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Structural, Morphological, and Optical Analysis of Copper Ferrite ($CuFe_2O_4$) Nanoparticles Synthesized by Co-Precipitation

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Abstract: Copper ferrite ($CuFe_2O_4$) nanoparticles were synthesized via the co-precipitation method and comprehensively characterized using X-ray diffraction (XRD), diffuse reflectance spectroscopy (DRS), energy-dispersive X-ray spectroscopy (EDS), and scanning electron microscopy (SEM). XRD analysis confirmed the formation of a cubic spinel structure with an average crystallite size of 20nm, a dislocation density of 2.46×10^{15} lines/m², and a crystallinity of 26.05%. The calculated unit cell volume corresponded well with standard $CuFe_2O_4$ values, confirming phase purity. Optical characterization by DRS revealed an energy band gap of 1.528 eV, indicating the material's suitability for photocatalytic and optoelectronic applications. SEM micrographs showed irregular, polycrystalline particles ranging from 200 nm to approximately 5 µm, exhibiting surface roughness, porosity, and agglomeration features attributed to the co-precipitation synthesis route. EDS analysis verified the elemental composition with a Cu:Fe atomic ratio close to 1:2, consistent with the stoichiometry of $CuFe_2O_4$, and confirmed a high oxygen content characteristic of the oxide spinel phase. The observed porous morphology and fine grain structure suggest that the synthesized $CuFe_2O_4$ nanoparticles possess favorable characteristics for magnetic, catalytic, and adsorption-based applications.

1. Introduction

Nanoparticles are materials with at least one dimension in the range of 1–100 nanometers. At this scale, materials exhibit novel physicochemical, optical, electrical, and magnetic properties that differ significantly from their bulk counterparts (Aldwayyan *et al.,* 2013; Joudeh and Linke, 2022; Krishna Podagatlapalli, 2025). These unique characteristics arise primarily due to the extremely high surface-area-to-volume ratio, a large fraction of surface atoms, and the manifestation of quantum confinement effects. The synthesis of nanoparticles aims to provide materials with unique properties for applications in medicine, electronics and environmental sciences, as well as to create more efficient and economical

catalysts (Abady *et al.,* 2024; Abouri *et al.,* 2024; Abbas *et al.*, 2025). Such features enhance their reactivity, catalytic efficiency, and tunable electronic behavior, making nanoparticles valuable across diverse scientific and industrial domains (Akartasse *et al.,* 2022; Hossain *et al.,* 2023; Vinukonda *et al.*, 2025). Among various nanomaterials, copper ferrite ($CuFe_2O_4$) nanoparticles have attracted considerable attention due to their remarkable magnetic behavior, chemical stability, and thermal robustness (Ghobadi, 2022; Akbar *et al.,* 2025; El Messaoudi *et al.*, 2025). They exhibit spinel-type crystal structures, where cations are distributed among tetrahedral and octahedral sites, influencing their magnetic and electronic properties. These attributes make copper ferrite nanoparticles promising candidates for applications in magnetic data storage, catalysis, targeted drug delivery, magnetic resonance imaging (MRI), and environmental remediation.

Spinel ferrite nanoparticles characterized by the general formula MFe_2O_4 (where M represents transition metals such as Co, Ni, Zn, Cu, etc.) have garnered substantial scholarly interest in recent years, attributed to their exceptional magnetic, electrical, and catalytic attributes. Notably, copper ferrite ($CuFe_2O_4$) (Adachi *et al*., 2024; Azzaoui *et al.,* 2024) is distinguished as a material of significant technological relevance, as it integrates semiconducting and magnetic properties that render it apt for a diverse array of applications, including catalysis, gas sensing, magnetic recording, and photocatalytic remediation of environmental pollutants. The distinctive characteristics of this compound stem from the mixed valence states of the iron and copper ions, along with the specific cation distribution within the spinel lattice framework.

$CuFe_2O_4$ exhibits a tetragonal spinel structure at ambient temperature, wherein Cu^{2+} ions predominantly occupy octahedral sites, while Fe^{3+} ions are spatially distributed between tetrahedral and octahedral sites. The structural, morphological, and optical characteristics of this ferrite are profoundly influenced by the synthesis methodology, precursor concentration, annealing temperature, and particle dimensions. Consequently, the meticulous adjustment of these parameters is vital for the optimization of the physicochemical properties of the material to meet specific application requirements (Naanaai *et al*., 2020).

