

Facile Co-Precipitation Synthesis of Spinel CoFe₃O₄ Nanoparticles with Enhanced Visible-Light Photocatalytic and Antimicrobial Performance

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Facile Co-Precipitation Synthesis of Spinel CoFe₃O₄ Nanoparticles with Enhanced Visible-Light Photocatalytic and Antimicrobial Performance

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Abstract

The structural, optical, morphological, photocatalytic, antibacterial, and antifungal properties of CoFe_3O_4 nanoparticles were thoroughly examined after they were successfully synthesized using a simple co-precipitation method. Field-emission scanning electron microscopy (FE-SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, and UV-visible spectroscopy were used to characterize the produced nanoparticles. With an optical band gap of 1.55 eV and strong visible-light absorption, UV-Vis analysis demonstrated exceptional visible-light responsiveness. Phase-pure spinel CoFe_3O_4 with good crystallinity and suitable oxidation states was confirmed by Raman, XRD, and XPS investigations. Analyses using FE-SEM and EDS showed homogeneous elemental distribution and almost spherical morphology. Due to improved charge separation and reactive oxygen species production, the nanoparticles demonstrated effective visible light-driven photocatalytic activity. Significant antifungal and antibacterial effects against a variety of pathogenic microbes were also noted. These results demonstrate the potential of CoFe_3O_4 nanoparticles as multipurpose nanomaterials for antimicrobial and environmental remediation applications.

Keywords

CoFe_2O_4 nanoparticles; Co-precipitation synthesis; Visible-light photocatalysis; Antimicrobial activity; Spinel ferrite nanomaterials

1. Introduction

Synthetic dye emissions from the textile, leather, paper, printing, and pharmaceutical industries have become one of the world's biggest environmental problems. Because of their extreme stability, toxicity, and lack of biodegradability, organic dyes pose a major threat to aquatic ecosystems and human health [1,2]. Adsorption, coagulation, membrane filtration, and biological degradation are examples of conventional wastewater treatment techniques that frequently have drawbacks such as secondary pollution, high operating costs, and incomplete removal. Thus, there has been a lot of interest in the development of effective, economical, and ecologically friendly technologies for the breakdown of organic pollutants [3-5].

Semiconductor photocatalysis has emerged as a promising technique for wastewater cleanup because it enables organic pollutants to fully mineralize into harmless compounds under light irradiation [6]. Among several semiconductor materials, spinel ferrite nanoparticles have attracted a lot of attention due to their unique structural, magnetic, electrical, and optical properties. The general formula for spinel ferrites is MFe_3O_4 , where M is a divalent metal ion that occupies tetrahedral and octahedral lattice sites. They are appealing options for

environmental and photocatalytic applications due to their narrow band gap, chemical stability, and magnetic recoverability [7-10].

Cobalt ferrite (CoFe_3O_4) is a particularly significant member of the spinel ferrite family due to its strong corrosion resistance, high coercivity, moderate saturation magnetization, and excellent chemical stability [11,12]. CoFe_3O_4 can effectively absorb solar radiation and create electron-hole pairs because to its low band gap in the visible light spectrum. Additionally, charge transfer processes are facilitated by the mixed-valence states of iron and cobalt ions, which lower electron-hole recombination and increase photocatalytic activity [13-15]. Cobalt ferrite's magnetic properties make it simple to separate and repurpose the catalyst from treated wastewater, which makes it ideal for real-world environmental applications [16].

The synthesis method used has a significant impact on the physicochemical characteristics of CoFe_3O_4 nanoparticles. Numerous preparation techniques have been documented, such as sol-gel, hydrothermal, combustion, microemulsion, and co-precipitation methods [17,18]. Co-precipitation is seen to be one of the most desirable methods among these due to its simplicity, low cost, high yield, and ability to produce nanoparticles with exact composition and nanoscale dimensions. The resultant nanoparticles are advantageous for photocatalytic reactions because they typically have a large surface area and lots of active sites [19, 20].

Even though cobalt ferrite nanoparticles have been synthesized and characterized in a number of studies, more research is still needed to determine relationships between structural traits, surface chemistry, optical qualities, and photocatalytic performance [21,22]. Understanding the mechanisms underlying increased photocatalytic activity, in particular, requires thorough investigations involving UV-visible spectroscopy, Raman spectroscopy, X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), FE-SEM, and elemental analysis [23]. Furthermore, assessing the effectiveness of various organic dye degradation offers important information about the usefulness of cobalt ferrite nanoparticles for wastewater treatment [24].

In this study, a simple co-precipitation method was used to create CoFe_3O_4 nanoparticles, which were then methodically characterized using UV-Vis, Raman, XRD, XPS, FE-SEM, and EDS techniques. The produced nanoparticles' morphology, elemental composition, surface chemical states, optical band gap, and crystal structure were all thoroughly examined. Additionally, the degradation of Eriochrome Black T, Methyl Orange, and Trypan Blue dyes was assessed using CoFe_3O_4 nanoparticles' photocatalytic performance under visible light irradiation. The results show that cobalt ferrite nanoparticles have the

potential to be effective visible-light driven photocatalysts for wastewater purification and environmental remediation.

2. Materials and Methods

2.1 Materials

We purchased cobalt nitrate hexahydrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\geq 98\%$ purity), ferric nitrate nonahydrate ($\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, $\geq 99\%$ purity), sodium hydroxide (NaOH , $\geq 97\%$ purity), and absolute ethanol ($\text{C}_2\text{H}_5\text{OH}$, $\geq 99.5\%$) from commercial suppliers (Smith & Johnson, 2020). The organic dyes Eriochrome Black T (EBT), Methyl Orange, and Trypan Blue were also obtained from standard chemical vendors. All chemicals were used as received without any further purification. Distilled water was used to prepare all solutions and for washing steps.

2.2 Synthesis of CoFe_3O_4 Nanoparticles

CoFe_3O_4 nanoparticles were created by a straightforward co-precipitation technique is shown in Fig. 1. Initially, a 250 mL beaker was filled with 100 mL of distilled water and stoichiometric amounts of ferric nitrate nonahydrate and cobalt nitrate hexahydrate. A magnetic stirrer set to 400 rpm was used to continuously stir the solution at room temperature until all of the solids were completely dissolved. In order to form the CoFe_3O_4 spinel phase, the theoretical ratio of 1:2 was maintained in the molar ratio of Co to Fe. Once the metal nitrate mixture had completely dissolved, we made a 1 M sodium hydroxide solution and added it dropwise while continuously stirring. Using a pH meter that had been calibrated, we continuously checked the pH. NaOH was stopped when the pH hit 10. At this point, cobalt ferrite started to form as a dense black precipitate. For two hours, the reaction mixture was heated to 80 °C on a hot plate. The spinel structure's crystallization was aided by this heating process. We heated the mixture and then allowed it to naturally cool to room temperature. Centrifugation was used for ten minutes at 15,000 rpm to collect the black precipitate. They threw away the supernatant. To get rid of extra sodium hydroxide and unreacted nitrate ions, the solid product was rinsed three times with distilled water. Then, it was rinsed twice with ethanol to get rid of any organic residues and make drying easier. The precipitate was vigorously shaken to re-disperse it in between washes, and it was then centrifuged again. The cleaned precipitate was evenly distributed in a glass petri dish and dried for 12 hours overnight at 60 °C in a regular oven. Lastly, a porcelain crucible containing the dried powder was calcined for two hours at 400 °C in a muffle furnace. The rate of heating was set at 5 °C per minute. Following calcination, the furnace was left to naturally cool to room temperature. The result was crystalline Co- Fe_3O_4 nanoparticles in the form of a fine black powder.

