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Synthesis, Structural, Dielectric, Optical, and Photocatalytic Properties of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ Spinel Chromite Prepared by the Sol-Gel Method

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Abstract

$\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel ferrite was successfully synthesized by the sol-gel method and investigated for its structural, vibrational, optical, dielectric, and photocatalytic properties. XRD confirmed the formation of a single-phase cubic spinel structure with the $Fd\bar{3}m$ space group, while FTIR spectra revealed the characteristic tetrahedral and octahedral metal-oxygen vibrations. UV-Vis diffuse reflectance analysis showed strong visible-light absorption with a direct optical band gap of 2.76 eV. Dielectric measurements revealed a frequency-dependent response consistent with Maxwell-Wagner interfacial polarization and Koop's theory. The AC conductivity obeyed Jonscher's power law, with the conduction mechanism attributed to correlated barrier hopping. Photocatalytic tests demonstrated approximately 90% methylene blue degradation after 180 min under visible-light irradiation, following pseudo-first-order kinetics. These results highlight $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ as a promising multifunctional material for photocatalytic and electronic applications.

Keywords: $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$; Spinel ferrite; Optical properties; Dielectric properties; Photocatalytic degradation.

1. Introduction

The increasing demand for advanced functional materials with tailored structural, optical, magnetic, and catalytic properties has stimulated extensive research on transition metal oxides [1,2,3]. Among these materials, spinel oxides with the general formula (AB_2O_4) have attracted considerable attention due to their remarkable chemical stability, versatile cation distribution, and tunable electronic structure. The unique arrangement of cations between tetrahedral (A) and octahedral (B) sites provides an effective pathway for modifying their physical and chemical properties, making spinel oxides suitable candidates for various technological applications, including photocatalysis, energy conversion, sensors, magnetic devices, and optoelectronic systems [4, 5].

Spinel AM_2O_4 ($M = Fe, Cr, Co, \dots$) represent an important subgroup of spinel oxides owing to the presence of chromium, iron... ions, which strongly influence their electronic configuration, optical response, and magnetic interactions [6, 7]. The strong M–O bonds within the octahedral sites contribute to their high thermal and chemical stability, while the substitution of divalent cations at the tetrahedral sites offers an efficient strategy to tailor their structural and functional properties. Mixed transition-metal containing Ni^{2+} , Cu^{2+} , and Fe^{3+} ions have received increasing interest because of their adjustable band structures, enhanced visible-light absorption, and favorable charge transport characteristics [8, 9].

The incorporation of multiple transition-metal cations into the spinel lattice can significantly modify the local crystal field, cation distribution, defect concentration, and electronic band structure. Nickel-containing spinels generally exhibit high chemical stability and interesting magnetic properties, whereas copper substitution can induce structural distortion due to the Jahn–Teller effect associated with Cu^{2+} ions, leading to modifications in electrical conductivity and optical behavior [10, 11]. Furthermore, the presence of Fe and Cr ions provides additional redox-active centers that may enhance charge transfer processes and promote catalytic activity [12, 13].

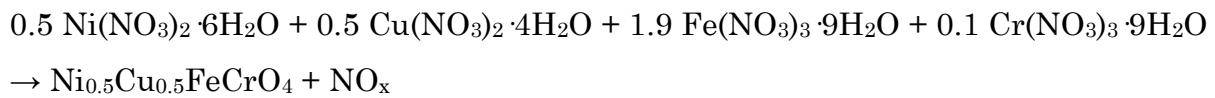
Among the different synthesis approaches, the sol–gel method has been widely employed for preparing spinel oxides because it enables good chemical homogeneity, controlled particle size, and the formation of highly crystalline phases at relatively moderate temperatures. The resulting structural characteristics strongly affect the distribution of cations, defect states, and surface properties, which are key parameters governing the performance of spinel materials [14, 15]. Recently, spinel have gained particular attention in photocatalytic applications for the degradation of organic pollutants due to their suitable band-gap energies and ability to utilize visible-light irradiation [16, 17]. The generation, separation, and migration of photogenerated electron–hole pairs are strongly influenced by the electronic structure and cationic arrangement within the spinel lattice. Therefore, controlling the chemical composition represents an effective approach for improving photocatalytic efficiency and extending the optical response toward the visible region [18, 19].

Despite extensive studies on individual ferrites and chromites, limited information is available concerning the structural, optical, electrical, magnetic, and photocatalytic properties of the mixed chromite $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$. The simultaneous incorporation of Ni^{2+} , Cu^{2+} , Fe^{3+} , and Cr^{3+} ions is expected to generate complex interactions within the spinel framework and provide new opportunities for tuning its functional properties.

In this work, $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel chromite was synthesized using the sol–gel method. A comprehensive investigation of its structural, vibrational, optical, dielectric, magnetic, and photocatalytic properties was performed using X-ray diffraction, FTIR spectroscopy, UV–Vis spectroscopy, impedance analysis and methylene blue degradation tests under visible-light irradiation. The relationship between the structural features, electronic properties, and photocatalytic performance is discussed in detail to highlight the potential of this material for advanced functional applications.

2. Experimental Procedure

The $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel chromite was synthesized using the sol–gel method, which is an effective approach for preparing homogeneous oxide materials with controlled chemical composition and improved structural uniformity. This synthesis route enables molecular-level mixing of the constituent elements before heat treatment, facilitating the formation of well-crystallized spinel phases. In addition, the sol–gel process provides effective control over nucleation, particle growth, and structural evolution through the adjustment of synthesis parameters such as pH, temperature, and complexing agents. Stoichiometric quantities of high-purity nitrate precursors were used as starting materials: nickel nitrate hexahydrate $\text{Ni}(\text{NO}_3)_2 \cdot 6(\text{H}_2\text{O})$, copper nitrate trihydrate $\text{Cu}(\text{NO}_3)_2 \cdot 3(\text{H}_2\text{O})$, iron(III) nitrate nonahydrate $\text{Fe}(\text{NO}_3)_3 \cdot 9(\text{H}_2\text{O})$, and chromium nitrate nonahydrate $\text{Cr}(\text{NO}_3)_3 \cdot 9(\text{H}_2\text{O})$. The precursors were accurately weighed according to the desired stoichiometric ratio to obtain the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ composition. The overall reaction for the formation of the spinel chromite can be expressed as:



The synthesis procedure was initiated by dissolving the nitrate precursors separately in distilled water under continuous magnetic stirring until a clear and homogeneous solution was obtained. The solutions were then mixed together, and ammonia solution was gradually added to adjust the pH and promote complex formation. The mixture was maintained under stirring at 70 °C until a stable and homogeneous sol was obtained. Citric acid ($\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$, $M = 210.14 \text{ g/mol}$) was subsequently introduced as a chelating agent to improve the distribution of metal ions, while ethylene glycol was added to enhance the stability and polymerization of the gel network. The obtained sol was heated gradually until gel formation occurred. The resulting gel was dried and thermally treated at 250 °C, producing a precursor powder. The obtained powder was thoroughly ground and subjected to

successive calcination treatments at 600, 700, and 800 °C, each maintained for 24 h, to enhance chemical homogeneity and promote the progressive crystallization of the spinel phase. Finally, the powder was calcined at 950 °C for 24 h, resulting in the formation of highly crystalline $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel powder.

The crystalline structure of the synthesized $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel was analyzed by X-ray diffraction (XRD) using a PANalytical X'Pert Pro diffractometer with $\text{Cu-K}(\alpha)$ radiation ($\lambda = 1.5406$ Å). The structural parameters were determined through Rietveld refinement analysis. The vibrational properties and characteristic metal–oxygen bonds of the spinel structure were investigated by Fourier transform infrared spectroscopy (FTIR) using an FTIR-8400S spectrometer in the range of 400–2000 cm^{-1} . The optical properties were examined at room temperature using a Shimadzu 3101 PC spectrophotometer. The absorption and reflectance spectra were recorded over the wavelength range of 200–2400 nm to determine the optical band-gap energy and related parameters.

The photocatalytic activity of the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel chromite was evaluated through the degradation of methylene blue (MB) aqueous solution under visible-light irradiation. The experiments were carried out in a cylindrical quartz photoreactor equipped with a 400 W quartz–iodine lamp as the irradiation source. A UV cut-off filter ($\lambda > 420$ nm) was placed between the lamp and the reactor to ensure selective visible-light excitation. For each experiment, 5 mg of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ catalyst was dispersed in 100 mL of MB solution with an initial concentration of 20 mg /L at pH = 6. Before irradiation, the suspension was magnetically stirred in the dark for 30 min to establish adsorption–desorption equilibrium between MB molecules and the catalyst surface. During visible-light irradiation, aliquots were withdrawn at regular time intervals (30–180 min), and the residual dye concentration was determined by measuring the absorbance intensity at 664 nm using UV–Visible spectroscopy. The photocatalytic degradation efficiency was calculated from the concentration ratio (C/C_0), where (C_0) represents the initial MB concentration and (C) is the concentration after a given irradiation time.

3. Results & discussions

3.1. X-ray diffraction analysis

Figure. 1 presents the X-ray diffraction (XRD) pattern of the synthesized $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ sample recorded over the 2θ range of $20\text{--}80^\circ$. The diffractogram exhibits sharp and well-defined reflections, indicating the good crystallinity of the synthesized material. The observed diffraction peaks can be indexed to the characteristic planes of a cubic spinel structure, namely (220), (311), (222), (400), (422), (511), and (440) [20,21]. Among these reflections, the (311) peak exhibits the highest intensity, as commonly observed for cubic spinel ferrites. The experimental reflections are in good agreement with the standard crystallographic pattern of a spinel structure, and no additional reflections associated with detectable secondary phases are observed within the experimental resolution [22]. These results indicate the formation of a single-phase $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel ferrite with a cubic structure belonging to the $\text{Fd}\bar{3}\text{m}$ space group (No. 227).

