn ferrites. Hard ferrites are ferrimagnetic materials that exhibit magnetism even after removing the applied magnetic field. It has a crystal structure composed of cubic blocks with spinel and hexagonal blocks containing metal ions. They exhibit a more powerful coercive force than metal magnetic ferrites. Barium ferrite (BaO6Fe2O3) and strontium ferrite (SrO6Fe2O3) are the most prominent permanent magnetic materials in practical use. Different ferrites execute significant functions in engineering and technology. Among them, spinel ferrite nanomaterials are considered one of the most significant inorganic nanomaterials owing to their improved electrical, magnetic, and catalytic properties [19-21].Customizability: Their properties can be precisely controlled through synthesis methods, making them highly adaptable to specific needs. Improved Performance: Nano ferrites often exhibit superior performance in terms of sensitivity, efficiency, and functionality compared to traditional ferrite materials. In summary, nano ferrites represent an exciting frontier in material science, offering enhanced properties and new possibilities for a wide range of technological applications. $CuCoFe_2O_4$ nano ferrites are a class of spinel ferrites known for their unique optical and electrical properties, which make them suitable for a variety of applications, including magnetic storage, catalysis, and biomedical uses. This paper reviews the synthesis methods, structural characteristics, magnetic and electrical properties, and potential applications of $CuCoFe_2O_4$ nano ferrites[3-4].

Copper cobalt nano ferrites (CuCoFe2O4) have garnered significant attention in recent years due to their unique optical properties and potential applications in various fields such as catalysis, magnetic storage, and biomedical applications. This paper provides a comprehensive review of the synthesis, structural characteristics, and optical properties of CuCoFe2O4 nanoparticles. Special focus is given to the mechanisms underlying their optical behavior and the influence of synthesis methods and particle size on these properties. Ferrites are a class of magnetic materials primarily composed of iron oxides combined with various metal ions. Among these, copper cobalt nano ferrites stand out due to their remarkable magnetic and optical properties, which are particularly useful in technological applications [4-6]. Nano ferrites have distinct advantages over their bulk counterparts, including enhanced surface area, quantum size effects, and tunable optical properties. The influence of synthesis techniques on particle size, morphology, and cation distribution is also discussed, highlighting the critical role these factors play in determining the material's properties. This paper aims to provide a comprehensive overview of $CuCoFe_2O_4$ nano ferrites, focusing on their synthesis, properties, and applications.

2. Materials and methods of Synthesis Techniques

All used precursors are nitrates provided by Merck and Sigma Aldrich chemicals with AR grade having 99.5% purity. Cobalt nitrate [Co(NO3)2 6H2O], Copper nitrate [Cu(NO3)2 6H2O], ferrous nitrate [Fe(NO3)3 9H2O] are precursors and citric acid [C6H8O7 H2O] act as burning agent and ammonia solution (NH3) is for maintaining the pH level of solution.

2. Synthesis of mixed co doped ferrites nano particles by Sol-gel method

A Sol-gel technique is one of the popular critical techniques to synthesize the inorganic oxides. The synthesis method greatly affects the properties of $CuCoFe_2O_4$ nano ferrites. The sol-gel method involves transitioning a solution (sol) into a solid (gel) phase. Metal nitrates or chlorides are typically used as precursors. This method offers control over the stoichiometry and particle size but requires careful handling of the reactants and conditions.

3. X-Ray Diffraction (XRD)

XRD analysis confirms the formation of the spinel structure and provides information on crystallite size and lattice parameters. The typical diffraction peaks for spinel ferrites are indexed to the (220), (311), (400), (422), (511), and (440) planes. Transmission Electron Microscopy (TEM). TEM provides detailed information on particle size and morphology. $CuCoFe_2O_4$ nanoparticles synthesized by sol-gel or hydrothermal methods often exhibit spherical shapes with sizes ranging from 5 to 50 nm.

Crystallite size $D=0.94\lambda/\beta\cos\theta$ ------------------------ (1)

Where D denotes the average crystallite size and β is the peak's full width at half-maxima (FWHM) [7]. Point of reflection and the point of occurrence are equivalent. From the unmistakable pinnacle of the XRD design, the Scherrer condition was utilized to decide the "D" crystallite size were obtained 23.5 nm to 43.10 nm shown in table1.