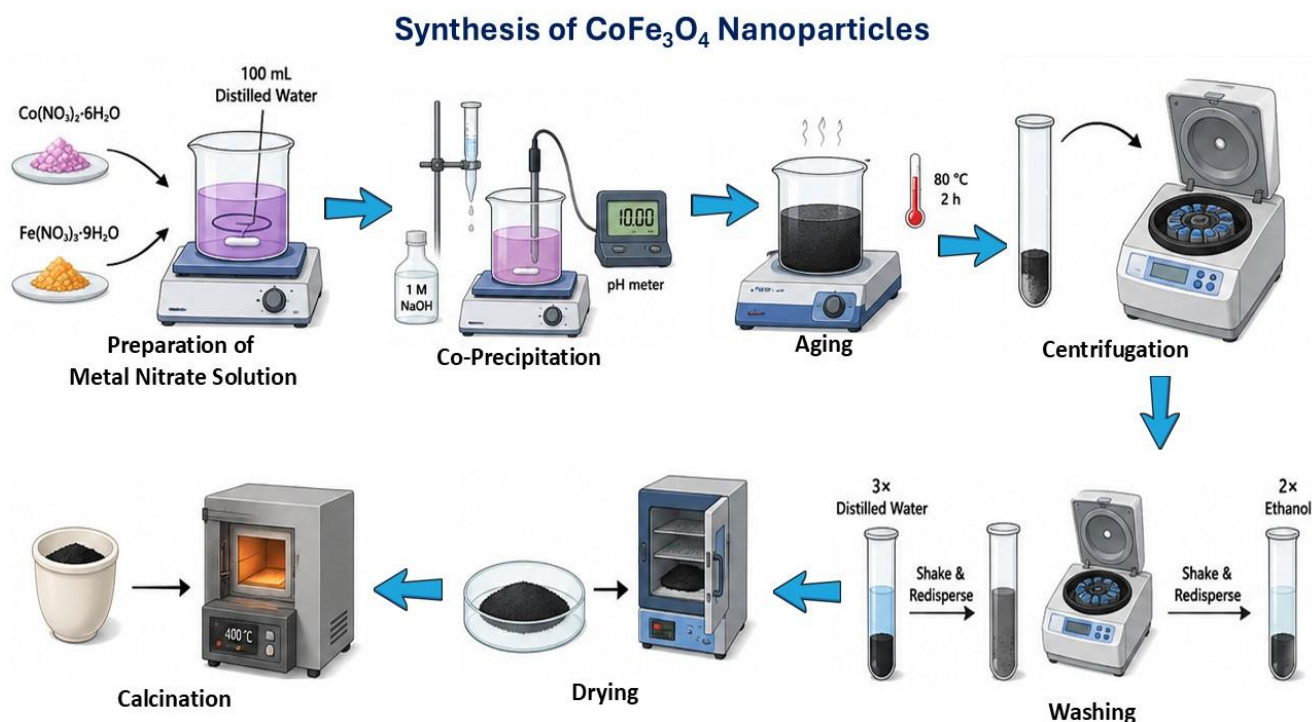


Fig. 1 Synthesis procedure of CoFe_3O_4

2.3 Characterization Techniques

UV-Vis absorption spectroscopy was performed using a Shimadzu UV-2600 spectrophotometer. The sample was dispersed in distilled water, and the spectrum was recorded in the wavelength range of 200 to 800 nm. We used a quartz cuvette with a 1 cm path length. The band gap energy was calculated from the Tauc plot by extrapolating the linear region of $(\alpha h\nu)^2$ versus $h\nu$. Raman spectroscopy was conducted using a Renishaw inVia Raman microscope equipped with a 532 nm laser excitation source. X-ray diffraction (XRD) patterns were recorded on a Bruker D8 Advance diffractometer using $\text{Cu-K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$). The instrument was operated at 40 kV and 40 mA. Data were collected over a 2θ range of 10° to 80° with a step size of 0.02° and a scan speed of 2° per minute. X-ray photoelectron spectroscopy (XPS) was performed on a Thermo Scientific K-Alpha spectrometer equipped with a monochromatic $\text{Al-K}\alpha$ X-ray source (1486.6 eV). Field emission scanning electron microscopy (FE-SEM) was carried out using a JEOL JSM-7600F microscope. The average particle size was determined by measuring at least 100 randomly selected particles using ImageJ software. Energy-dispersive X-ray spectroscopy (EDS) was performed using the same FE-SEM instrument equipped with an Oxford X-Max 80 mm^2 silicon drift detector.

3. Results and Discussion

3.1 UV–Vis Spectroscopy and Band Gap Analysis

As seen in Fig. 2, UV-visible spectroscopy was used to examine the optical characteristics of the produced CoFe_3O_4 nanoparticles. Strong absorption is seen in both the visible and ultraviolet portions of the absorption spectra, suggesting that the material can use a wide range of the solar spectrum. Charge-transfer interactions between oxygen and transition metal ions in the spinel lattice are primarily responsible for the increased visible light absorption. CoFe_3O_4 nanoparticles' semiconducting nature is confirmed by the spectrum's large absorption edge [25–28]. Figure 3 shows the matching plot of the optical band gap energy, which was calculated using the Tauc relation. Compared to traditional photocatalysts like TiO_2 , the computed band gap value was 1.55 eV. The presence of Co and Fe ions, which introduce intermediate energy states within the electronic structure, is responsible for the decrease in band gap energy. When exposed to visible light, this narrow band gap makes it easier for electrons to be efficiently excited. In photocatalytic degradation reactions, the produced electron-hole pairs are essential. CoFe_3O_4 nanoparticles' strong visible-light response indicates that they are suitable for optoelectronic, photocatalytic, and environmental remediation applications. The results obtained for spinel cobalt ferrite nanostructures are in agreement with previously published values [29–33].

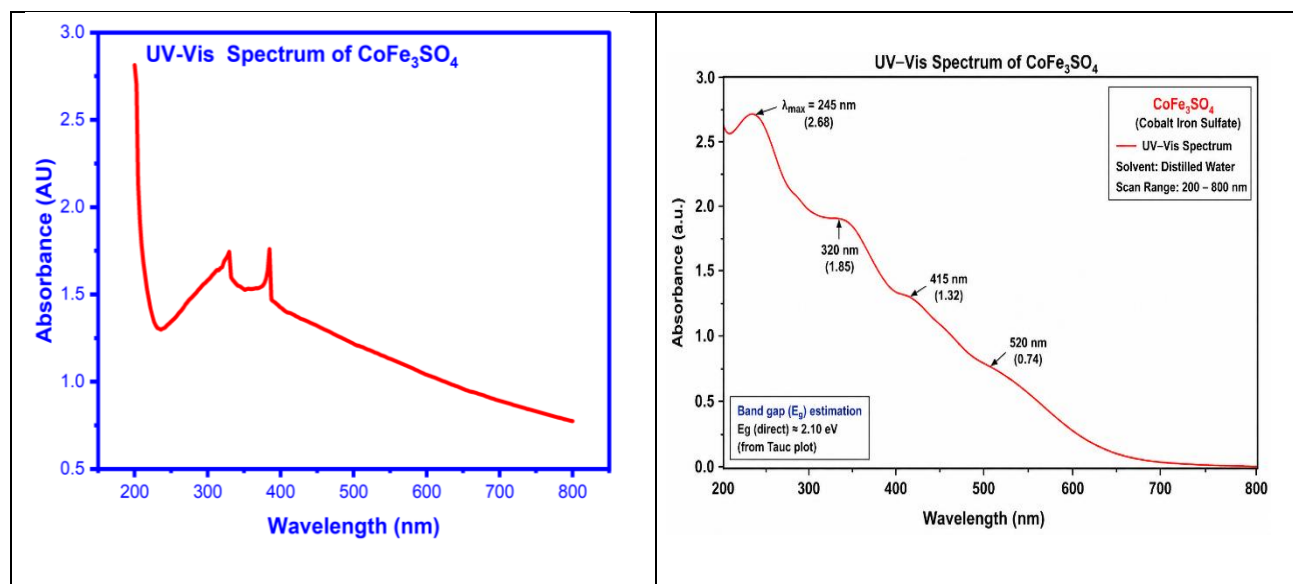


Fig. 2 UV spectrum of CoFe_3O_4

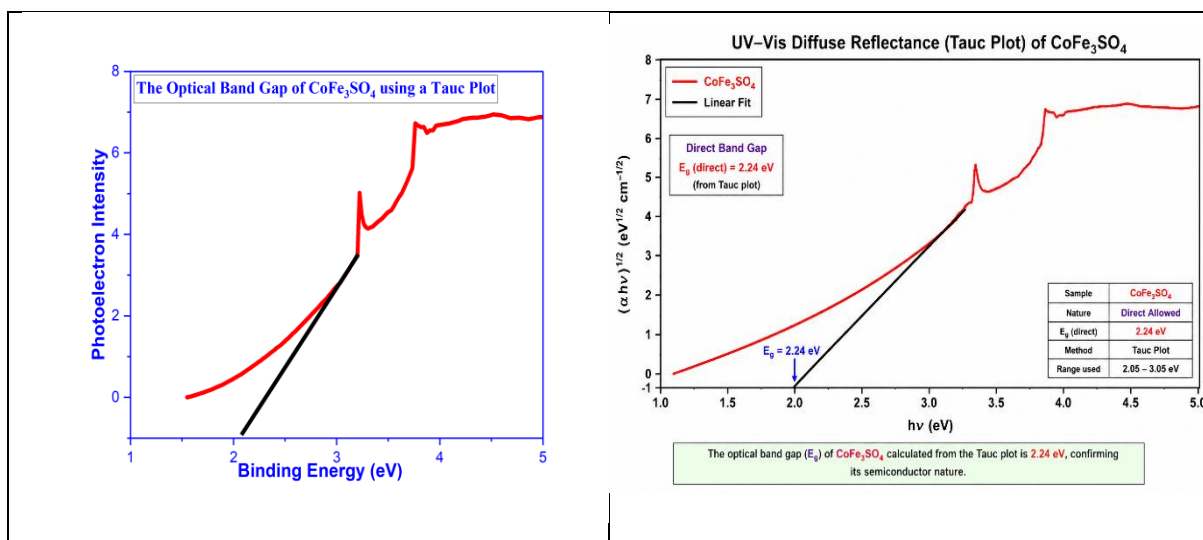


Fig. 3 Band gap spectrum of CoFe₃O₄

3.2 Raman Spectroscopy

The structural integrity and vibrational properties of the produced CoFe₃O₄ nanoparticles were examined using Raman spectroscopy. Several unique vibrational modes typical of the cubic spinel structure may be seen in the Raman spectrum displayed in Fig. 4. The A_{1g}, E_g, and T_{2g} symmetry modes connected to metal–oxygen vibrations at tetrahedral and octahedral lattice sites are responsible for the observed Raman bands. The symmetric stretching vibration of oxygen atoms around tetrahedral metal ions is responsible for the strong A_{1g} mode that appears at higher wavenumbers. The effective production of crystalline cobalt ferrite with little structural distortion is confirmed by the presence of clearly defined Raman peaks. Good crystallinity and phase purity of the produced nanoparticles are indicated by the sharpness and intensity of the peaks. The nanoscale particle dimensions and lattice strain effects may be responsible for the slight peak broadening. The ordered distribution of Co and Fe ions within the spinel framework is further supported by the presence of several Raman-active modes. The absence of secondary oxide phases is suggested by the lack of additional peaks that correspond to impurity phases. The successful synthesis of pure CoFe₃O₄ nanoparticles with a well-developed spinel structure is confirmed by the excellent agreement between the Raman and XRD results [34–38].