Among the diverse synthesis methodologies, including sol–gel, hydrothermal, and combustion techniques, the co-precipitation method is frequently favored due to its simplicity, economic viability, and capacity to yield homogeneous nanoparticles with precise stoichiometry. Furthermore, this wet-chemical approach facilitates meticulous control over particle size and crystallinity through the modulation of variables such as pH, temperature, and calcination conditions (Azzaoui et al., 2025).

Copper ferrite ($CuFe_2O_4$) nanoparticles have garnered extensive attention due to their unique magnetic, catalytic, and optical properties, which are largely influenced by their crystal structure and morphology. The co-precipitation method is a widely adopted synthesis technique because of its simplicity, cost-effectiveness, and scalability (Rushmittha *et al.,* 2023; Dippong *et al.,* 2021). Rushmittha *et al.* (2023) demonstrated the successful synthesis of copper ferrite nanoparticles using this method, highlighting the importance of optimizing reaction parameters such as pH and temperature to tailor the particle size and properties. Similarly**,** Hoang *et al.,* (2022) investigated the structural and magnetic properties of Ho-doped $CuFe_2O_4$ nanoparticles prepared by co-precipitation, underscoring the versatility of this technique for doping and functionalization. Moreover, copper ferrite nanoparticles synthesized through co-precipitation have shown promising applications in environmental remediation, such as the adsorption of toxic Cr(VI) ions from aqueous solutions, emphasizing their catalytic efficacy. Additionally, mineral-based synthesis utilizing co-precipitation combined with

microwave techniques has been reported to produce $CuFe_2O_4$ nanoparticles with controlled size and enhanced properties, expanding the scope of synthesis methods to include hybrid approaches. These studies collectively establish co-precipitation as a robust method for producing copper ferrite nanoparticles with desirable physicochemical characteristics and potential for diverse applications Masunga *et al.*, (2021). Copper ferrite $CuFe_2O_4$ nanoparticle , a type of spinel ferrite have attracted significant attention due to their narrow band gap , chemical stability , low cost , and magnetic and semiconducting properties Agouriane *et al*., (2016). The co-precipitation method is one of the most efficient and environmentally friendly techniques for synthesizing metal ferrite nanoparticle, it allows precise control over particle size, stoichiometry and homogeneity at relatively low synthesis temperatures (El Foulani *et al.* 2017; Akhtar *et al*. 2018; Hoang *et al.* 2022). Compared to other synthesis routes such as sol-gel hydrothermal or combustion methods, co-precipitations offer the advantages of simplicity, scalability, and high yield making it suitable for large scale production of $CuFe_2O_4$ nanoparticles Dippong *et al.,* (2021). In this study, $CuFe_2O_4$ nanoparticles were synthesized via the co-precipitation method and characterized to understand their structural, morphological, and optical properties.

2. Methodology

2.1 Materials

Copper Nitrate Trihydrate ($Cu(No_3)_2.3H_2O$) Iron Nitrate Nonahydrate($Fe(No_3).9H_2O$) Sodium Hydroxide(NaOH) Ethanol (C_2H_5OH), Distilled water or deionized water.

2.2 Copper Ferrite Nanoparticles Synthesis

$CuFe_2O_4$ nanoparticles were synthesized using the co-precipitation method due to its simplicity and effectiveness in controlling particle size and stoichiometry. In this process, aqueous solutions of $Cu(NO_3)_2$ and $Fe(NO_3)_3$ were prepared separately and then mixed in a molar ratio of 1:2 under continuous magnetic stirring at room temperature. A 1 M NaOH solution was added dropwise to the mixture until the pH reached 9–10, leading to the formation of a dark brown precipitate. The resulting suspension was stirred for an additional 2 hours to ensure complete reaction and uniform precipitation. The precipitate was then allowed to settle, filtered, and thoroughly washed several times with distilled or deionized water and ethanol to remove any residual ions or impurities. The washed sample was dried in a hot air oven at 110 °C for 3 hours. Finally, the dried powder was calcined at 500 °C for 1.5 hours in a furnace to obtain pure, crystalline $CuFe_2O_4$ nanoparticles.