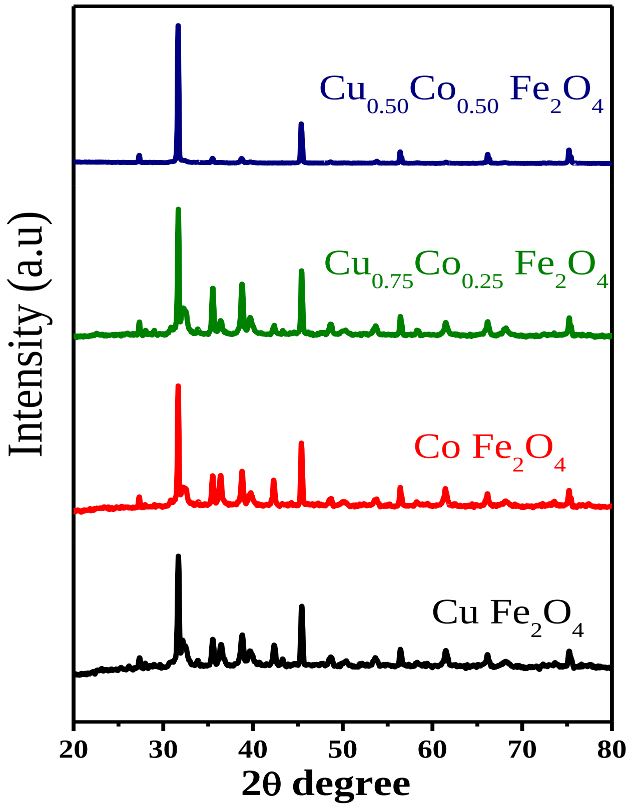

Fig1. PXRD patterns

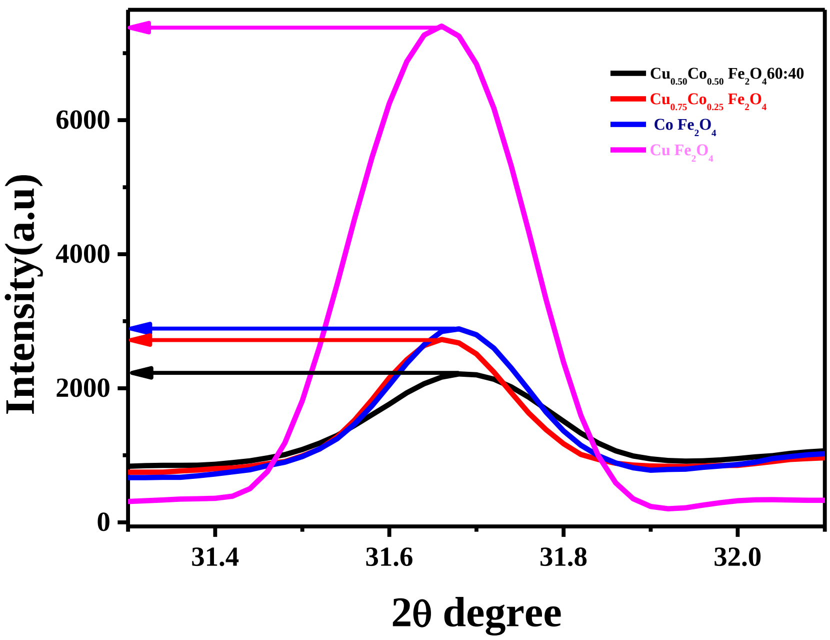

Fig2. Enlarged PXRD patterns of specific range

Table1. Crystallite Size, % Crystallinity and Energy band gap

S.No	**Composition**	**Crystallite Size(nm)**	**% Crystallinity**	**Energy band gap (eV)**
1	Cu Fe_2O_4	48.74175	92.98%	1.86
2	Co Fe2O4	23.67389	90.58%	1.84
3	Cu0.75Co0.25 Fe2O4	22.06031	88.84%	1.81
4	Cu0.50Co0.50 Fe2O4	24.93659	79.61%	1.78