The absence of detectable secondary phases suggests that the constituent cations are incorporated into the spinel lattice without the formation of crystalline impurity phases. In the cubic spinel structure, the cations are distributed between tetrahedral (A) and octahedral [B] sites, while O^{2-} ions form the anionic sublattice. The positions and relative intensities of the diffraction reflections depend on the lattice parameter, cation distribution, and degree of structural ordering. The lattice parameter and unit-cell volume obtained from the XRD analysis are summarized in **Table. 1**.

The average crystallite size was initially estimated using the Debye–Scherrer equation [23]: $D = \frac{k\lambda}{\beta \cos\theta}$

where D is the average crystallite size, K is the Scherrer constant (taken as 0.9), λ is the wavelength of Cu-K α radiation ($1.5406 \text{ \AA}$), β is the full width at half maximum (FWHM) of the selected diffraction peak expressed in radians after correction for instrumental broadening, and θ is the corresponding Bragg angle.

The crystallite size obtained by this method represents the average size of coherently diffracting domains rather than the physical grain size. Because peak broadening can originate from both finite crystallite size and lattice microstrain, the Williamson–Hall (W–H) approach was subsequently employed to separate these two contributions [24]. Using the uniform deformation model, the W–H equation can be expressed as: $\beta \cos \theta = \frac{k\lambda}{D} + 4\varepsilon \sin \theta$

where ε represents the lattice microstrain. In the plot of $\beta \cos \theta$ versus $4 \sin \theta$, the intercept corresponds to $\frac{k\lambda}{D}$, from which the crystallite size is obtained, whereas the slope gives the microdeformation.

The corresponding W–H plot is presented in **Figure. 1**, and the calculated microstructural parameters are listed in **Table. 1**. The obtained microstructural parameters provide complementary information on the structural characteristics of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$. The presence of microstrain can be related to local lattice distortions associated with structural imperfections, such as vacancies, dislocations, grain boundaries, and variations in the local bonding environment. The dislocation density was estimated from the crystallite size using the relation: $\delta = \frac{1}{D^2}$

where δ represents the dislocation density. This parameter provides an approximate indication of the density of crystallographic defects within the coherently diffracting domains. Variations in crystallite size, microstrain, and dislocation density can influence the electrical, dielectric, and magnetic properties of spinel ferrites through their effects on charge transport and magnetic interactions. To further confirm the crystal structure and obtain reliable structural parameters, Rietveld refinement of the XRD pattern was performed using the FullProf Suite software.

The experimental, calculated, and difference profiles are presented in **Figure. 1**. A good agreement is observed between the experimental and calculated profiles over the investigated angular range, while the difference profile remains relatively small. The calculated Bragg positions are also consistent with the observed

diffraction maxima. The refinement therefore supports the cubic $Fd\bar{3}m$ structural model for $Ni_{0.5}Cu_{0.5}FeCrO_4$. The refined lattice parameter, unit-cell volume, reliability factors, and other structural parameters are summarized in **Table. 1**. For $Ni_{0.5}Cu_{0.5}FeCrO_4$, the refined lattice parameter is $a = 8.36(3) \text{ \AA}$, corresponding to a unit-cell volume of $V = 585.19(7) \text{ \AA}^3$. The refinement gives $R_p = 9.13\%$, $R_{exp} = 7.08\%$, and $\chi^2 = 1.83$. The relatively low value of χ^2 , together with the good agreement between the experimental and calculated profiles, indicates an acceptable quality of the Rietveld refinement.

The distribution of cations between the tetrahedral (A) and octahedral [B] sites is an important structural feature of spinel ferrites because it strongly influences their electrical, dielectric, and magnetic properties. In a general AB_2O_4 spinel structure, cation distribution is governed by several factors, including site preference, ionic size, charge neutrality, crystal-field stabilization, and cation–oxygen bonding [25,26]. For $Ni_{0.5}Cu_{0.5}FeCrO_4$, the Ni^{2+} , Cu^{2+} , Fe^{3+} , and Cr^{3+} cations may occupy both tetrahedral (A) and octahedral (B) sites, although their site preferences differ. Ni^{2+} generally exhibits a strong preference for octahedral coordination, while Cr^{3+} strongly favors octahedral sites. Cu^{2+} can occupy either tetrahedral or octahedral sites, and its local coordination environment may be influenced by its Jahn–Teller-active character. Fe^{3+} can also be distributed between the two crystallographic sites. Therefore, a mixed or partially inverse cation distribution can be expected, rather than a strictly normal spinel configuration.

In the absence of experimentally refined site occupancies, a possible cation distribution consistent with the chemical stoichiometry and the expected site preferences can be represented as: $[Cu_x^{2+}Fe_{1-x}^{3+}]_A[Ni_{0.5}^{2+}Cu_{0.5-x}^{2+}Fe_x^{3+}Cr^{3+}]_BO_4^{2-}$

where x represents the fraction of Fe^{3+} occupying the tetrahedral A site. This expression satisfies the overall cation stoichiometry and charge neutrality of $Ni_{0.5}Cu_{0.5}FeCrO_4$. However, the exact value of x cannot be established from the chemical composition alone and should only be assigned when reliable A- and B-site

occupancies are obtained from the structural refinement or complementary spectroscopic analysis. Therefore, the proposed distribution should be regarded as a plausible structural model rather than a definitive determination of the cation arrangement.

The cation distribution between the A and B sites directly affects the magnetic superexchange interactions, particularly those mediated through A–O–B and B–O–B pathways. Consequently, the interionic distances and bond angles associated with the tetrahedral and octahedral sites are important structural parameters for interpreting the magnetic and electrical behavior of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ [25,26]. The cation–cation (Me–Me) and cation–oxygen (Me–O) distances, together with the corresponding bond angles, were calculated from the refined structural parameters using the appropriate crystallographic relationships, and the resulting values are summarized in **Table. 1**. These parameters provide information on the local structural environment of the A and B sites and can help explain the evolution of exchange interactions and charge-carrier transport within the spinel lattice.

3.2. Infrared properties

Fourier transform infrared (FTIR) spectroscopy was employed to investigate the vibrational characteristics of the synthesized ferrite samples and to gain insight into their local structural order. Typically, spinel ferrites exhibit two characteristic absorption bands corresponding to the metal–oxygen stretching vibrations at the tetrahedral (A) and octahedral (B) sites of the spinel lattice [27, 28]. As shown in **Figure. 2**, the FTIR spectra of the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ samples exhibit the characteristic absorption bands associated with the metal–oxygen vibrations of the spinel structure. The main absorption band located at approximately 556 cm^{-1} is assigned to the tetrahedral metal–oxygen stretching vibration ν_A , whereas the octahedral vibration ν_B is observed in the lower wavenumber region around 405 cm^{-1} . The relatively high position of the ν_A band indicates strong metal–oxygen interactions at the tetrahedral sites, reflecting the influence of cation distribution

and structural ordering within the spinel lattice. This behavior can be associated with the improved crystallinity and reduced structural disorder of the material [29]. In addition to the characteristic spinel vibrations, a weak absorption band centered around 886 cm⁻¹ is assigned to C–H bending vibrations, originating from residual organic species remaining after the synthesis process [30]. Another absorption band observed near 1654 cm⁻¹ is attributed to the stretching vibration of the carbonyl (C=O) group, suggesting the presence of trace organic residues adsorbed on the sample surface [31].

3.3. Electric analysis

3.3.1. DC conductivity analysis

Figure. 3 (a) presents the temperature dependence of the DC electrical conductivity (σ_{dc}) of the Ni_{0.5}Cu_{0.5}FeCrO₄ compound. The σ_{dc} values were extracted from AC conductivity measurements performed at a low frequency of 90 Hz. The conductivity exhibits a sharp increase in the temperature range of 80–400 K, followed by a slower variation between 400 and 580 K. Moreover, a transition from semiconducting to metallic behavior is observed at the semiconductor–metal transition temperature (T_{SM}) of approximately 500 K. This behavior is consistent with the frequency-dependent conductivity evolution observed at elevated temperatures. The relatively high conductivity values indicate the presence of efficient charge transport mechanisms within this spinel structure [32,33]. To further investigate the dominant conduction mechanism in the Ni_{0.5}Cu_{0.5}FeCrO₄ compound, the variation of $\ln(\sigma_{dc})$ as a function of the reciprocal temperature ($1000/T$) was plotted, as shown in **Figure. 3(b)**. The obtained linear relationship over the investigated temperature range suggests that the conductivity follows an Arrhenius-type thermally activated conduction process, which can be expressed as follows [34, 35, 36]:

$$\sigma_{dc} = \sigma_0 e^{-\frac{E_a}{k_B T}}$$

where σ_0 represents the pre-exponential factor, E_a is the thermal activation energy, and k_B corresponds to the Boltzmann constant. The linear behavior observed in the

Arrhenius plot over the whole investigated temperature range confirms that the electrical conduction mechanism is governed by a thermally activated process [44]. The activation energy (E_a) was calculated from the slope of the linear fitting region and was found to be approximately 0.473 eV. This value is comparable to those reported for other zinc-based semiconducting materials [34]. The presence of a single activation energy value suggests the involvement of a unique type of charge carrier and indicates the existence of a single dominant charge emission mechanism within the studied temperature range [35,36].