2.3 Product characterisation

The synthesized copper ferrite ($CuFe_2O_4$) nanoparticles were comprehensively characterized using a range of analytical techniques. X-ray diffraction (XRD) analysis confirmed the formation of a single-phase cubic spinel structure and was utilized to estimate the average crystallite size. Scanning electron microscopy (SEM) revealed the surface morphology and provided insights into the particle size distribution. The elemental composition and stoichiometric ratio of the constituent elements were verified through energy-dispersive X-ray spectroscopy (EDS). Furthermore, the optical characteristics, including the optical band gap, were examined using diffuse reflectance spectroscopy (DRS). The combined outcomes of these characterization techniques confirm the successful synthesis of phase-pure $CuFe_2O_4$ nanoparticles exhibiting nanoscale dimensions with well-defined structural, morphological, optical and compositional properties.

3. Results and Discussion

3.1 Structural Analysis X-Ray Diffraction (XRD)

The crystallite size of the sample was determined using X-ray diffraction (XRD) analysis. Multiple prominent peaks from the XRD pattern were selected and fitted to obtain accurate data as shown in **Figure 1.** The average crystallite size was calculated using the Scherrer equation, considering the full width at half maximum (FWHM) of each peak. Based on the fitting of multiple peaks, the calculated average crystallite size was found to be approximately 20 nm. This result suggests that the material exhibits nanoscale crystallites, which may significantly impact its physical and chemical properties.

The X-ray diffraction (XRD) pattern of the synthesized $CuFe_2O_4$ nanoparticles was analyzed to determine the crystal structure and phase purity of the sample as sown in **Figure 2.** The diffraction peaks observed were compared with the standard JCPDS card no. 77-0010, which corresponds to copper ferrite. The positions and intensities of the peaks matched well with the standard data, confirming the successful formation of copper ferrite. Based on this comparison, the crystal structure of the synthesized nanoparticles was identified as a cubic spinel copper ferrite structure.

3.2 Dislocation Density

Dislocation density gives a measure of the number of dislocations (defects) in a crystal structure per unit volume. Dislocation Density is calculated using the formula:

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

where δ is dislocation density and D is crystallite size.
Therefore, the dislocation density of the synthesized sample is found to be 2.464×10^{15}lines/m^2.