4. Scanning Electron Microscope (SEM) Studies of Copper Cobalt Ferrites (Cu-Co-Fe_2O_4)

Figure.3. shows the scanning Electron Microscopy (SEM) is a critical technique for studying the morphology and microstructure of $CuCoFe_2O_4$ ferrites at the nanoscale. SEM provides high-resolution images that offer insights into particle size, shape, surface morphology, and aggregation behavior, which are essential for understanding and optimizing the properties of these materials for various applications.1. Sample Preparation for SEM Proper sample preparation is crucial for obtaining high-quality SEM images [7-9]. The surface morphology observed in SEM images includes:Surface Texture: The texture of the nanoparticle surfaces can be smooth or rough, affecting their reactivity and catalytic properties.Porosity: SEM can help identify the presence of pores or voids within the nanoparticles, which are relevant for applications in catalysis and adsorption.3. Detailed SEM Analysis. SEM allows for the observation of finer details, such as:Crystallinity: Although SEM does not provide direct information about crystallinity, high-resolution images can show well-defined facets that suggest high crystallinity. SEM images revealed that the nanoparticles were nearly spherical with a uniform size distribution around 20-30 nm. SEM images showed significant aggregation, with primary particles clustering into larger aggregates. Surface Features: The particles exhibited rough surfaces, which could enhance their catalytic activity. The observed morphology and size distribution can be correlated with magnetic and electrical properties, aiding in the design of materials for specific applications. The combination of high-resolution imaging and elemental analysis makes SEM an indispensable tool in the research and development of nano ferrites [9-10].

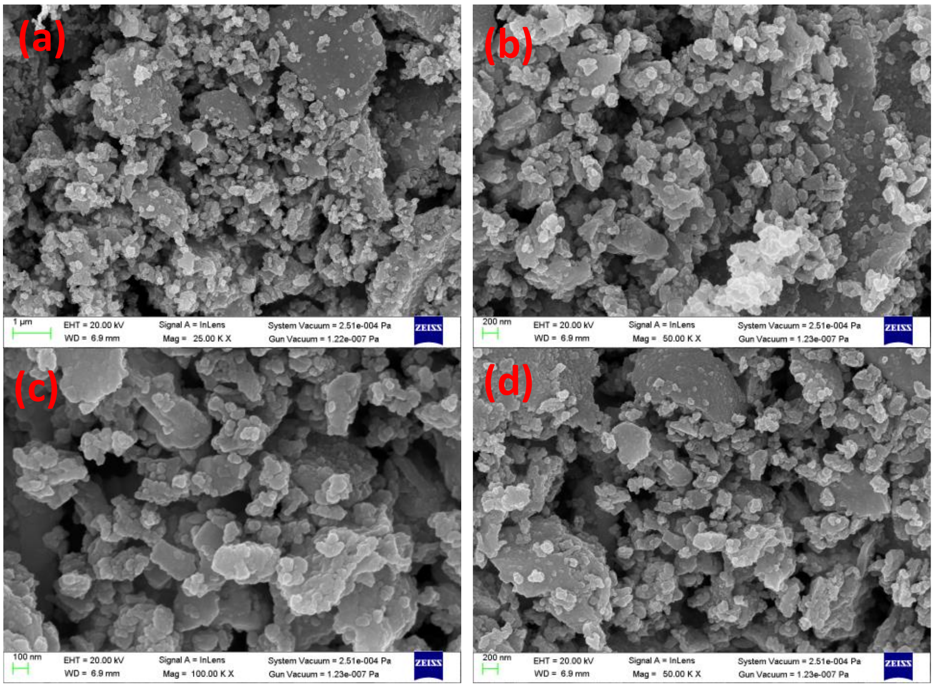

Fig3. SEM images of (a)Pure Cu Fe2O4 (b) Pure Co Fe2O4 (c)$Cu_{0.75}Co_{0.25}Fe_2O_4$ (d) $Cu_{0.50}Co_{0.50}Fe_2O_4$ nano ferrites

5.Transmission Electron Microscopy (TEM)