3.3.2. AC conductivity analysis

The analysis of AC conductivity provides valuable information about the charge transport mechanism involved in the conduction process and allows the investigation of its dependence on frequency and temperature. The frequency dispersion of the electrical conductivity is generally described by Jonscher's universal power law [32], expressed as follows:

$$\sigma_{dc} = AW^s$$

where A is a constant, ω represents the angular frequency, and s is the frequency exponent, which provides information about the interaction between mobile charge carriers and their surrounding lattice. The exponent s depends strongly on both temperature and the intrinsic properties of the material. The variation of s with temperature is an important parameter for elucidating the dominant conduction mechanism. Physically, the value of s reflects the nature of the charge transport process: for $s \leq 1$, the conduction mechanism is generally associated with a hopping process accompanied by translational motion of charge carriers, whereas for $s > 1$, the charge transport is mainly governed by localized hopping between neighboring sites [37]. Therefore, the temperature dependence of the frequency exponent s for the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ compound is presented in **Figure. 4**.

At high frequencies, the conductivity response exhibits pronounced oscillations and an unstable behavior, as indicated by the dashed vertical line. This anomalous response is mainly attributed to parasitic effects arising from the measurement system, including stray inductance, stray capacitance, and instrumental noise.

These effects become increasingly significant in the high-frequency region and distort the intrinsic electrical response of the sample. Therefore, this frequency range was excluded from the fitting procedure, and only the physically stable region below the dashed line was considered for the analysis of the AC conductivity using Jonscher's power-law model as depicted in **Figure. 5**.

Furthermore, as shown in **Figure. 6**, the frequency exponent s exhibits a temperature-dependent behavior, indicating a change in the dominant conduction mechanism. Below 500 K, the variation of s is consistent with the non-overlapping small polaron tunneling (NSPT) model, suggesting that charge carriers move through thermally activated tunneling between localized states [38]. Above 500 K, the behavior of s becomes consistent with the correlated barrier hopping (CBH) model, indicating that charge transport occurs through thermally assisted hopping of charge carriers over potential barriers between localized states. The transition from the NSPT to the CBH mechanism at approximately 500 K suggests a change in the dominant charge-transport process with increasing temperature. In the CBH regime, the temperature dependence of the exponent s can be described using the Mott–Davis relation [39], expressed as follows:

$$s = 1 - \frac{6k_B T}{W_M}$$

The potential barrier height W_M was determined from the linear fitting of the (s) exponent as a function of temperature, as shown in **Figure. 6**. The calculated W_M value was found to be approximately 0.21 eV, indicating the energy barrier associated with the correlated hopping of charge carriers between localized states. This relatively low barrier height suggests that charge carriers can overcome the potential barrier relatively easily at elevated temperatures, thereby facilitating the hopping process and contributing to the observed increase in AC conductivity. Interestingly, the obtained (W_M) value is close to the activation energy ($E_a=0.223$ eV) determined from the temperature dependence of the DC conductivity. The good agreement between (W_M) and (E_a) further supports the applicability of the (NSPT) model to describe the charge-transport mechanism in the investigated material.

Similar behavior, where the potential barrier estimated from the temperature dependence of the Jonscher exponent is comparable to the activation energy obtained from conductivity measurements, has been reported for various semiconducting ferrites and spinel oxides. This consistency indicates that localized charge carriers, most likely associated with defect-related states and/or mixed-valence cations, participate in the thermally activated hopping conduction mechanism.

3.4. Impedance analysis

3.4.1. Analysis of the real and imaginary part of the complex impedance

Figure. 7 illustrates the frequency dependence of the real part of the impedance (Z') at different temperatures for the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ compound. The Z' values are relatively high in the low-frequency region and progressively decrease with increasing frequency, revealing the semiconducting nature of the material. This behavior can be explained by the enhanced mobility of charge carriers and the gradual release of trapped charges at higher frequencies [40]. At low frequencies, a frequency-independent plateau region is observed, which extends over a wider frequency range as the temperature increases. This trend indicates a decrease in the relaxation time of the charge carriers with increasing temperature, resulting from the thermally activated generation of additional mobile charge carriers. Moreover, the low Z' values observed in the high-frequency region suggest a reduction in space charge polarization and a decrease in the potential energy barrier for charge transport [41, 42]. The similar evolution of Z' with frequency at different temperatures further confirms the existence of localized charge regions and indicates a decrease in the resistive contribution of the material [43].

To investigate the relaxation behavior of the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ compound, the frequency dependence of the imaginary part of the impedance (Z'') at different temperatures is presented in **Figure. 8**. The Z'' spectra exhibit asymmetric peaks located at characteristic frequencies, known as the relaxation frequencies (f_r). The appearance of these peaks confirms the occurrence of a relaxation phenomenon within the material. The maximum value of Z'' corresponds to the frequency at

which the transition between resistive and capacitive responses takes place. This relaxation process is related to the response time required for charge carriers to follow the applied alternating electric field. The position and temperature-induced shift of the relaxation peaks provide valuable information about the mobility and dynamic behavior of the charge carriers.

Moreover, the decrease in the peak amplitude with increasing temperature indicates a reduction in the resistive contribution of the material due to enhanced charge carrier mobility [44]. The temperature dependence of the relaxation peaks demonstrates that the relaxation process is strongly influenced by thermal activation effects [45, 46]. Furthermore, the displacement of the Z'' maxima toward higher frequencies with increasing temperature suggests a shortening of the relaxation time and an increase in the hopping rate of charge carriers. This behavior can be attributed to the thermally activated mobility of charge carriers and confirms the presence of a non-Debye relaxation mechanism [47].

3.4.2. Nyquist diagram analysis

To correlate the impedance response with the microstructural characteristics of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$, the complex impedance spectra were analyzed using Nyquist plots, as shown in **Figure. 9** for temperatures of 460 and 500 K. The spectra exhibit depressed semicircular arcs whose diameters decrease with increasing temperature, indicating a progressive reduction in the electrical resistance and an enhancement of thermally activated charge transport [48, 49]. The larger arc observed at 460 K reflects a higher resistive contribution, whereas the smaller arc at 500 K indicates improved charge-carrier mobility. The centers of the arcs are located below the real axis, revealing a deviation from ideal Debye relaxation and indicating a non-Debye relaxation behavior, which can be associated with a distribution of relaxation times in the material [50,51, 52]. The decrease in the arc diameter with temperature is consistent with the semiconductor-like conduction behavior observed from the temperature dependence of the electrical conductivity.

The experimental impedance spectra were fitted using the equivalent electrical circuit shown in **Figure. 9**. The proposed circuit incorporates resistive elements (R_1 ,

R_2 and R_3) and constant phase elements (CPE_1 and CPE_2) to account for the resistive and non-ideal capacitive contributions of the different electrically active regions of the material [53]. The good agreement between the experimental data and the fitted curves confirms the suitability of the proposed equivalent circuit for describing the electrical response of $Ni_{0.5}Cu_{0.5}FeCrO_4$. The use of CPEs instead of ideal capacitors accounts for the non-ideal relaxation behavior arising from structural disorder, defects, grain-size distribution, and localized charge-carrier dispersion in the polycrystalline material [54, 55]. Moreover, the decrease in the resistance values with increasing temperature confirms the thermally activated nature of charge transport, in agreement with the Arrhenius behavior observed for the DC conductivity [56]. These results indicate that both bulk and interfacial contributions play an important role in the electrical response of $Ni_{0.5}Cu_{0.5}FeCrO_4$.

3.5. Optical properties:

3.5.1. Value of the gap energy:

The UV–Vis absorption spectrum of cubic spinel $Ni_{0.5}Cu_{0.5}FeCrO_4$, recorded over the 200–2400 nm wavelength range, is presented in **Figure. 10**. The observed optical absorption can mainly be explained by two types of electronic processes [57, 58, 59]. The first is related to intra-ionic electronic transitions involving Fe^{3+} ions, particularly transitions from the $3d^5$ ground-state configuration to higher-energy electronic states. The second contribution originates from band-to-band photoexcitation, in which photons promote electrons from the O-2p-dominated valence band to the Fe and Cr-3d-derived conduction band [60]. These electronic transitions are responsible for the strong absorption observed in the UV–visible region and reflect the characteristic electronic structure of the spinel ferrite [57, 59].

The optical band gap was subsequently estimated using the Kubelka–Munk approach. The Kubelka–Munk function, $F(R)$, is related to the absorption coefficient, α , according to $\alpha = S \times F(R)$, where S represents the scattering

coefficient. For a diffuse-reflectance measurement, $F(R)$ is determined from the reflectance R using the following expression [61,62]: $F(R) = \frac{\alpha}{S} = \frac{(1-R)^2}{2R}$.

Besides the Tauc method, the optical band gap was further determined using the Kubelka–Munk formalism applied to the diffuse reflectance data: $(\alpha * hv) = A(hv - E_g)^{\frac{1}{n}}$.