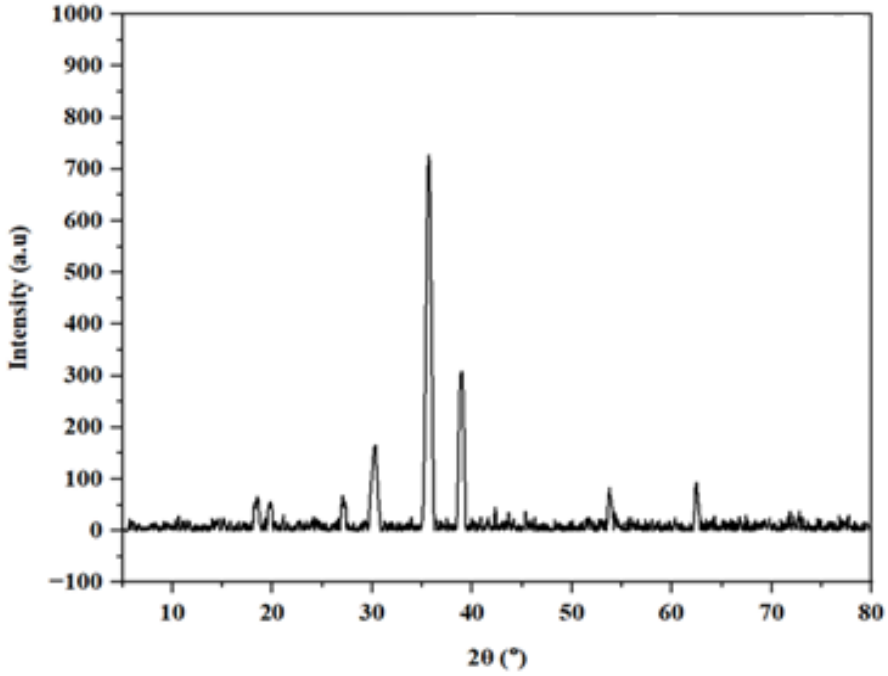

Figure 1. XRD spectra for copper ferrite nanoparticles

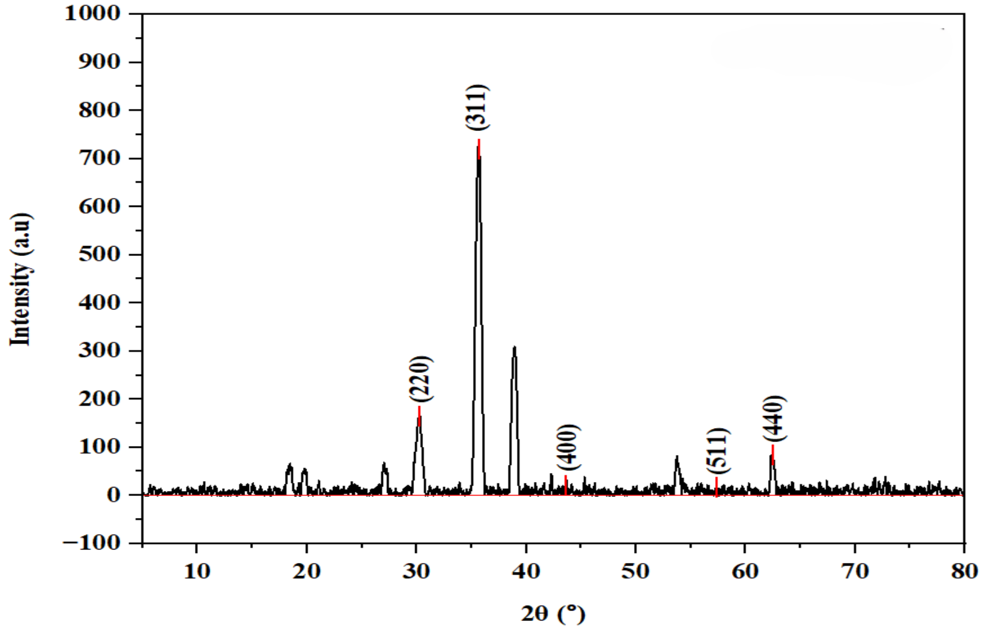

Figure 2. Miller indices found by comparing peaks with JCPDS card No.77-0010

3.3 Unit Cell Volume

The unit cell volume is the volume occupied by the smallest repeating unit in a crystal lattice. It represents the three-dimensional space that one unit cell (the basic structural unit of a crystal) occupies. A unit cell is the smallest group of atoms that, when repeated in all directions, forms the entire crystal structure. Unit Cell Volume V can be calculated as

$$V = a^3 \quad \text{.....................................(2)}$$

Where, a is lattice constant.

The unit cell volume of the synthesized $CuFe_2O_4$ is 579.882 × 10^6 pm^3, which is the same as the standard value for $CuFe_2O_4$.

3.4 Crystallinity of the sample

Crystallinity refers to the degree of structural order in a solid material, where atoms or molecules are arranged in a regular, repeating pattern can be calculated as,

$$Crystallinity = \frac{Area\ of\ crystalline\ peaks}{Area\ of\ all\ peaks\ (crystalline + Amorphous)}\ X\ 100 \quad \text{..........................(3)}$$

Found approximately 26% crystallinity.

3.5 Optical Analysis DRS (Diffuse Reflectance Spectroscopy)

The DRS analysis of copper ferrite ($CuFe_2O_4$) nanoparticles primarily provides insight into their optical properties, particularly the band gap energy, which is crucial for applications like photocatalysis and solar cell.Conversion of reflectance (R) to absorbance using the Kubelka-Munk function $F(R) = (1-R)^2/2R$**.**After obtaining F(R), plot graph of $(F(R)\cdot h\nu)^2$ vs Photon Energy(hν) as shown in **Figure 3**. After analyzing DRS data, the optical band gap of synthesized copper ferrite nanoparticles is found to be Eg = 1.5280 eV using the Tauc Plot Method.