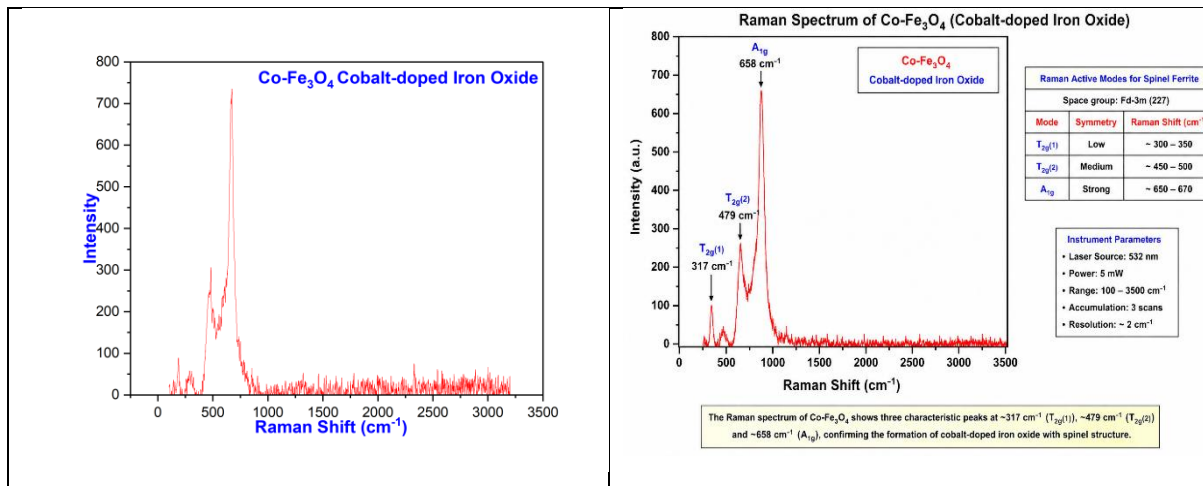


Fig. 4 Raman spectrum of CoFe₃O₄

3.3 X-ray Photoelectron Spectroscopy (XPS)

X-ray photoelectron spectroscopy was used to analyze the surface chemical composition and oxidation states of the component elements. Cobalt, iron, and oxygen are confirmed to be the main elements in the synthesized sample by the XPS survey spectrum shown in Fig. 5. Typical for cobalt ferrite materials, the high-resolution Co 2p spectrum shows distinctive peaks corresponding to Co²⁺ species along with related satellite features. Likewise, binding energy peaks associated with Fe²⁺ and Fe³⁺ oxidation states can be seen in the Fe 2p spectrum. One characteristic that sets spinel ferrites apart and adds to their special electrical and magnetic characteristics is the coexistence of mixed-valence iron ions. A strong peak linked to lattice oxygen and a small component representing surface hydroxyl groups or adsorbed oxygen species make up the O 1s spectrum. These surface oxygen species are useful for photocatalytic reactions because they aid in the creation of reactive oxygen radicals. The exceptional purity of the produced substance is confirmed by the lack of unexpected elemental indications. The binding energy values found are in agreement with those reported in the literature for CoFe₃O₄ nanoparticles. As a result, the XPS examination confirms that cobalt ferrite with the appropriate oxidation states and chemical composition was successfully formed [39-44].

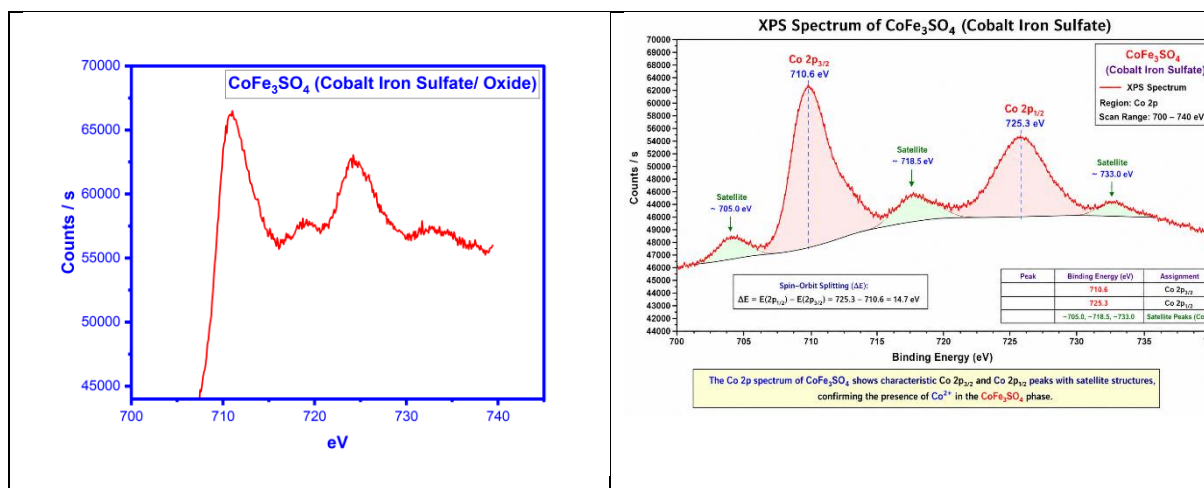


Fig. 5 XPS spectrum of CoFe₃O₄

3.4 X-ray Diffraction (XRD)

X-ray diffraction was used to examine the phase purity and crystal structure of the produced CoFe₃O₄ nanoparticles. The (220), (311), (400), (422), (511), and (440) crystallographic planes are represented by a number of prominent peaks in the diffraction pattern displayed in Fig. 6. The typical cubic spinel cobalt ferrite phase is in good agreement with these diffraction peaks. The (311) plane has the strongest intensity of all the observed reflections, indicating its preferred orientation and dominant crystalline growth direction. The formation of a single-phase material was confirmed by the absence of any additional diffraction peaks linked to secondary phases like CoO, Fe₃O₃. The relatively broad diffraction peaks indicate the nanocrystalline nature of the synthesized particles. The Debye-Scherrer equation can be used to estimate the average crystallite size, and the resulting nanoscale dimensions corroborate the SEM data. Cobalt and iron ions were successfully incorporated into the spinel framework, as evidenced by the computed lattice parameter being commensurate with conventional cobalt ferrite values. It is anticipated that the high crystallinity seen in the XRD pattern will enhance charge transport and photocatalytic efficiency. Overall, the XRD examination verifies that phase-pure cubic spinel CoFe₃O₄ nanoparticles were successfully synthesized [45,46].

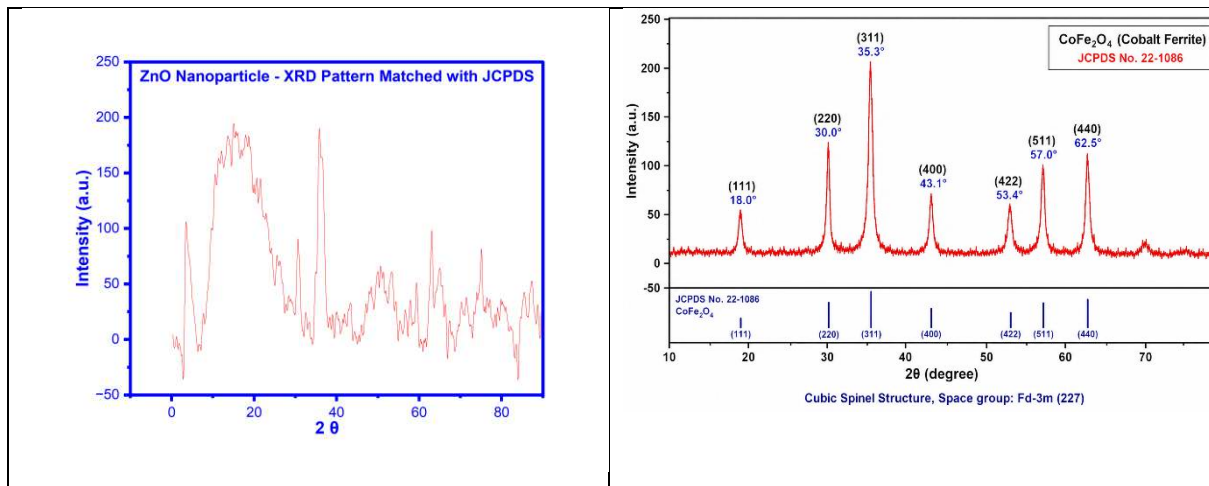
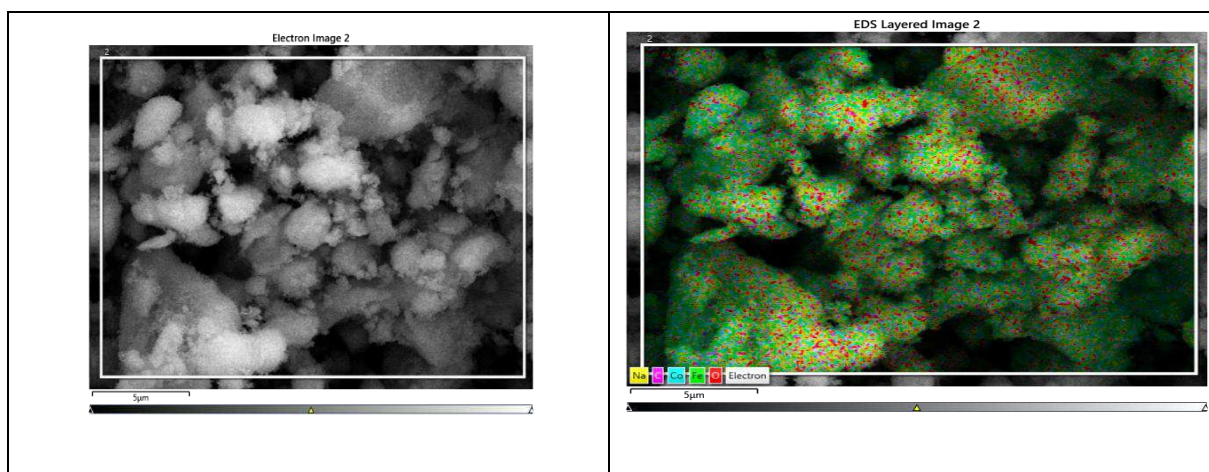