In the Tauc relationship, (A) denotes a proportionality constant, (hv) is the photon energy, and (E_g) represents the optical band-gap energy. The exponent (n) depends on the nature of the electronic transition, with $(n = 1/2)$ corresponding to a direct allowed transition and $(n = 2)$ to an indirect allowed transition. For diffuse-reflectance measurements, the absorption coefficient can be replaced by the Kubelka–Munk function $(F(R))$, leading to the modified Tauc–Kubelka–Munk approach. Accordingly, plots of $([F(R)hv]^{1/2})$ versus (hv) and $([F(R)hv]^2)$ versus (hv) can be used to assess the direct and indirect optical transitions, respectively [63, 64]. The optical band gap is obtained by extrapolating the linear portion of the corresponding curve to the photon-energy axis, where the intercept gives the (E_g) value. This approach is particularly suitable for estimating the band gap of powdered materials from diffuse-reflectance spectra using the following equation: $(F(R) * hv)^n = A(hv - E_g)$.

The optical band gap energy (E_g) was subsequently determined using the Tauc approach. The plot of $[F(R)hv]^2$ versus photon energy (hv) is presented in **Figure. 11**. Assuming a direct allowed transition, the optical band gap was obtained by extrapolating the linear portion of the Tauc plot toward the photon-energy axis at $[F(R)hv]^2=0$. The resulting optical band gap of $Ni_{0.5}Cu_{0.5}FeCrO_4$ was estimated to be approximately 2.76 eV. The obtained band gap indicates that $Ni_{0.5}Cu_{0.5}FeCrO_4$ is a semiconducting material with significant optical absorption in the near-UV and visible regions. The observed band gap can be associated with the electronic structure of the spinel/chromite lattice, particularly the interactions between O-2p states and the 3d states of Ni, Cu, Fe, and Cr. In addition, the cation distribution

over the tetrahedral and octahedral sites, crystallite size, structural defects, lattice distortion, and oxygen vacancies can significantly influence the electronic band structure and consequently the measured optical band gap [56, 66]. The presence of several transition-metal cations in the Ni–Cu–Fe–Cr–O framework may also introduce additional localized electronic states, thereby modifying the optical absorption edge.

The optical band gap was additionally evaluated by derivative spectrophotometry (DS) as an independent method for determining the absorption-edge position. The first derivative of the reflectance with respect to wavelength, $(dR/d\lambda)$, was analyzed to locate the wavelength associated with the most pronounced change in reflectance. As shown in **Figure. 12**, the derivative spectrum yields an optical band-gap energy of approximately 2.54 eV. This result is in good agreement with the value obtained from the Tauc–Kubelka–Munk analysis. The slight difference between the two approaches can be related to the distinct mathematical procedures used to determine the absorption edge, together with the effects of structural disorder, defect states, and absorption-edge broadening. The consistency of the results obtained by both methods supports the semiconducting nature of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.

The degree of structural and electronic disorder was further evaluated through the Urbach energy (E_u). The Urbach energy was determined from the exponential absorption-edge region by applying a linear fit to $\ln[F(R)]$ as a function of photon energy ($h\nu$), as shown in **Figure. 13**. The resulting E_u value provides information about the localized states and disorder present near the band edges. A relatively high Urbach energy generally indicates increased structural disorder, lattice defects, cationic disorder, and localized electronic states [67]. In $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$, such disorder may originate from the coexistence and possible redistribution of Ni^{2+} , Cu^{2+} , Fe^{3+} , and Cr^{3+} ions within the spinel lattice, as well as from local lattice distortions and oxygen-related defects. The combination of a relatively low optical band gap and the resulting optical response suggests that this material may be promising for visible-light photocatalytic and optoelectronic applications [68].

3.6. Photocatalytic Activity

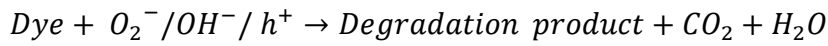
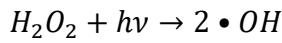
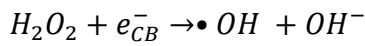
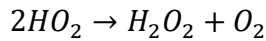
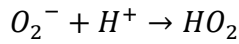
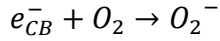
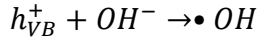
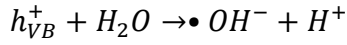
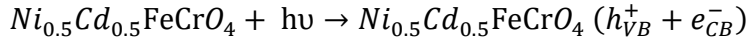
Heterogeneous photocatalysis is regarded as an efficient and environmentally sustainable approach for the removal of persistent organic contaminants, particularly synthetic dyes from wastewater [69,70]. Methylene blue (MB) is widely used as a model pollutant because of its stable aromatic structure, strong optical absorption, and convenient monitoring by UV–visible spectroscopy. Accordingly, the photocatalytic activity of the synthesized $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel was evaluated using MB as a representative organic pollutant, as shown in **Figure. 14**.

Spinel oxides with the general formula AB_2O_4 have attracted considerable interest for photocatalytic applications because of their structural stability, chemical durability, and tunable electronic properties. In the present work, $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ crystallizes in a cubic spinel structure, as confirmed by X-ray diffraction analysis. The FTIR spectrum also confirms the characteristic metal–oxygen vibrations of the spinel lattice. In addition, the optical analysis gives a band-gap energy of approximately 2.56 eV, indicating that the material can absorb a portion of the visible-light spectrum. These structural, vibrational, and optical characteristics make $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ a suitable candidate for visible-light-driven photocatalytic applications [71-73].

Based on the structural, vibrational, electrical, and optical results, a plausible photocatalytic mechanism for MB removal can be proposed, as schematically illustrated in **Figure. 15**. Under visible-light irradiation, photons with energy equal to or greater than the band-gap energy ($E_g = 2.56$ eV) can promote electrons from the valence band (VB) to the conduction band (CB), generating photogenerated electron–hole pairs. The electrical measurements indicate thermally activated charge transport in the material, which may facilitate charge-carrier migration. The photogenerated carriers can subsequently participate in interfacial oxidation–reduction reactions at the catalyst surface [70-74].

The photogenerated holes in the valence band may react with surface hydroxyl groups or water molecules to generate highly reactive hydroxyl species, while conduction-band electrons may interact with dissolved oxygen to produce

superoxide species [71,72, 75]. Following plausible mechanism may be proposed for the degradation of dyes using $Ni_{0.5}Cd_{0.5}FeCrO_4$ nanoparticles [72].



The generated reactive species may attack MB molecules and promote their progressive decomposition into intermediate products. Because no radical-scavenger experiments or EPR measurements were performed, the participation of $\bullet OH$ and $\bullet O_2^-$ species should be regarded as a proposed mechanism rather than an experimentally confirmed identification of the dominant reactive species. Similarly, complete mineralization to CO_2 and H_2O cannot be established solely from UV–visible absorbance measurements as represented in **Figure. 15**. Therefore, the observed MB removal is reasonably attributed to the combined contribution of visible-light absorption, photogenerated charge carriers, charge transport, and surface reactions [70-75].

The photocatalytic activity of $Ni_{0.5}Cu_{0.5}FeCrO_4$ was evaluated using an aqueous MB solution with an initial concentration of 20 mg L⁻¹ under visible-light irradiation ($\lambda > 400$ nm). For the experiment, 100 mL of MB solution containing the photocatalyst was placed in a quartz photoreactor and continuously stirred to ensure homogeneous dispersion of the catalyst particles. Before irradiation, the suspension was maintained in the dark to establish adsorption–desorption equilibrium between MB molecules and the catalyst surface. The photocatalytic reaction was then conducted for 180 min, and aliquots were periodically collected and analyzed by UV–visible spectroscopy [71,73, 76].

The evolution of the MB absorption spectra during photocatalytic treatment is presented in **Figure. 16**. A progressive decrease in the characteristic absorption band of MB at approximately 655 nm was observed with increasing irradiation time, indicating the gradual removal of MB from the solution. After 180 min of visible-light irradiation, approximately 90% of MB was removed. The removal efficiency was calculated according to: $R (\%) = \left[\frac{(A_0 - A)}{A_0} \right] \times 100$

where A_0 is the initial maximum absorbance of the MB solution and A is the absorbance measured after a given irradiation time. To distinguish the contribution of adsorption from the light-induced process, a dark adsorption experiment was performed by maintaining the catalyst/MB suspension without irradiation. This preliminary step allows the decrease in MB concentration caused by adsorption to be distinguished from the subsequent photocatalytic removal [75, 76].

As shown in **Figure. 17**, approximately 90% MB removal was achieved after 180 min of visible-light irradiation. The removal rate gradually decreased with increasing irradiation time. This behavior can be attributed primarily to the decreasing concentration of available MB molecules and the progressive occupation of surface-active sites by adsorbed molecules and reaction intermediates. These effects can reduce the probability of interaction between the remaining MB molecules and the photogenerated reactive species during the later stages of irradiation [72,73,77].

The photocatalytic performance of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ can be related to the combined effects of its structural, vibrational, electrical, and optical properties. The stable cubic spinel structure provides the crystalline framework, while the FTIR results confirm the characteristic metal–oxygen vibrations. The optical band gap of 2.56 eV enables visible-light absorption, whereas the electrical response indicates the ability of the material to support charge transport. These characteristics can collectively contribute to the generation and migration of photogenerated charge carriers and consequently to the observed MB removal.

The comparison with related spinel materials presented in **Table. 3** indicates that photocatalytic performance is influenced by several parameters rather than by crystallite size alone. A smaller crystallite size can increase the accessible surface area and the number of surface-active sites, which may favor pollutant adsorption and surface reactions. However, differences in crystal structure, metal–oxygen bonding, electronic structure, charge transport, defect states, and optical absorption can also influence photocatalytic behavior. Therefore, a direct universal correlation between crystallite size, activation energy, and photocatalytic efficiency cannot be established from the available data.