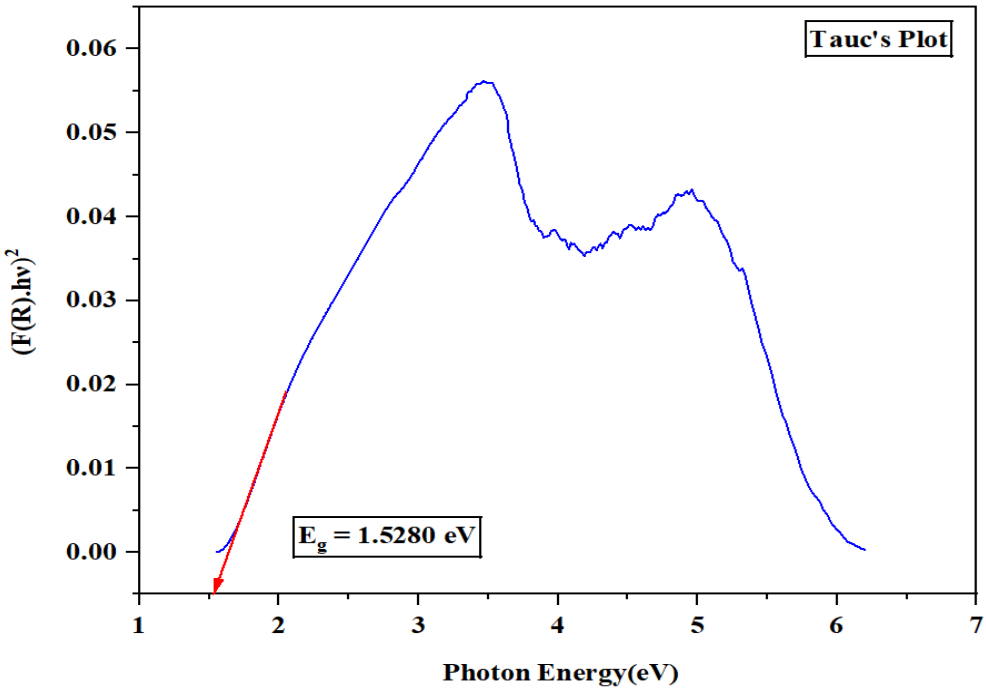

Figure 3. Tauc Plot

3.6 Morphological Analysis Scanning Electron Microscopy (SEM)

The SEM micrographs revealed that the synthesized $CuFe_2O_4$ nanoparticles exhibited an irregular spherical morphology with slight agglomeration, which is common due to magnetic interactions among particles. The particle size distribution was fairly uniform, and the observed nanostructure provided a large surface area-to-volume ratio as shown in **Figure 4**. The copper ferrite nanoparticles consist of irregular, polycrystalline particles with rough surfaces. The particle sizes vary widely, ranging from approximately 200 nanometres to 4–5 micrometres, indicating a broad size distribution. Due to the co-precipitation synthesis method, the particles exhibit noticeable agglomeration. The surfaces of the larger particles display fine grains, suggesting incomplete sintering or the presence of a porous structure. This porous texture is particularly beneficial for catalytic or adsorption-based applications, such as in water filtration systems.

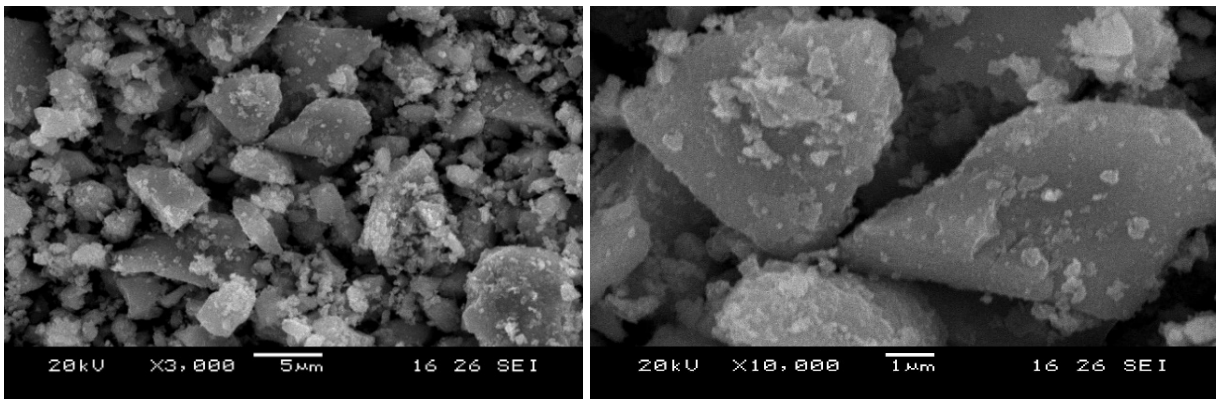

Figure 4. SEM Micrograph of Copper Ferrite ($CuFe_2O_4$)

3.7 Energy-Dispersive X-ray Spectroscopy (EDS) Analysis

Energy Dispersive X-ray Spectroscopy (EDS) is used to confirm the elemental composition of the copper ferrite nanoparticles by detecting characteristic X-rays emitted when the sample is exposed

to an electron beam. The EDS spectrum shows distinct peaks corresponding to copper, iron, and oxygen, validating the material's composition as shown in **Figure 5**. The material identified as $CuFe_2O_4$ (Copper Ferrite) from the EDS results and morphology analysis confirms the successful synthesis of a well-known spinel ferrite with notable magnetic and catalytic properties. Copper ferrite is characterized by a spinel crystal structure where copper and iron ions occupy specific tetrahedral and octahedral sites within an oxygen lattice. This structural arrangement influences its electrical, magnetic, and catalytic behaviour, making it suitable for various applications including photocatalysis, magnetic devices, sensors, and biomedical uses.