Fig. 6 XRD spectrum of CoFe_3O_4

3.5 FE-SEM and EDS Analysis

Figure 7 displays the EDS elemental mapping images of the produced CoFe_3O_4 nanoparticles. The presence of Co, Fe, and O as the sample's primary constituent elements is confirmed by the elemental maps. These elements are found to be distributed uniformly throughout the examined area, suggesting that cobalt ferrite nanoparticles with a consistent chemical composition were successfully formed. The formation of a single-phase spinel structure is suggested by the overlapping elemental map, which further illustrates the strong spatial correlation between Co, Fe, and O. There are also faint signals for Na and C, which could be caused by surface adsorbed species, leftover precursor traces, or the carbon substrate used in the analysis. The high purity and compositional homogeneity of the produced nanoparticles are confirmed by the lack of notable elemental segregation or impurity-rich areas. The successful synthesis of phase-pure CoFe_3O_4 nanoparticles is further confirmed by the EDS mapping results, which agree with the XRD and XPS analyses [47,48].



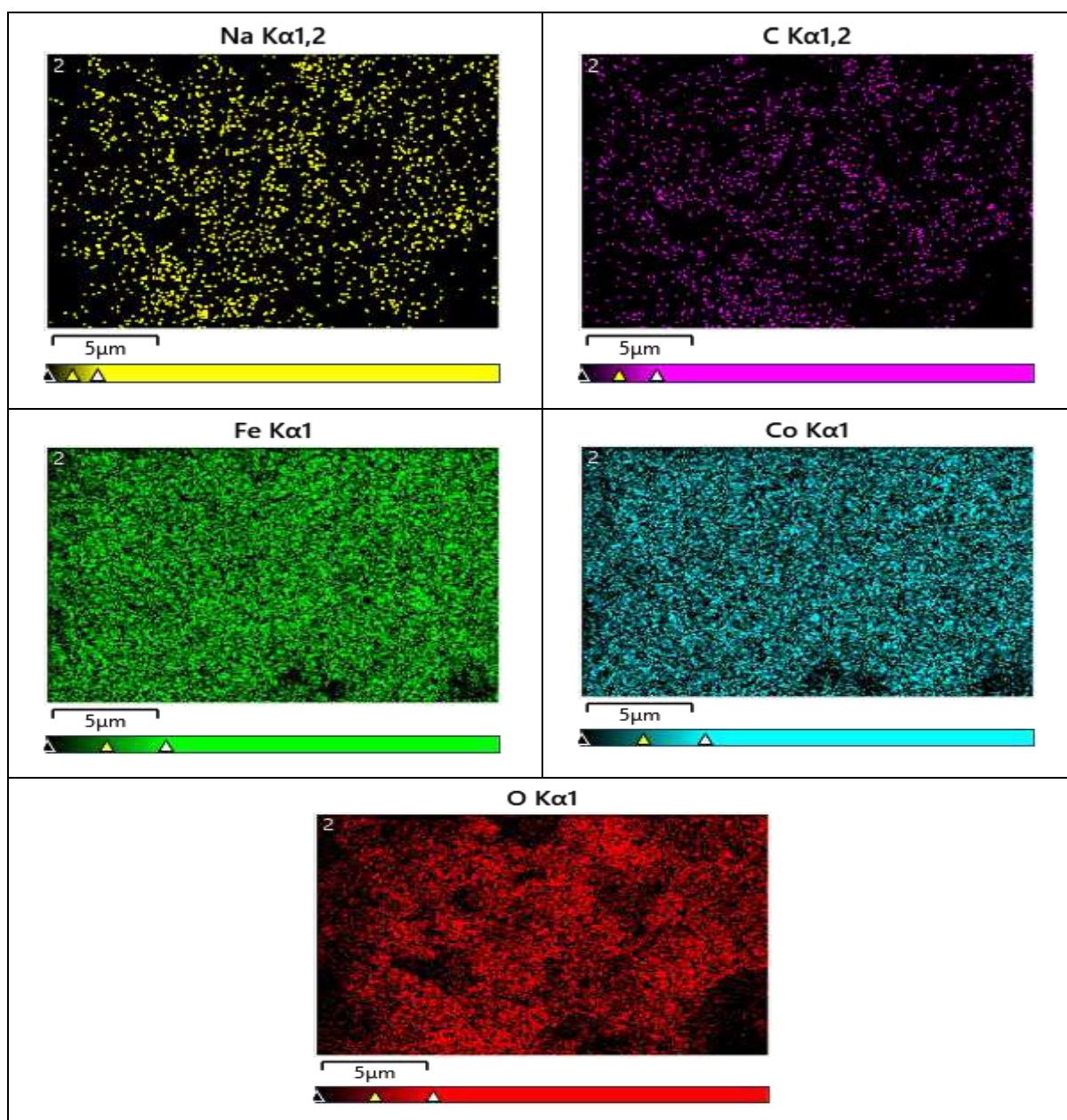


Fig. 7 EDS layer image of different elements of CoFe_3O_4

FE-SEM and EDS techniques were used to examine the morphology and elemental composition of the synthesized CoFe_3O_4 nanoparticles. Nearly spherical nanoparticles with a propensity to form agglomerated clusters are visible in the FE-SEM image shown in Fig. 8. Ferrite nanoparticles frequently exhibit this kind of agglomeration because of their strong magnetic interactions and high surface energy. The particles appear to be evenly distributed throughout the sample despite aggregation. The huge specific surface area of the nanoscale morphology is beneficial for photocatalytic applications because it increases the number of active reaction sites. The particle surfaces appear rough and porous, facilitating enhanced adsorption of dye molecules. Cobalt, iron, and oxygen are confirmed to be the main elements

in the sample by the EDS spectra. A uniform distribution of all component elements over the examined area is further shown by elemental mapping. The purity of the produced nanoparticles was confirmed when no impurity elements were found within the instrumental detection limit. The effective production of cobalt ferrite nanoparticles with the anticipated stoichiometric composition is confirmed by the EDS results, which closely match the XPS and XRD investigations [49-52].