Figure.4. shows the TEM is a powerful technique used to analyze the structural and morphological properties of nanomaterials, including copper-cobalt ferrites (Cu-Co ferrites). Here's a detailed outline of what a TEM analysis of Cu-Co nano ferrites typically involves. Nanoparticle Synthesis Cu-Co ferrites can be synthesized using methods such as sol-gel. The synthesized nanoparticles are dispersed in a solvent (e.g., ethanol) and sonicated to form a uniform suspension. A drop of this suspension is then placed on a TEM grid (typically a carbon-coated copper grid) and dried. Cu-Co ferrite nanoparticles were synthesized using a sol-gel method and analyzed using TEM. The HRTEM images revealed well-defined lattice fringes with an interplanar spacing corresponding to the spinel structure of ferrites. SAED patterns confirmed the cubic spinel phase with no secondary phases detected. The particle size distribution, determined from TEM images, showed an average particle size of 20 to 43.5 nm with a relatively narrow size distribution.. High-resolution images also revealed the presence of twin boundaries and occasional stacking faults, which are typical in nanostructured materials. This comprehensive approach provides a thorough understanding of the structural, morphological, and compositional properties of Cu-Co ferrite nanoparticles using TEM[9-10].

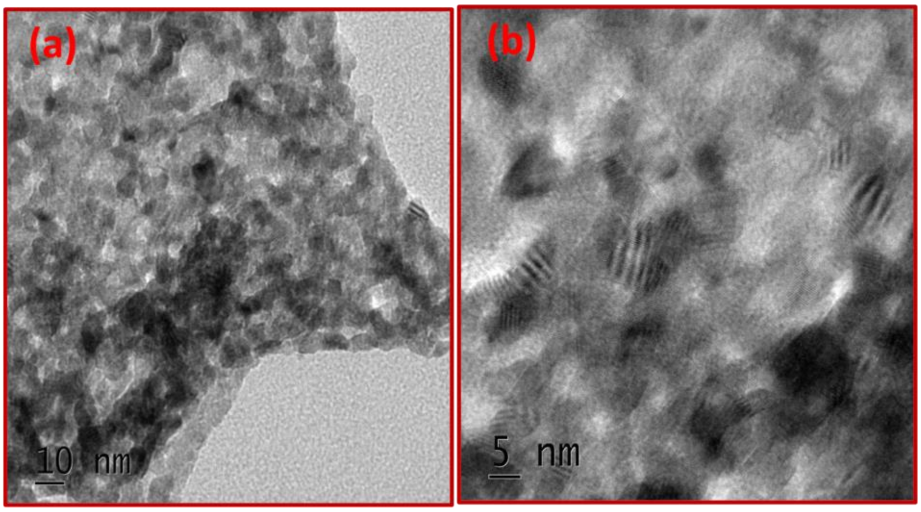

Fig4. TEM images of $Cu_{0.50}Co_{0.50}Fe_2O_4$ nano ferrites

6. Optical Properties

Figure.5. and 6. Shows the optical properties of CuCoFe2O4 nanoparticles are influenced by factors such as particle size, synthesis method, and surface modifications. Key optical properties include absorbance, band gap energy The absorbance spectra of CuCoFe2O4 nanoparticles typically exhibit strong absorption in the UV-Visible region. [15]. The optical band gap energy, which can be determined from Tauc plots, is a critical parameter that influences the material's potential applications in optoelectronics and photocatalysis [11-12]. Nano-sized ferrites often display a larger band gap compared to their bulk counterparts due to quantum confinement effects shown in table1.