The electrical properties can provide useful information about charge transport in the material, but the Maxwell–Wagner model primarily describes interfacial polarization and dielectric relaxation. It should therefore not be used as direct evidence for the photocatalytic mechanism. Instead, the electrical results can be considered supportive evidence that charge transport occurs within the spinel material, while the optical results demonstrate its ability to absorb visible light.

The recyclability and structural stability of a photocatalyst are important parameters for evaluating its potential practical application. To assess the reusability of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$, the catalyst was recovered after each photocatalytic cycle, washed several times with deionized water, and reused under identical experimental conditions. As shown in **Figure. 18**, the photocatalytic activity remained relatively stable over five consecutive MB degradation cycles, with only a slight decrease in removal efficiency after repeated use. This decrease may be associated with partial aggregation of catalyst particles during recovery and/or the adsorption of residual MB molecules or reaction intermediates on the catalyst surface, which can partially block active sites [72-75]. The maintained activity after five cycles indicates good stability and recyclability of the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel.

The photocatalytic degradation kinetics of MB were further investigated by monitoring the normalized concentration (C/C_0) as a function of irradiation time. **Figure. 19** shows a continuous decrease in C/C_0 , confirming the progressive removal of MB in the presence of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$. During the first 60 min of

irradiation, approximately 62% of the initial MB concentration was removed, indicating a relatively high initial removal rate. The subsequent decrease in the slope of the degradation curve can be related to the lower concentration of MB and the progressive occupation of active surface sites.

The experimental data were fitted using the pseudo-first-order kinetic model, which is commonly applied to heterogeneous photocatalytic degradation processes at relatively low pollutant concentrations: $\log \frac{C_0}{C} = -kt$

where k is the apparent pseudo-first-order rate constant (min^{-1}), C_0 is the initial MB concentration, C is the MB concentration at irradiation time t , and t is the irradiation time.

Figure. 20 presents the linear plot of $\ln(C_0/C)$ versus irradiation time. A high linear correlation was obtained, with $R^2 \approx 0.997$, indicating that the MB removal process can be reasonably described by a pseudo-first-order kinetic model. The apparent rate constant calculated from the slope of the linear fit was ($k = 0.00985 \text{ min}^{-1}$). The corresponding half-life, calculated from $t_{1/2} = \frac{\ln 2}{k}$, is approximately 70.4 min.

The decrease in the apparent reaction rate at prolonged irradiation times may result from the lower concentration of MB and the progressive occupation of accessible surface sites by adsorbed molecules and reaction intermediates. Consequently, the availability of active sites for the interaction between MB and photogenerated reactive species decreases during the later stages of irradiation [71-75].

Finally, adsorption should be considered an important preliminary step in the overall photocatalytic process. Adsorption brings MB molecules into close contact with the catalyst surface and may facilitate subsequent interfacial charge-transfer and oxidation reactions. Thus, the overall MB removal efficiency can result from the combined contribution of surface adsorption and light-induced photocatalytic reactions [77-80]. In the present $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ system, the observed photocatalytic performance is therefore reasonably related to the combined

structural stability, metal–oxygen bonding, charge-transport characteristics, and visible-light absorption associated with the spinel material.

Conclusion:

In conclusion, $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ spinel ferrite was successfully synthesized by the sol–gel method, yielding a single-phase cubic spinel structure with the $Fd\bar{3}m$ space group. FTIR analysis confirmed the characteristic metal–oxygen vibrations at tetrahedral and octahedral sites. The dielectric response exhibited a strong frequency dependence, consistent with Maxwell–Wagner interfacial polarization and Koop’s theory. The AC conductivity followed Jonscher’s power law, with NSPT conduction below 500 K and a transition to the CBH mechanism above 500 K. The activation energy (E_a) was estimated at 0.223 eV, while the potential barrier height (W_M) was approximately 0.21 eV, with their close values supporting the proposed hopping mechanism.

Optical analysis revealed strong visible-light absorption with a direct band gap of 2.56 eV. Photocatalytic experiments showed approximately 90% methylene blue degradation after 180 min under visible-light irradiation, following pseudo-first-order kinetics. These combined properties demonstrate the potential of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ as a multifunctional material for photocatalytic and electronic applications.

Data availability

Upon a reasonable request, the data that support this study's findings are available from the corresponding author.

Conflict of interest

The authors have no competing interests that are relevant to the content of this article to declare.

Authors contributions

All authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, analysis, design, and writing. The final manuscript was read and approved by all authors.

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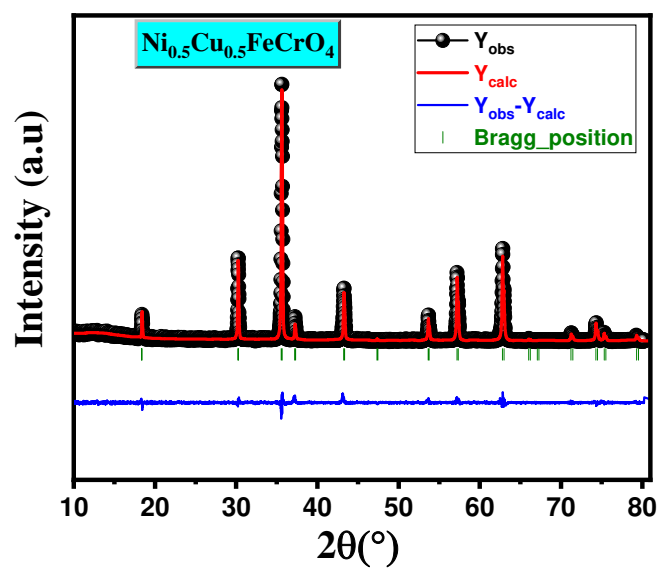


Fig.1: x-ray diffraction pattern with refinement of Rietveld for $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.

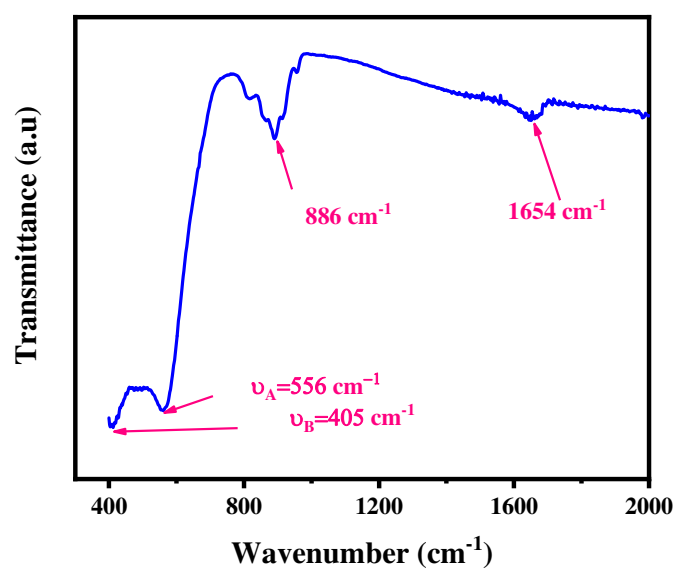


Figure 2: FT-IR spectrometer of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$

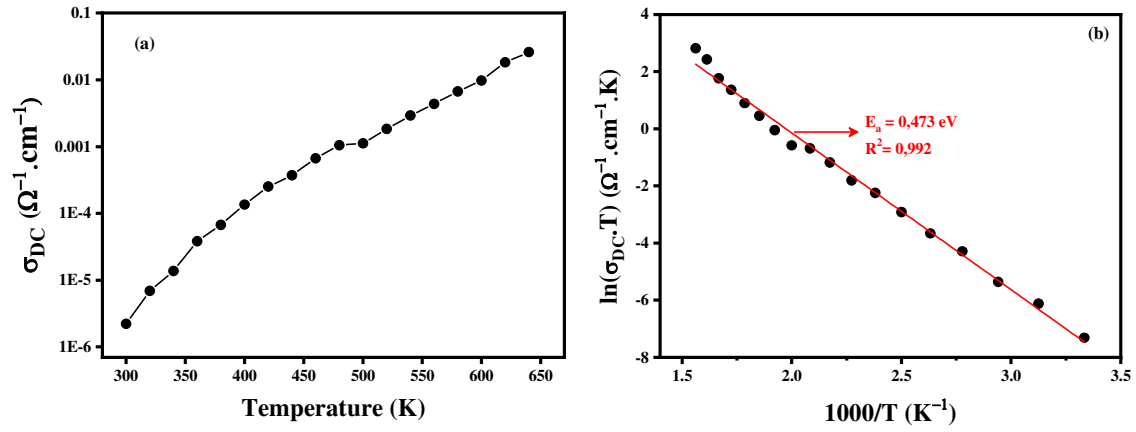


Figure. 3. a: Thermal evolution of electrical DC conductivity of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.
Figure. 3 b: Variation of electrical DC conductivity versus of $1000/T$ of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.