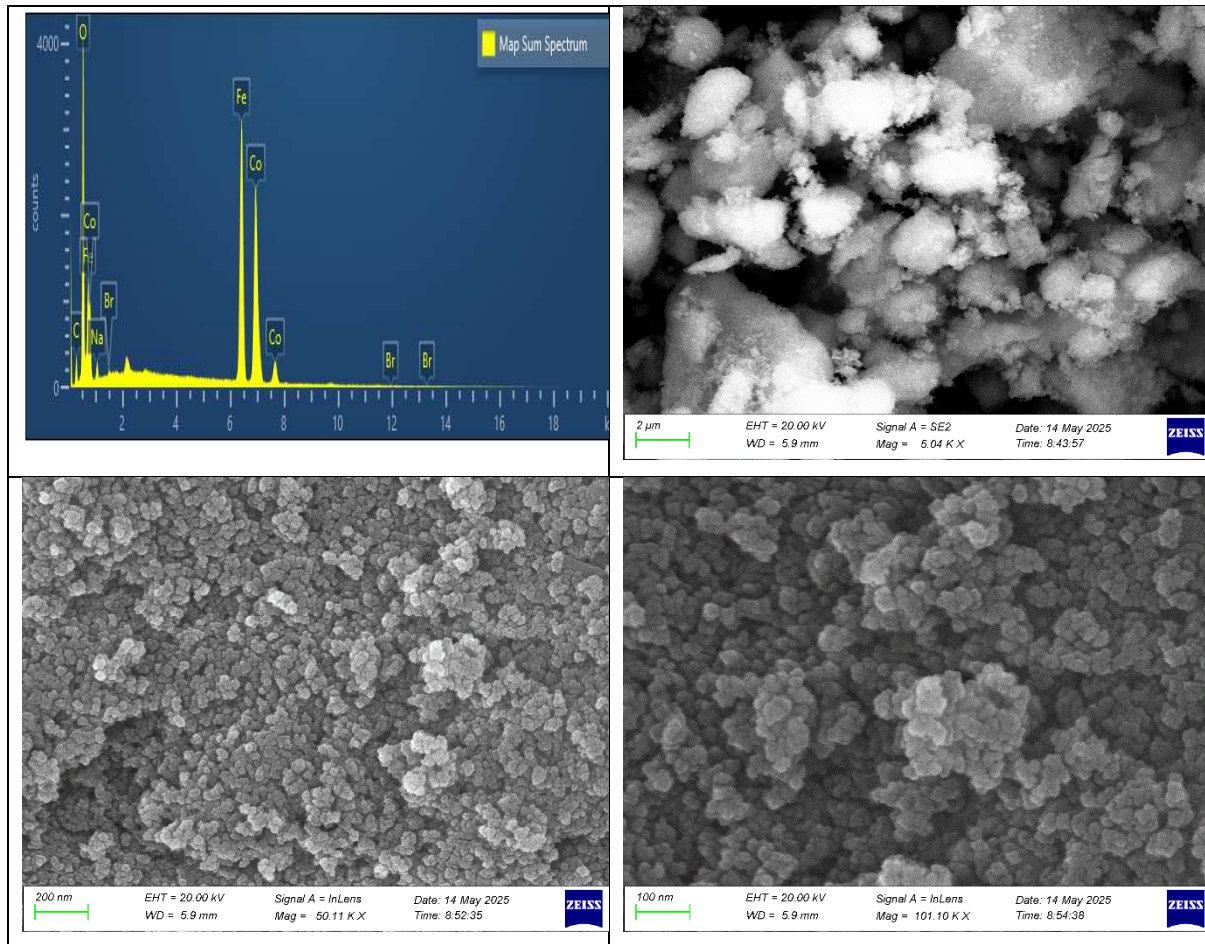


Fig. 8 FE-SEM with EDX of CoFe_3O_4

3.6 Raw Intensity Profiles and Processed Differential Signals

Figure 9 displays the processed differential signals and raw intensity profiles from the experimental samples. The intensity profiles offer important details about the distribution of particles and microstructural homogeneity in the produced material. Differences in local density and particle arrangement are indicated by variations in intensity across the examined regions. The processed differential signals improve the detection of structural boundaries and highlight minute variations in intensity patterns. Excellent reproducibility of the synthesis process is suggested by similar profile characteristics found in all three samples. The

differential curves reveal consistent particle distribution and homogeneous microstructural features throughout the sample. Localized changes in surface morphology or nanoparticle aggregation could be the cause of the profiles' slight variances. The lack of significant structural flaws or phase segregation is indicated by the absence of sudden intensity shifts. The stability and homogeneity of the produced nanoparticles are further supported by the findings. Such a homogeneous microstructure is advantageous for photocatalytic performance because it ensures efficient interaction between light, catalyst, and pollutant molecules. Consequently, the successful production of structurally consistent CoFe_3O_4 nanoparticles is supported by the intensity profile analysis [53-55].

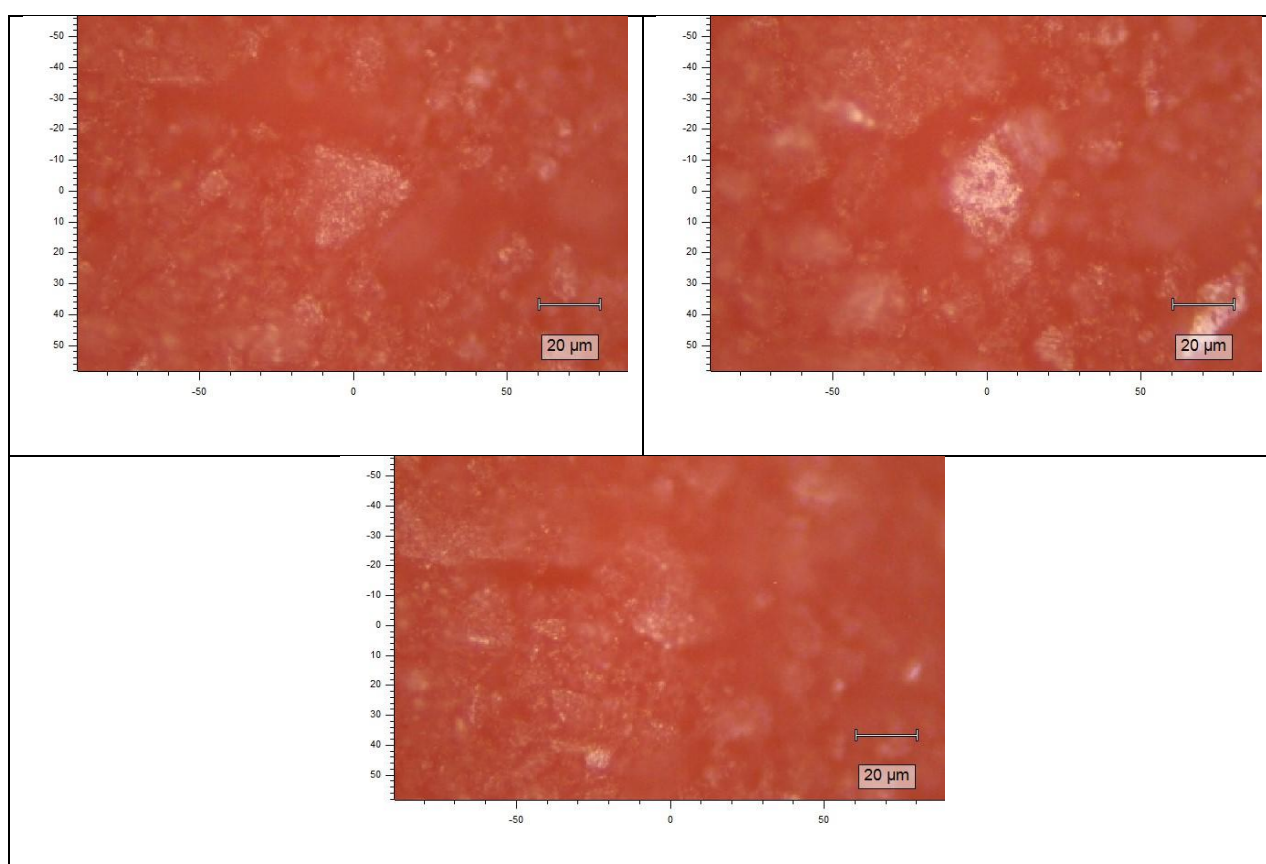


Fig. 9 Raw intensity profiles and processed differential signals from three experimental samples (a, b, c) at 50 $\times$ magnification of CoFe_3O_4

3.7 Photocatalytic Degradation Studies

The photocatalytic activity of the synthesized CoFe_3O_4 nanoparticles was evaluated under visible-light irradiation using organic dye solutions as model pollutants. As the irradiation period increases, the degradation patterns displayed in Fig. 10 reveal a notable decrease in dye concentration. The narrow band gap of CoFe_3O_4 , which facilitates effective absorption of visible light and electron–hole pair production, is responsible for the improved photocatalytic

activity. Positively charged holes are left behind when electrons are stimulated from the valence band to the conduction band by light. These charge carriers move to the surface of the catalyst and take part in oxidation-reduction processes. Superoxide radicals are produced when photogenerated electrons react with dissolved oxygen molecules, and hydroxyl radicals are produced when holes react with water molecules. The intricate organic structures of the dye molecules are attacked by these extremely reactive oxygen species. Dye adsorption, surface charge interactions, and catalyst activity are some of the variables that affect the degradation efficiency. Successful photocatalytic degradation is confirmed by the steady drop in absorbance intensity. The obtained results demonstrate the potential of CoFe_3O_4 nanoparticles as effective photocatalysts driven by visible light for wastewater treatment applications [56,57].