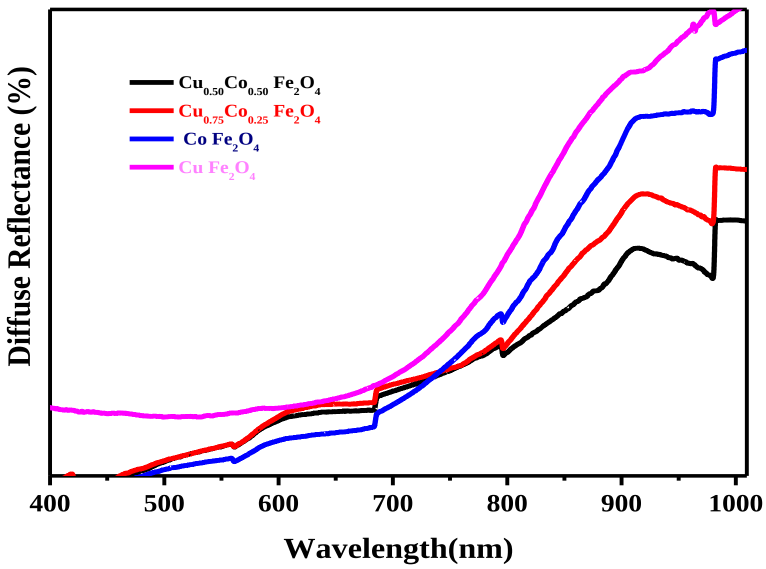

Fig.5. UV-Vis Spectra of Diffuse Reflectance and wavelength

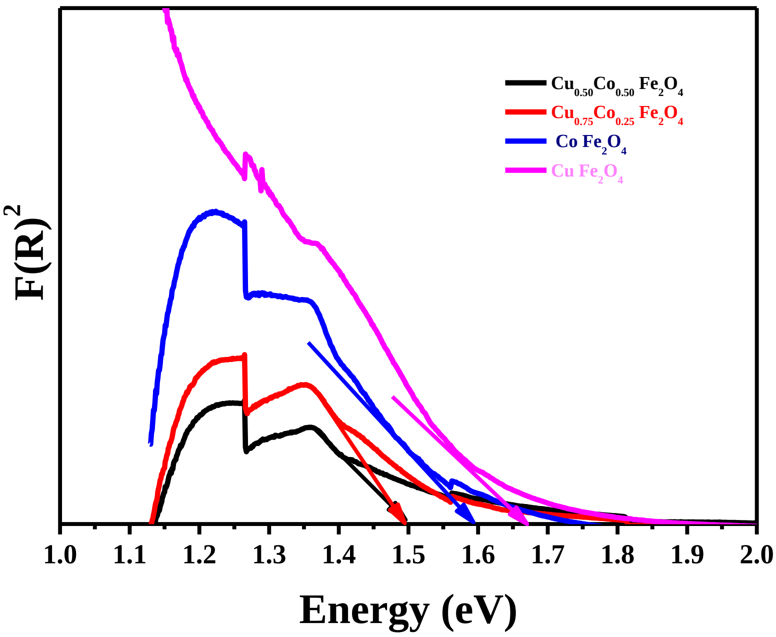

Fig.6. UV-Vis Spectra of Energy band gap

Antibacterial activity

With the rising threat of antibiotic-resistant bacteria, there is an urgent need for new antibacterial agents. Nano ferrites, particularly those involving transition metals like copper and cobalt, offer a novel approach due to their potent antimicrobial properties and biocompatibility. Copper cobalt nano ferrites ($CuCo_2O_4$) have been identified as potential candidates for antibacterial applications because of their ability to generate reactive oxygen species (ROS), disrupt bacterial cell membranes, and interfere with cellular processes [9-12].

Mechanisms of Action

The antibacterial activity of copper cobalt nano ferrites is primarily attributed to several mechanisms:

1. Generation of Reactive Oxygen Species (ROS): CuCo nanoparticles can catalyze the formation of ROS, which damage bacterial cell membranes, proteins, and DNA.

2. Membrane Disruption: The nanoparticles interact with bacterial cell membranes, causing physical disruptions and leakage of cellular contents.

3. Metal Ion Release: Release of Cu^{2+} and Co^{2+} ions can interfere with vital cellular processes, leading to bacterial cell death.

Studies have shown that Cu Co nanoparticles exhibit significant antibacterial activity against a range of pathogenic bacteria, including Gram-positive (e.g., Staphylococcus aureus) and Gram-negative (e.g., Escherichia coli) strains. The effectiveness is influenced by factors such as nanoparticle size, concentration, and the presence of functional groups on the surface. The high surface area to volume ratio of nanoparticles enhances their interaction with bacterial cells, while the magnetic properties may facilitate targeted delivery and controlled release [12-14]. Additionally, the synergistic effects of copper and cobalt ions contribute to the overall antibacterial activity detailed shown in table2 and figure.5.