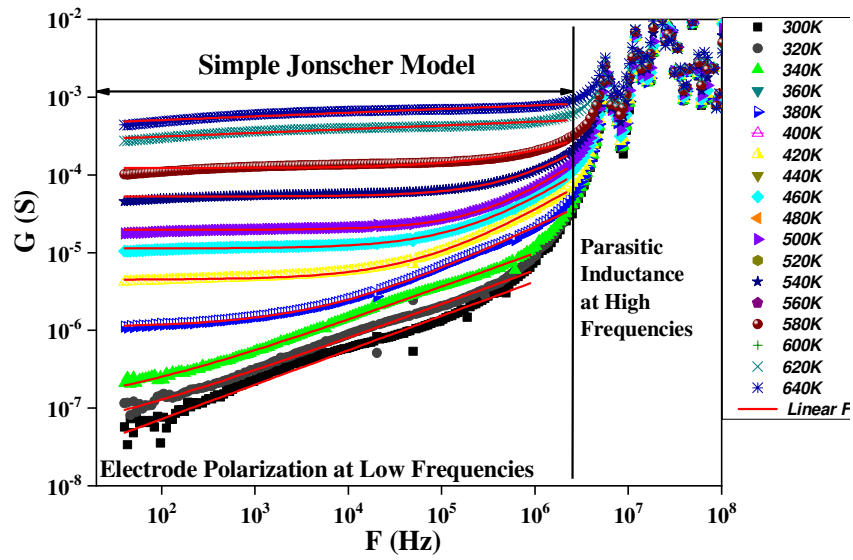


Figure 4. Variation of the conductivity as a function frequency of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ ferrite at different temperatures.

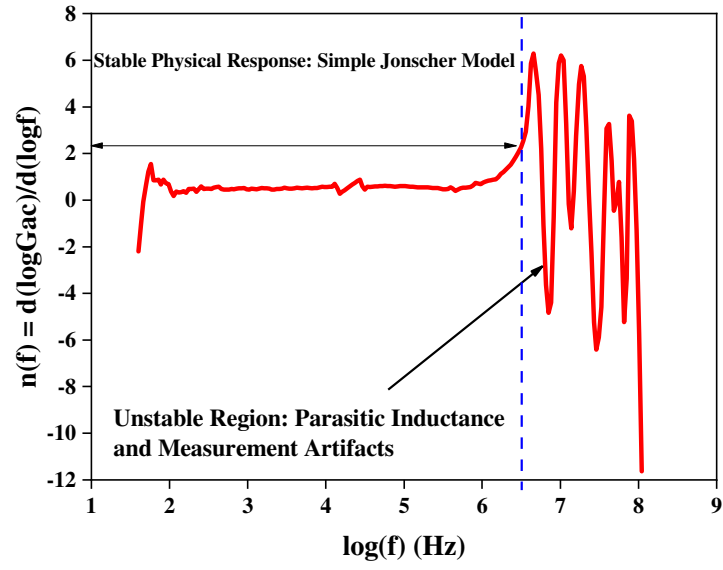


Figure 5. AC conductivity response in the stable low-frequency and unstable high-frequency regimes.

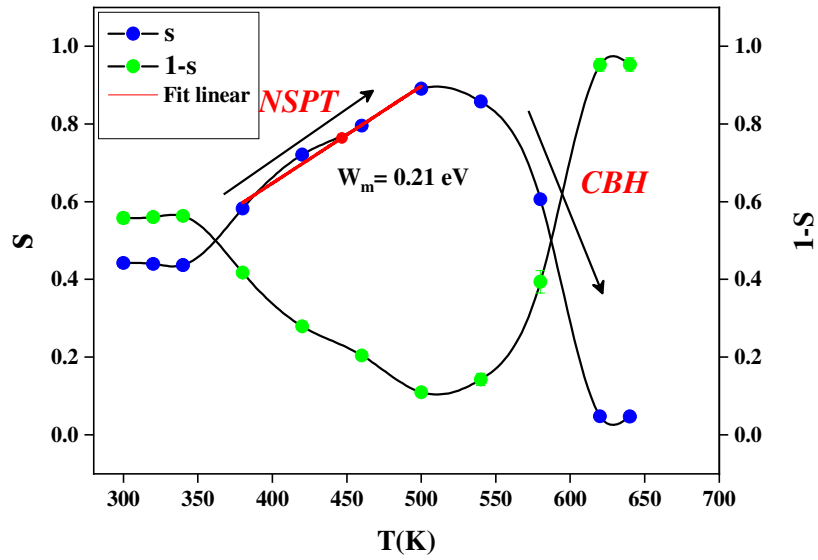


Figure. 6. Temperature dependence of the exponent 's' and '1-s' of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.

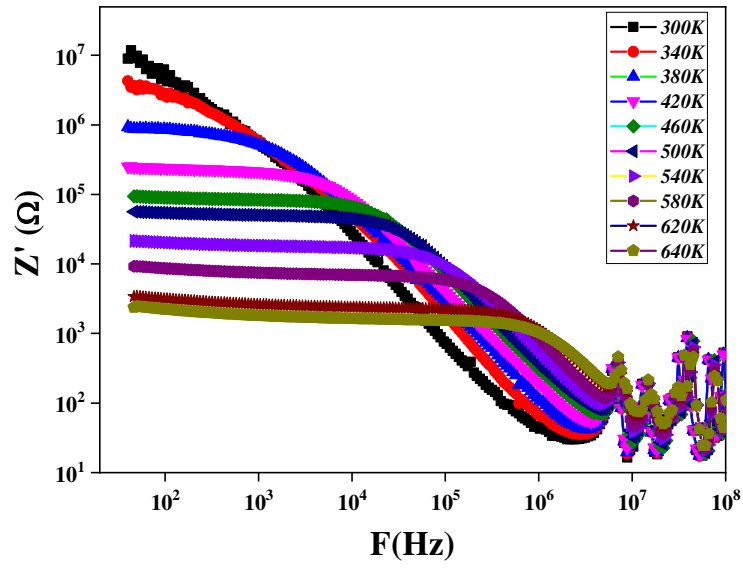


Figure. 7. Frequency dependence of the real part of impedance at different temperatures of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$

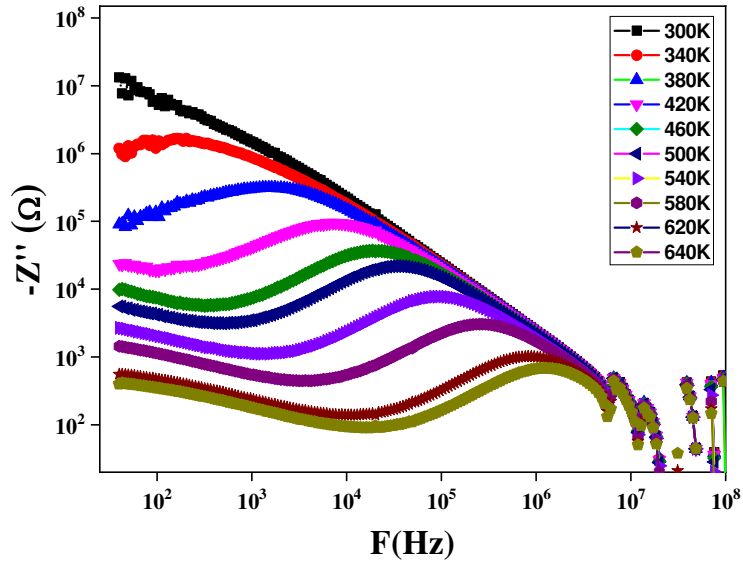


Figure. 8. Frequency dependence of the imaginary part of impedance at different temperatures of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.

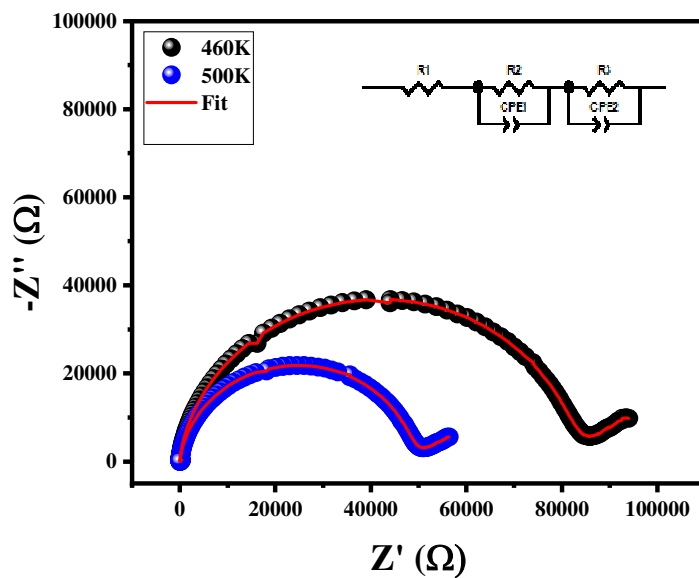


Figure. 9. Equivalent circuit modeling at 460 K and 500 K of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$.