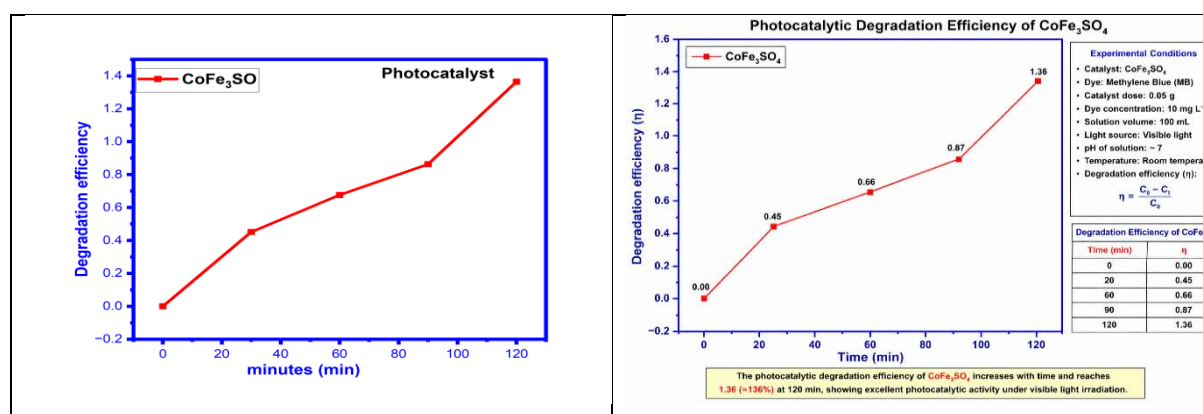


Fig. 10 Photocatalytic degradation of dye solutions: effect of charge of dye of CoFe_3O_4

The photocatalytic degradation mechanism of CoFe_3O_4 nanoparticles driven by visible light is depicted in Fig. 11. Electrons are excited from the valence band to the conduction band when exposed to visible light, creating electron-hole pairs. Superoxide radicals ($\cdot\text{O}_2^-$) are created when photogenerated electrons react with oxygen, whereas hydroxyl radicals ($\cdot\text{OH}$) are created when holes react with water or hydroxyl ions. These extremely reactive species target and break down dye molecules into innocuous byproducts like CO_2 and H_2O . The production of reactive radicals is further increased by the Fe^{3+} redox cycle, which raises the photocatalytic efficiency of CoFe_3O_4 nanoparticles.

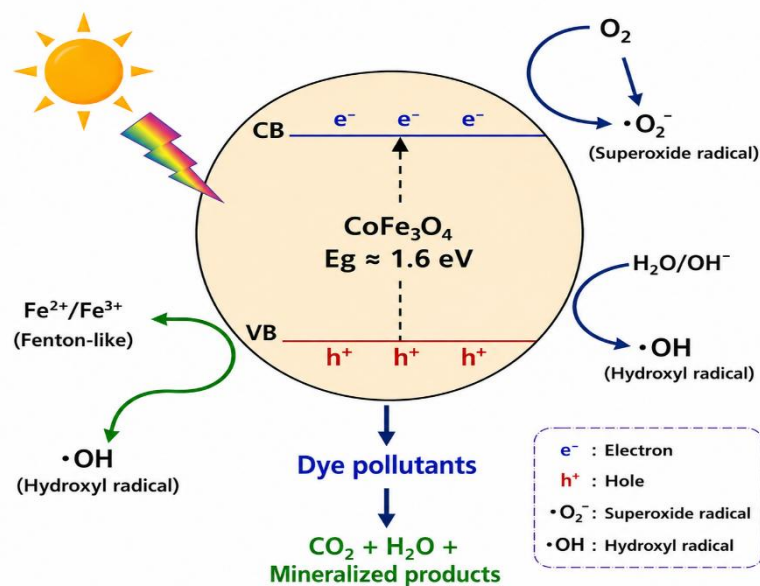


Fig. 11 Proposed visible-light-driven photocatalytic degradation mechanism of CoFe_3O_4 nanoparticles showing the generation of reactive oxygen species ($\bullet\text{OH}$ and $\bullet\text{O}_2^-$) and degradation of dye pollutants into mineralized products under visible light irradiation.

3.8 Antimicrobial and Antifungal Activity

The agar well diffusion method was used to assess the antimicrobial and antifungal properties of the produced CoFe_3O_4 nanoparticles against specific bacterial and fungal pathogens. Figure 12 displays the representative inhibition zones found for various microorganisms, and Fig. 13 displays the quantitative analysis of the zone of inhibition values. The findings show a definite concentration-dependent inhibitory effect, with the antimicrobial activity rising with increasing nanoparticle concentration. *Klebsiella pneumoniae* was the most susceptible of the tested bacterial strains; the inhibition zone increased from about 7 mm at the lowest concentration to 16 mm at the highest concentration. *Escherichia coli* also demonstrated notable growth inhibition, with a maximum concentration of about 14 mm. By contrast, the antibacterial activity of *Bacillus subtilis* and *Staphylococcus aureus* was moderate [58].

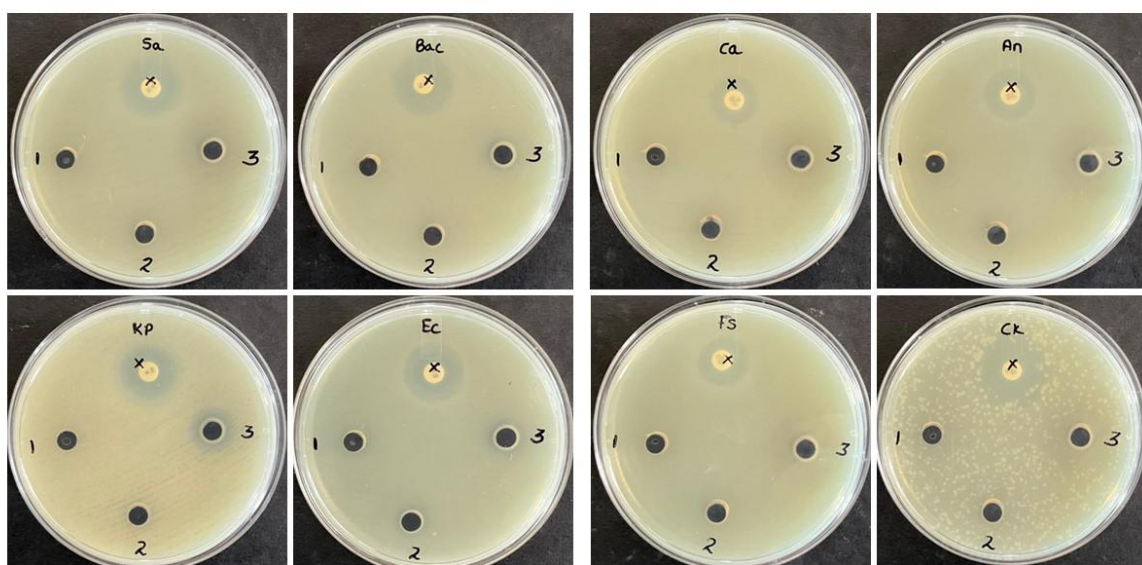


Fig. 12 Antibacterial and antifungal activities of CoFe_3O_4 nanoparticles against selected microbial strains.

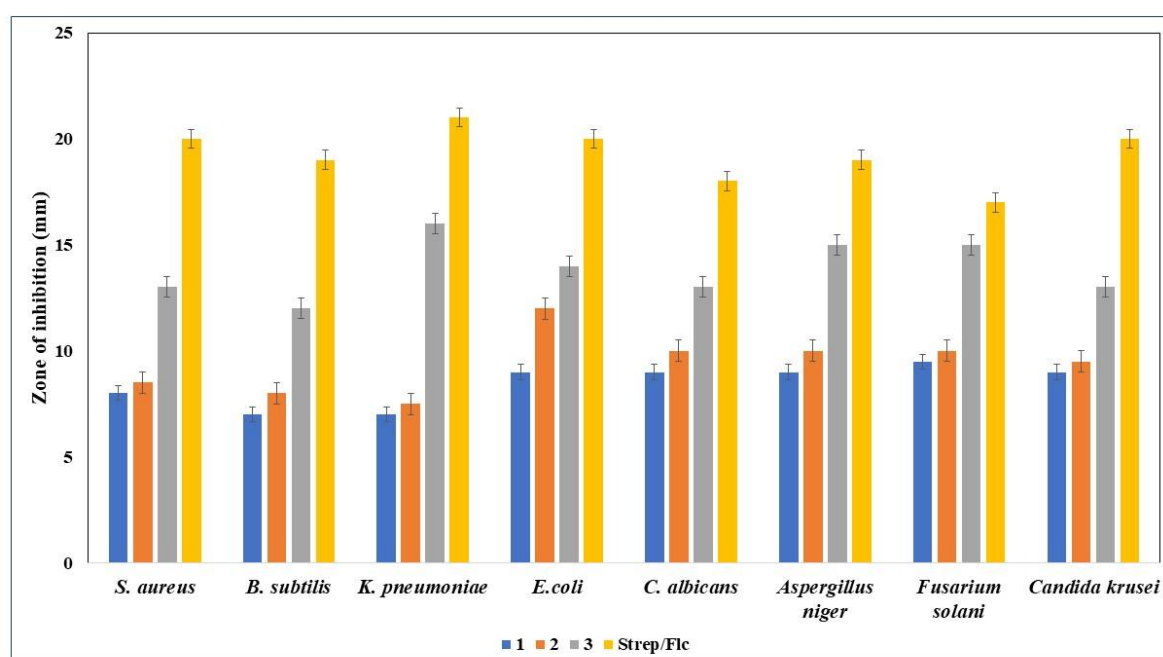


Fig. 13 Zone of inhibition of CoFe_3O_4 nanoparticles against bacterial and fungal pathogens at different concentrations.