Test	**Zone of inhibition in diameter (mm)**			
	control—DMSO/distilled water	$Cu_{0.50}Co_{0.50}$ Fe_2O_4	$Cu_{0.75}Co_{0.25}$ Fe_2O_4	Streptomycin.
E. coli	*10* ±SE	*26*±SE	*23*±SE	*38*±SE
S.typhimurium	*10* ±SE	*25*±SE	*24*±SE	*37*±SE
E. aerogenes	*10*±SE	*22*±SE	*21*±SE	*28*±SE
P. aerogenes.	*10* ±SE	*24*±SE	*25*±SE	*30*±SE

Table 2. $Cu_{0.50}Co_{0.50}$ Fe_2O_4 (A) E. coli, (B)S. typhimurium, (C)E. aerogenes and (D)P. aerogenes. 1.—control—DMSO/distilled water 2— $Cu_{0.50}Co_{0.50}$ Fe_2O_4; 3- $Cu_{0.75}Co_{0.25}$ Fe_2O_4 4—streptomycin.

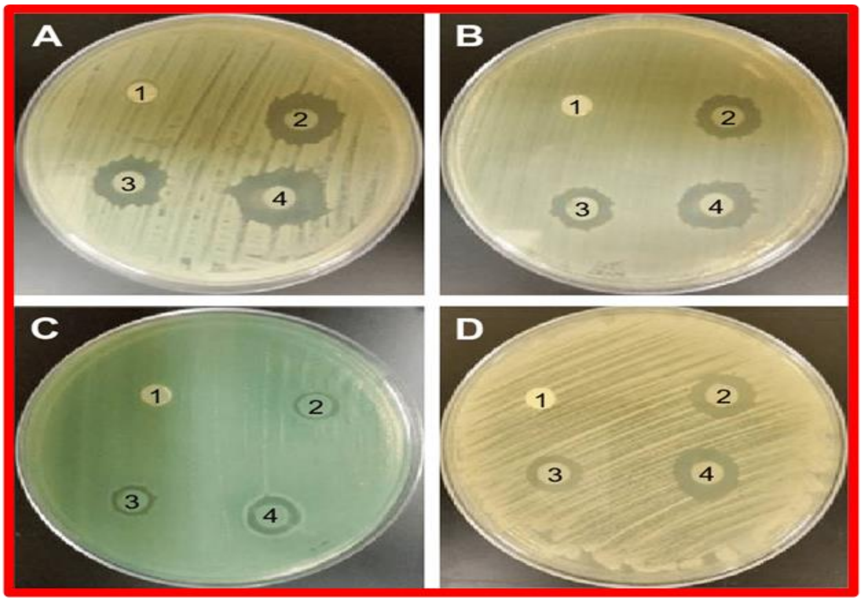

Fig. 7. $Cu_{0.50}Co_{0.50}$ Fe_2O_4 (A) E. coli, (B)S. typhimurium, (C)E. aerogenes and (D)P. aerogenes. 1.—control—DMSO/distilled water 2— $Cu_{0.50}Co_{0.50}$ Fe_2O_4; 3- $Cu_{0.75}Co_{0.25}$ Fe_2O_4 4—streptomycin.

Conclusion

Copper doped cobalt nano ferites were suscefully prepared via sol-gel method. It possesses a monophasic cubic-spinel lattice structure with an average crystallite size ranging from 24.10 nm to 43.50nm. The morphological characteristics were shown using SEM analysis, which revealed the almost spherical form of grains with sizes ranging from 24.10 nm to 43.50nm its good agreements for the TEM analysis and obtained from the PXRD patterns..Nano ferrites have distinct advantages over their bulk counterparts, including enhanced surface area, quantum size effects, and tunable optical properties i.e band gap was obtained 1.78 to 1.86eV. Studies have shown that Cu Co nanoparticles exhibit significant antibacterial activity against a range of pathogenic bacteria, including Gram-positive (e.g., Staphylococcus aureus) and Gram-negative (e.g., Escherichia coli) strains. The influence of synthesis techniques on particle size, morphology, and cation distribution is also discussed, highlighting the critical role these factors play in determining the material's properties. This paper aims to provide a comprehensive overview of $CuCoFe_2O_4$ nano ferrites, focusing on their synthesis, properties, and applications.

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