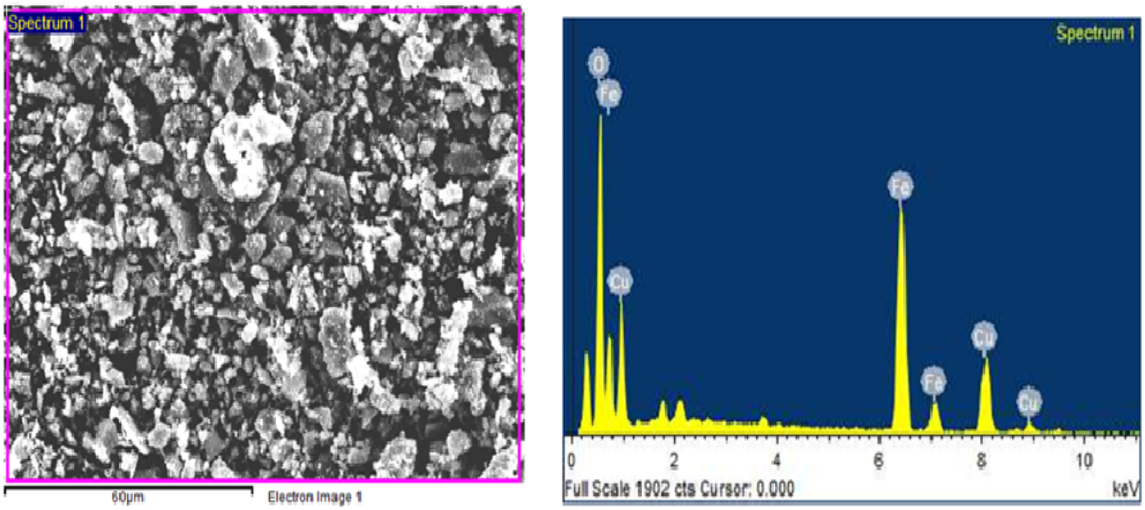

Figure 5. Energy Dispersive X-ray Spectrum

Table 1 showing the elemental composition from EDS analysis reveals that the atomic ratio of iron (Fe) to copper (Cu) is approximately 2:1. This ratio is consistent with the stoichiometry of copper ferrite ($CuFe_2O_4$), confirming that the correct phase has been synthesized. Additionally, the high oxygen content detected supports the formation of an oxide compound with a spinel crystal structure (Ortiz-Quiñonez *et al.* 2018; Raghavendra *et al.* 2025). The presence of oxygen in significant amounts confirms the oxide framework characteristic of spinel ferrites, where oxygen ions form a close-packed lattice with metal ions occupying interstitial tetrahedral and octahedral sites. These compositional findings from EDS validate both the elemental proportions and the oxide nature of the synthesized copper ferrite nanoparticles, providing strong evidence for the successful preparation of $CuFe_2O_4$ with the expected spinel structure.

Table 1. Elemental Composition from EDS

S/N	Element	Weight %	Atomic %
1	O K	48.81	74.84
2	Fe K	33.55	16.05
3	Cu K	21.64	9.10
	Total	100	100

Conclusion

Copper ferrite ($CuFe_2O_4$) nanoparticles were successfully synthesized through a cost-effective co-precipitation method and comprehensively characterized using a suite of analytical techniques. X-ray diffraction (XRD) analysis confirmed the formation of a cubic spinel phase with nanoscale

crystallinity, while diffuse reflectance spectroscopy (DRS) revealed an optical band gap indicative of favourable photo responsive behaviour. Energy-dispersive X-ray spectroscopy (EDS) validated the stoichiometric Cu:Fe ratio and confirmed the oxide nature of the synthesized material. Scanning electron microscopy (SEM) micrographs exhibited a wide particle size distribution with irregular morphology, agglomeration, and a porous surface texture, features that are beneficial for catalytic and adsorption-based applications. The integrated structural, morphological, and optical analyses demonstrate that the synthesized $CuFe_2O_4$ nanoparticles possess promising functional properties for use in catalysis, magnetic devices, and environmental remediation technologies.

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