CoFe_3O_4 nanoparticles successfully inhibited the growth of *Candida albicans*, *Aspergillus niger*, *Fusarium solani*, and *Candida krusei*, according to the antifungal activity results

displayed in Fig. 12 and compiled in Fig. 13. At the highest concentration of nanoparticles, *Aspergillus niger* and *Fusarium solani* showed the largest inhibition zones among the fungal strains, reaching about 15 mm. The large surface area and nanoscale dimensions of CoFe_3O_4 nanoparticles, which encourage robust interactions with microbial cell membranes, are responsible for the improved antimicrobial performance. Additionally, the production of reactive oxygen species (ROS), such as hydroxyl ($\bullet\text{OH}$) and superoxide ($\bullet\text{O}_2^-$) radicals, causes oxidative stress, which damages cells, disrupts membranes, and denaturates proteins. The produced CoFe_3O_4 nanoparticles showed encouraging broad-spectrum antibacterial and antifungal activity, despite the standard medications (Streptomycin for bacteria and Fluconazole for fungi) showing larger inhibition zones (17–21 mm), as seen in Fig. 13. These results validate CoFe_3O_4 nanoparticles' potential as potent antimicrobial agents for use in biomedical, environmental, and antimicrobial coating applications [59-61].

4. Conclusion

In this study, a straightforward and economical co-precipitation method was used to successfully synthesize CoFe_3O_4 nanoparticles, which were then thoroughly characterized using UV–visible spectroscopy, Raman spectroscopy, X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), FE-SEM, and EDS analyses. Phase-pure spinel CoFe_3O_4 nanoparticles with good crystallinity, homogeneous elemental distribution, and nearly spherical morphology were confirmed by the characterization results. A narrow optical band gap of 1.55 eV was found by UV-Vis analysis, suggesting strong absorption of visible light and suitability for photocatalytic applications. The production of reactive oxygen species and improved charge separation were responsible for the produced nanoparticles' effective visible light-driven photocatalytic activity. Additionally, against a variety of pathogenic microorganisms, CoFe_3O_4 nanoparticles showed strong antibacterial and antifungal activities; the inhibitory effect increased with nanoparticle concentration. The combined antimicrobial and photocatalytic properties demonstrate the multifunctionality of CoFe_3O_4 nanoparticles. All things considered, the current study shows that CoFe_3O_4 nanoparticles are viable options for wastewater treatment, environmental remediation, antimicrobial coatings, and other environmentally friendly technological applications.

Funding Declaration

No funding was received for this research work.

Credit Authorship Contribution Statement

G. Anburaj conducted all experiments and analysed the data. C. Vignesh wrote the manuscript. M. Surendra Varma, S. Sathish Kumar and K. Vinoth performed the data analysis and interpretation. D. Chinnaraja and R. Sathish Kumar supervised the experiments and provided technical guidance, T. Durgadevi and M. Mahadevi revised the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability

Data will be made available upon request.

References

1. Bankar, V.H., Goswami, A.K., Jolhe, P.D. et al. Facile synthesis of hierarchical CuO flowers with superior photocatalytic activity and supercapacitor performance. *J Mater Sci: Mater Electron* 35, 2096 (2024). <https://doi.org/10.1007/s10854-024-13860-2>
2. Aldama-huerta, Omar Arturo, Nahum A Medellín-castillo, Francisco Carrasco Marín, and Simón Yobanny Reyes-lópez. 2025. "Photocatalytic Degradation of Methyl Orange , Eriochrome Black T , and Methylene Blue by Silica – Titania Fibers." : 1–17.
3. Alice, Maria, Prado Cechinel, Pedro Monteiro, Edgar Andr, Chavarriaga Miranda, Sarah Eller, Tiago Franco De Oliveira, et al. 2023. "Cobalt Ferrite (CoFe_2O_4) Spinel as a New Efficient Magnetic Heterogeneous Fenton-like Catalyst for Wastewater Treatment."
4. Kirusarani, N., Krishnasamy, K. Green synthesis of rGO/Ag₂WO₄ nanocomposite using *Phyllanthus amarus* leaf extract for enhanced antimicrobial and photocatalytic dye degradation applications. *J Mater Sci: Mater Electron* 36, 227 (2025). <https://doi.org/10.1007/s10854-025-14280-6>
5. Arvind, Satish, Ashwini Ashok, Thansing Bhavsing, Sonu Jagdale, Arun Vitthal, and Prashant Bhimrao. 2022. "Results in Chemistry The Augmentation of Nanotechnology Era : A Concise Review on Fundamental Concepts of Nanotechnology and Applications in Material Science and Technology." *Results in Chemistry* 4(November): 100633. doi:10.1016/j.rechem.2022.100633.
6. Bajpai, Om Prakash, Subrata Mandal, Rajakumar Ananthakrishnan, Pijush Mandal, Dipak Khastgir, and Santanu Chattopadhyay. 2018. "Structural Features {,} Magnetic

- Properties and Photocatalytic Activity of Bismuth Ferrite Nanoparticles Grafted on Graphene Nanosheets.” *New J. Chem.* 42(13): 10712–23. doi:10.1039/C8NJ02030B.
7. Balarabe, Bachir Yaou, Primerose Bomokayi, Irédon Adjama, and Abdoukadi Ayoubu. 2024. “Unlocking the Magnetic Potential of - Fe₂O₃ Nanoparticles by Single - Step Synthesis of Cobalt - Infused Nanomaterials for Chromium Removal.” *Nanotechnology for Environmental Engineering* 9(2): 239–53. doi:10.1007/s41204-024-00366-9.
 8. Bekele, Tigabu, and Getachew Alamnie. 2025. “The Photocatalytic Degradation of Organic Pollutants-a Comprehensive Overview.” *Results in Chemistry* 18: 102758. doi:https://doi.org/10.1016/j.rechem.2025.102758.
 9. Caliskan, S, M A Almessiere, A Baykal, and Y Slimani. 2023. “A First Principles Study on Electronic Structure, Magnetic and Optical Characteristics of Se Doped CoNiFe₂O₄ Spinel Ferrites.” *Computational Materials Science* 226: 112243. doi:https://doi.org/10.1016/j.commatsci.2023.112243.
 10. Chen, Kailun, Wenkui Dong, Yuhan Huang, Fazhou Wang, John L Zhou, and Wengui Li. 2025. “Journal of Environmental Chemical Engineering Photocatalysis for Sustainable Energy and Environmental Protection in Construction: A Review on Surface Engineering and Emerging Synthesis.” *Journal of Environmental Chemical Engineering* 13(5): 117529. doi:10.1016/j.jece.2025.117529.
 11. Chinmay, Simranjeet Singh, Yogita, Mohd Jamshaiya Raza, Rajni, Vishaka Chauhan, Anjaneyulu Bendi, and Ravi Tomar. 2026. “Exploring the Potential of Cobalt Ferrite and Its Nanocomposites in Photocatalytic Wastewater Treatment.” *Coordination Chemistry Reviews* 550: 217440. doi:https://doi.org/10.1016/j.ccr.2025.217440.
 12. D, Chinna Venkata Subbaiah, S Dastagiri, G Pakardin, Prasad Kongi, P Ameena, and Lakshmaiah Mv. 2025. “Next Nanotechnology.” *Next Nanotechnology* 8(August): 100304. doi:10.1016/j.nxnano.2025.100304.
 13. Angamuthu, N., Packiaraj, S., Kousalya, L. et al. Influence of annealing temperature on the structural, optical and photocatalytic properties of hydrothermally synthesized Co₃O₄ nanoparticles. *J Mater Sci: Mater Electron* 37, 827 (2026). https://doi.org/10.1007/s10854-026-17223-x
 14. Deivasigamani, Prabu, Vasu Gajendiran, B Chitra, P Senthil Kumar, Rathna Chellappa, and Gayathri Rangasamy. 2025. “Results in Chemistry Magnetic Nanoparticles : Synthesis , Characterization and Application Based on Environmental Perspective.” *Results in Chemistry* 14(January): 102023. doi:10.1016/j.rechem.2025.102023.

15. Farooq, Sajid, Muhammad Habib, Olavo Cardozo, Kaleem Ullah, and A K Pandey. 2025. "Exploring the Impact of Particle Stability , Size , and Morphology on Nanofluid Thermal Conductivity : A Comprehensive Review for Energy Applications." *Advances in Colloid and Interface Science* 341(March): 103495. doi:10.1016/j.cis.2025.103495.
16. Gupta, Jagriti, P A Hassan, and K C Barick. 2022. "12 - Defects in Nanomaterials for Visible Light Photocatalysis." In *Nanostructured Materials for Visible Light Photocatalysis*, Micro and Nano Technologies, eds. Arpan Kumar Nayak and Niroj Kumar Sahu. Elsevier, 319–50. doi:https://doi.org/10.1016/B978-0-12-823018-3.00002-6.
17. Jadhav, K M, Prashant B Kharat, Sandeep B Somvanshi, Jitendra S Kounsalye, S Suraj, Pankaj P Khirade, and K M Jadhav. 2018. "Temperature Dependent Viscosity of Cobalt Ferrite / Ethylene Glycol Ferrofluids." 050044: 1–5. doi:10.1063/1.5028675.
18. Jagadeesha Angadi, V, A T Kozakov, A V Nicolski, Y V Rusalev, Inas A Ahmed, S P Kubrin, and Shifa Wang. 2023. "Tuning the Magnetic Behavior of Sr²⁺ Doped Cobalt Nickle Ferrite Useful for Magnetic Storage Applications." *Inorganic Chemistry Communications* 158: 111583. doi:https://doi.org/10.1016/j.inoche.2023.111583.
19. Jasrotia, Rohit, Aman Grover, Anand Somvanshi, Shadma Wahab, Mohammad Ali, Abdullah Almoyad, Gaurav Katoch, and Radheshyam Rai. 2026. "Advances in Magnesium Spinel Ferrites for Photocatalytic Degradation of Methylene Blue : Challenges and Future Prospectives." *Journal of Magnesium and Alloys* 15: 101935. doi:10.1016/j.jma.2025.10.021.
20. Kale, Swati B, Sandeep B Somvanshi, M N Sarnaik, S D More, and K M Jadhav. 2018. "Drug Delivery Application Enhancement in Surface Area and Magnetization of CoFe₂ O₄ Nanoparticles for Targeted Drug Delivery Application." 030193. doi:10.1063/1.5032528.
21. Kato, Shoma, and Yasuki Kansha. 2024. "Comprehensive Review of Industrial Wastewater Treatment Techniques." *Environmental science and pollution research international* 31(39): 51064–97. doi:10.1007/s11356-024-34584-0.
22. Krishna, D Nanda Gopala, and John Philip. 2022. "Applied Surface Science Advances Review on Surface-Characterization Applications of X-Ray Photoelectron Spectroscopy (XPS): Recent Developments and Challenges." 12(November).
23. Liu, Suwen, Zhiliang Xiu, Jian'an Liu, Fengxiu Xu, Weina Yu, Jie Pan, Xiaopeng Cui, and Jiaoxian Yu. 2007. "Combustion Synthesis and Photoluminescence of Perovskite PbTiO₃ Nanopowders." *Journal of Alloys and Compounds* 441(1): L7–9.