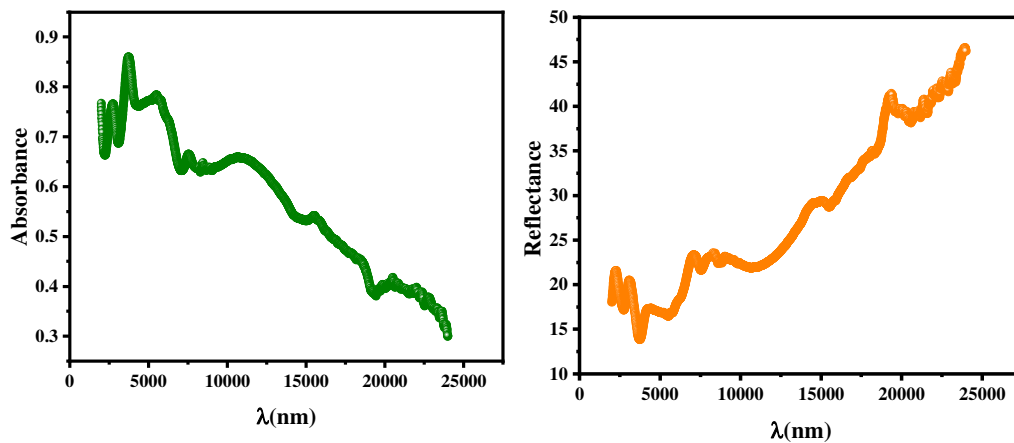


Figure. 10: Variations with wavelength of absorption and reflection coefficients Amplitude

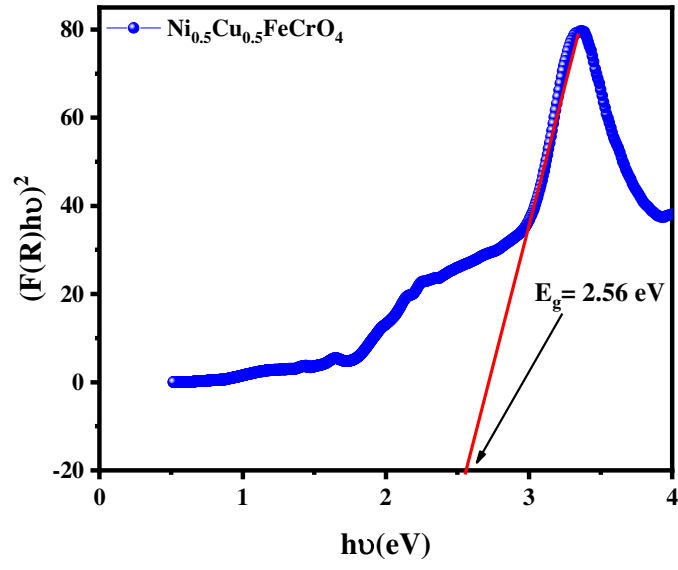


Figure. 11: plot of $(F(R)hv)^2$ versus $h\nu$ (E_g is the direct and the indirect band gap)

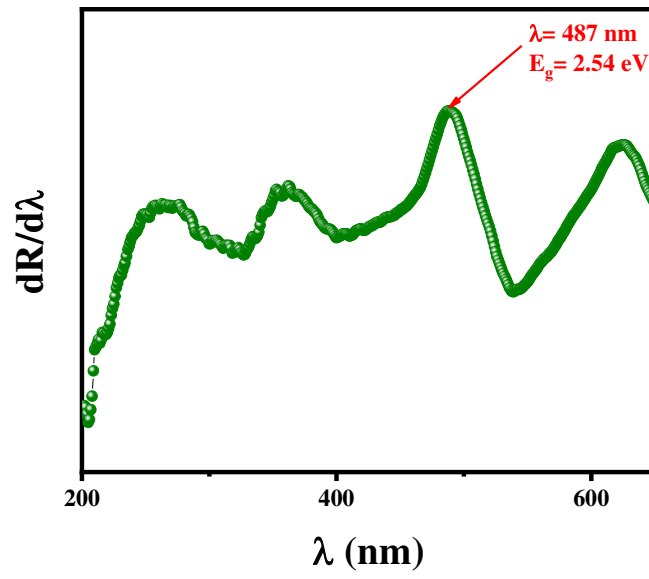


Figure. 12: The variation of $dR/d\lambda$ versus λ

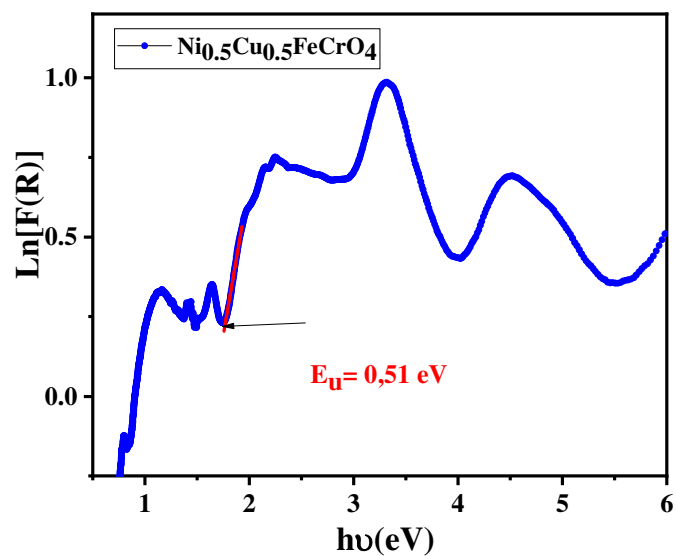


Figure. 13: Evolution of the Urbach energy for the $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ compound

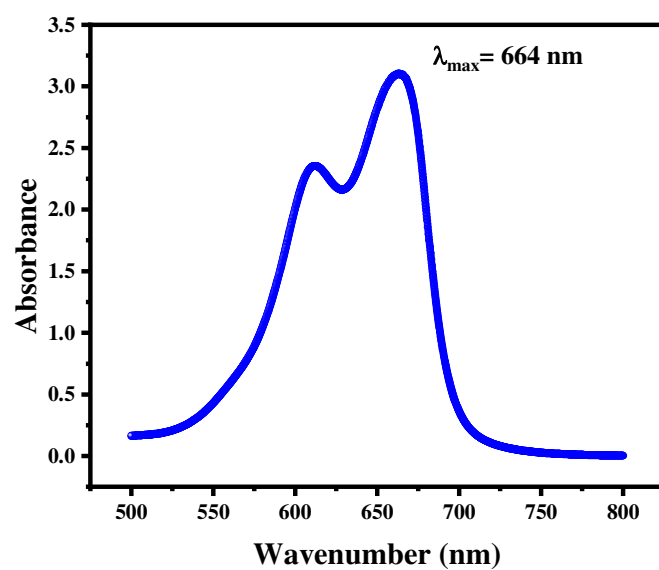


Figure. 14. UV-visible absorption profile of methylene blue during photodegradation without additives or catalysts.

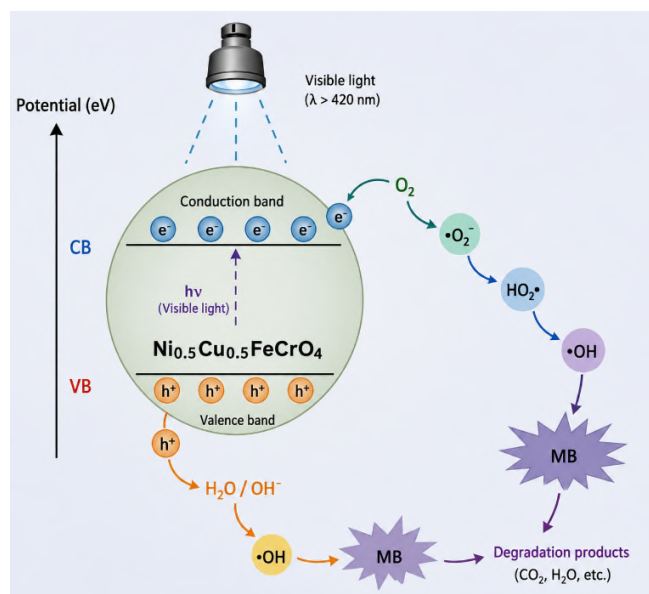


Figure. 15: Schematic illustration of the photocatalytic degradation mechanism of MB.

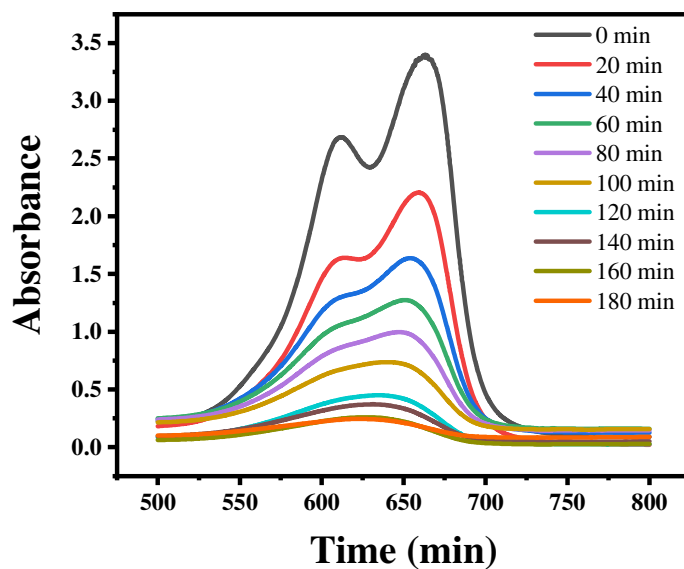


Figure. 16: Time-dependent absorption spectra of MB solution in visible light

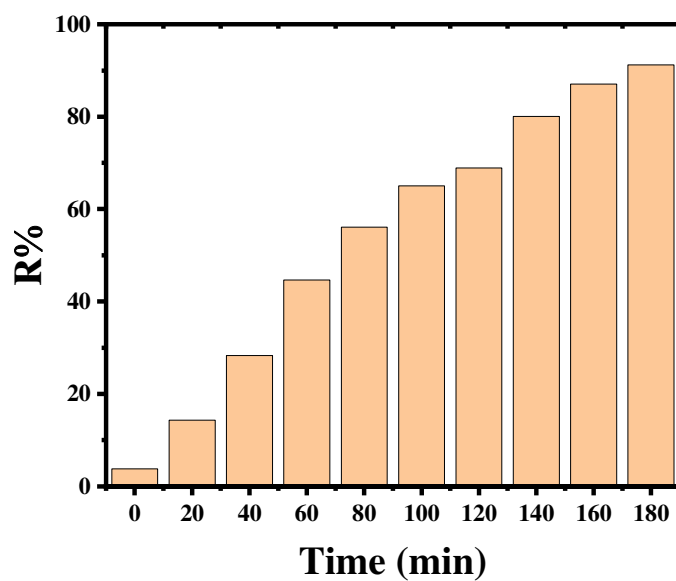


Figure. 17: Degradation efficacy profile of Mb under UV light irradiation photocatalytic activity

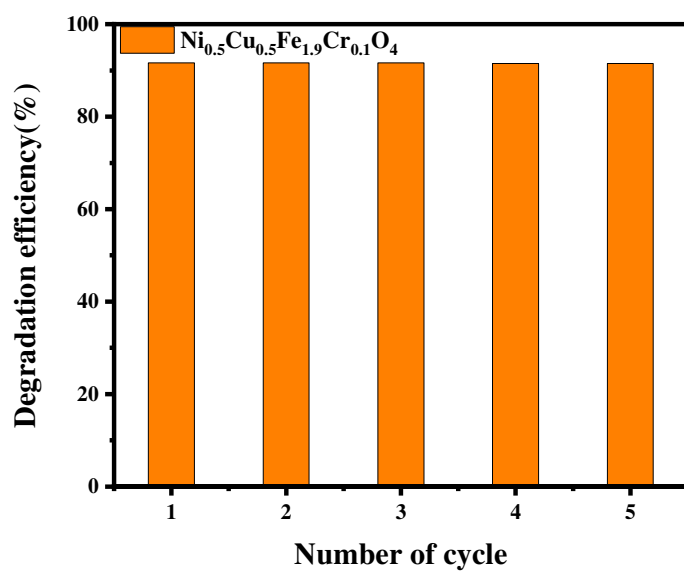


Figure. 18: Photodegradation of MB after five cycles in presence of $\text{Ni}_{0.5}\text{Cu}_{0.5}\text{FeCrO}_4$ photocatalyst

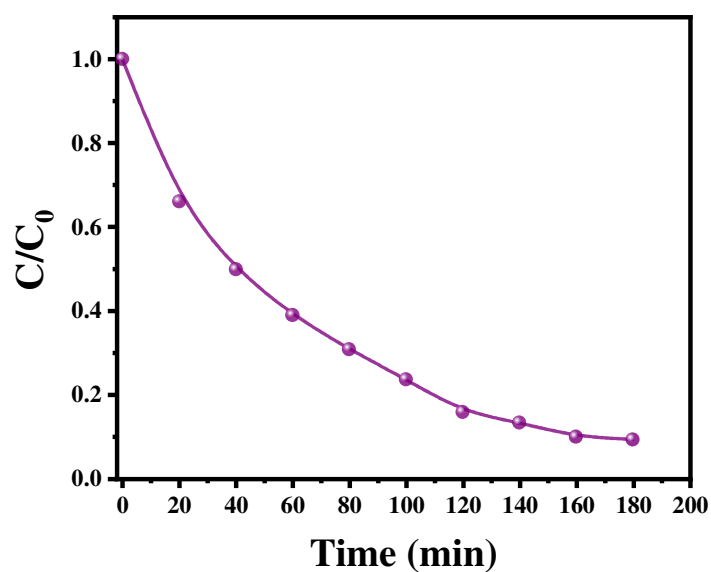


Figure. 19: Changes in (C_t/C_0) as functions of time for the photodegradation of MB dye in the presence of $Ni_{0.5}Cu_{0.5}FeCrO_4$ sample with different catalyst concentrations

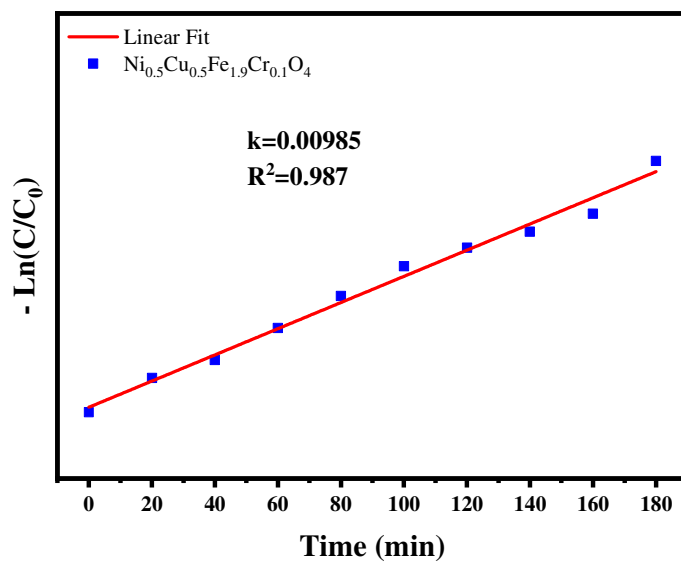


Figure. 20: Changes in $-\ln(C_t/C_0)$ as functions of time for the photodegradation of MB dye in the presence of $Ni_{0.5}Cu_{0.5}FeCrO_4$ sample

Table. 1: Rietveld refinement of structural parameters for Nd_{0.5}Ce_{0.5}CoO₃ perovskite. The numbers in parentheses are estimated standard deviations to the last significant digit. Biso: the isotropic Debye–Waller factor. R_A and R_B: bond distance. $\theta_{(A-B)}$ and $\theta_{(B-B)}$: bond angle. Agreement factors of profile R_p, weighted profile R_{wp} and structure R_F. χ^2 : the goodness of fit

Sample			Ni _{0.5} Cu _{0.5} FeCrO ₄	
Space group			<i>Fd</i> $\bar{3}m$	
Cell parameters	Cell constant <i>a</i> (Å)		8.36 (3)	
	Cell Volume <i>V</i> (Å ³)		584.1 (7)	
Atoms	Tetrahedral A site (Cu/Fe)	Wyckoff positions		8a
		Site summety		$\bar{4}3m$
		Atomic positions	<i>x</i> = <i>y</i> = <i>z</i>	1/8
		Occupancy factors		0.5/0.5
		<i>B</i> _{iso} (Å ²)		1.07 (2)
	Octahedral B site (Ni/Fe/Cr)	Wyckoff positions		16d
		Site summety		$\bar{3}m$
		Atomic positions	<i>x</i> = <i>y</i> = <i>z</i>	1/2
		Occupancy factors		0.5/0.5/1
		<i>B</i> _{iso} (Å ²)		1.03 (2)
	O	Wyckoff positions		32e
		Site summety		3m
		Atomic positions	<i>x</i> = <i>y</i> = <i>z</i>	0.252 (7)
		Occupancy factors		4
		<i>B</i> _{iso} (Å ²)		0.942 (1)
Structural parameters	<i>D</i> _{XRD} (nm)		19.59	
	<i>D</i> _{WH} (nm)			
	ρ _x (g/cm ³)		5.899	
	<i>R</i> _A (Å)		1.985 (6)	
	<i>R</i> _B (Å)		2.17 (6)	
	Θ _{A-O-B} (°)		121.4 (2)	
	Θ _{B-O-B} (°)		96.2 (2)	
Agreement factors	<i>R</i> _p (%)		9.13	
	<i>R</i> _{exp} (%)		7.08	
	<i>R</i> _{wp} (%)		9.57	
	<i>R</i> _F (%)		3.88	
	χ ² (%)		1.83	

Table. 2: General information on methylene blue

Property	Description
Chemical name	Methylene Blue (Methylthioninium Chloride)
Chemical formula	C ₁₆ H ₁₈ ClN ₃ S
Molar mass	319.85 g/mol
Appearance	Blue crystalline powder
Water solubility	Soluble (35 g/L at 25 °C)
Melting point	100–110 °C (decomposition)
Main applications	Dye, antiseptic agent, photosensitizer
Maximum absorption wavelength (λ_{max})	664 nm (in water)
pKa	3.8
Toxicity	Moderately toxic if ingested or inhaled

Tab.3: Photocatalytic properties of spinel chromite AM₂O₄

Sample	Poluant/s	C. time (min)	L. source	R. capacity %	D _g (nm)	E _g (eV)	Ref
Ni _{0.5} Cu _{0.5} FeCrO ₄	MB	180	UV-Vis	~90		2.56	This study
CuCr ₂ O ₄	MB	-	Vis	80.6	5-35	1.4	[70]
(NiCd) _{0.5} Cr ₂ O ₄	MB	180	UV-Vis	73	38.5	2.2	[72]
Ni _{0.6} Mg _{0.4} Cr ₂ O ₄	MB	90	UV-Vis	65	15.16	2.36	[73]
NiCr ₂ O ₄	MB	90	Vis	40	20.23	2,1	[73]
NiFe ₂ O ₄	MB	240	Natural sunlight	98.51	18.71	1.43–1.45	[74]
CuFe ₂ O ₄	MB	45	Vis	87.13	29	2.03	[76]