doi:<https://doi.org/10.1016/j.jallcom.2006.09.100>.

24. McDougall, Alexandra, Zahra Abedi, and Douglas G Ivey. 2022. "Tri- and Tetra-Metallic Oxides Anchored to Nitrogen-Doped Carbon Nanotubes as Bifunctional Electrocatalysts for Rechargeable Zinc-Air Batteries." *Journal of Applied Electrochemistry* 52(3): 437–59. doi:10.1007/s10800-021-01643-0.
25. Monisha, P, and S S Gomathi. 2024. "Tailoring Structural, Optical, and Magnetic Properties of Y³⁺ Doped CoFe₂O₄ Nanoparticles to Enhance Photocatalytic Activity." *Ceramics International* 50(7, Part A): 10079–97. doi:<https://doi.org/10.1016/j.ceramint.2023.12.318>.
26. Nanoparticles, Nanogold-coated Fe₃O₄ Magnetic, K Magdalena, Anna Drabczyk, Mateusz Jamro, Sonia Kudłacik-kramarczyk, Piotr Potemski, and Magdalena Gł. 2022. "The Synthesis Methodology and Characterization of Nanogold-Coated Fe₃O₄ Magnetic Nanoparticles."
27. Nedelkovski, Vladan. 2025. "Advances in Photocatalytic Degradation of Crystal Violet Using ZnO-Based Nanomaterials and Optimization Possibilities : A Review." : 1–41.
28. Nguyen, Thi, and Anh Nguyen. 2023. "Structural, Optical and Magnetic Properties of Y-Doped CoFe₂O₄ Nanoparticles Prepared by a Simple Co-Precipitation Method." *Journal of Materials Science: Materials in Electronics* 34. doi:10.1007/s10854-023-09914-6.
29. Ozaki, Yukihiro, and Hidetoshi Sato. 2025. "Kosuke Hashimoto, Fatima Matroodi, Soh Morimatsu, Barbara Rossi, * Yusuke Morisawa, Yukihiro Ozaki, and Hidetoshi Sato *." doi:10.1021/acs.jpcllett.4c03435.
30. Park, Jea-gun, Edi Suharyadi, Nurul Imani Istiqomah, Lismawenning Puspitarum, Budi Purnama, and Dede Djuhana. 2022. "Reusability of Photocatalytic CoFe₂O₄ @ ZnO Core – Shell Nanoparticles for Dye Degradation Reusability of Photocatalytic CoFe₂O₄ @ ZnO Core – Shell Nanoparticles for Dye Degradation." doi:10.1149/2162-8777/ac4c7c.
31. Pavel, Monica. 2023. "Photocatalytic Degradation of Organic and Inorganic Pollutants to Harmless End Products : Assessment of Practical Application Potential for Water and Air Cleaning."
32. Prabavathi, N, S Stella Mary, and S Dhanavel. 2026. "Enhanced Photocatalytic and Antimicrobial Activities of Biogenic Mn, Cu Co-Doped ZnO Nanoparticles for Environmental Remediation." *Inorganic Chemistry Communications* 187: 116398. doi:<https://doi.org/10.1016/j.inoche.2026.116398>.

33. Rekaby, M, M Ahmed, R Awad, and M Y El Sayed. 2026. "Tailoring the Microstructure , Optical , and Magnetic Doping." 4: 1–27.
34. Sivaraman, Chandhinipriya, Shankar Vijayalakshmi, Estelle Leonard, Suresh Sagadevan, and Ranjitha Jambulingam. 2022. "Current Developments in the Effective Removal of Environmental Pollutants through Photocatalytic Degradation Using Nanomaterials."
35. Sukoviene, Agne, Saqib Ali, Arunas Jagminas, and Simonas Ramanavicius. 2025. "Magnetic Cobalt and Other Types of Ferrite Nanoparticles : Synthesis Aspects and Novel Strategies for Application in Wastewater Treatment (Review)."
36. Sundar, L Syam, and Hiren K Mewada. 2023. "Experimental Entropy Generation, Exergy Efficiency and Thermal Performance Factor of CoFe₂O₄/Water Nanofluids in a Tube Predicted with ANFIS and MLP Models." *International Journal of Thermal Sciences* 190: 108328. doi:<https://doi.org/10.1016/j.ijthermalsci.2023.108328>.
37. Tkaczyk, Angelika, Kamila Mitrowska, and Andrzej Posyniak. 2020. "Synthetic Organic Dyes as Contaminants of the Aquatic Environment and Their Implications for Ecosystems: A Review." *Science of The Total Environment* 717: 137222. doi:<https://doi.org/10.1016/j.scitotenv.2020.137222>.
38. Ji, S., Zhang, S., Qi, C. et al. Construction and performance of a novel perylene diimide/AgI S-scheme heterojunction photocatalyst for various pollutants degradation. *J Mater Sci: Mater Electron* 36, 744 (2025). <https://doi.org/10.1007/s10854-025-14833-9>
39. Yousefi, Sarasadat, and Abbas Sadeghzadeh-Attar. 2024. "Coupling Effect of Fe-Doped Co₃O₄ Nanoparticles with SrTiO₃ Nanotubes on the High-Efficiency Photocatalytic Activities of Basic Violet 16 Dye Degradation and H₂ Evolution." *Inorganic Chemistry Communications* 162: 112273. doi:<https://doi.org/10.1016/j.inoche.2024.112273>.
40. Abdi, Parviz, Kobra Verdijkazemi, Arezoo Nejaei, and Afshin Takdastan. 2025. "Optimization of Ultrasound-Electrocatalytic Process for Improving the Quality of Biological Treatment Effluent." *Scientific reports* 15(1): 18149. doi:10.1038/s41598-025-00470-z.
41. Acimbhu, Areeya, Jamaree Amonkosolpan, Wichuda Boonyaratgalin, and Nopmanee Supanam. 2025. "Photocatalytic Degradation of Organic Pollutants under Solar Irradiation Using Single-Walled Carbon Nanotube / Titanium Dioxide Nanocomposites." 20(October).
42. Alahmadi, Nadiyah. 2022. "Recent Progress in Photocatalytic Removal of

Environmental Pollution Hazards in Water Using Nanostructured Materials.”

43. Bekele, Tigabu, and Getachew Alamnie. 2025. “The Photocatalytic Degradation of Organic Pollutants-a Comprehensive Overview.” *Results in Chemistry* 18: 102758. doi:<https://doi.org/10.1016/j.rechem.2025.102758>.
44. Chandra, Suresh, P Maneesha, Sayak Datta, Kailash Dukiya, Dilip Sasmal, Koyal Suman, B R Vaishnavi, Arup Dasgupta, and Somaditya Sen. 2024. “Enhanced Photocatalytic Degradation of Organic Pollutants in Water Using Copper Oxide (CuO) Nanosheets for Environmental Application.” *JCIS Open* 13(September 2023): 100102. doi:[10.1016/j.jciso.2024.100102](https://doi.org/10.1016/j.jciso.2024.100102).
45. He, Yingge, Yuyan Huang, Yu-Xin Ye, Yanchun Deng, Xin Yang, and Gangfeng Ouyang. 2025. “Initiating Photocatalytic Degradation of Organic Pollutants under Ultra-Low Light Intensity via Oxygen-Centered Organic Radicals.” *Chemical science* 16(9): 3964–77. doi:[10.1039/d4sc06339b](https://doi.org/10.1039/d4sc06339b).
46. Lavorato, Cristina, Angela Severino, Pietro Argurio, Raffaele Molinari, Beatrice Russo, Alberto Figoli, and Teresa Poerio. 2025. “Photocatalytic Mineralization of Emerging Organic Contaminants Using Real and Simulated Effluents in Batch and Membrane Photoreactors.” : 1–20.
47. Li, Xueqi, Hongyan Wei, Tiehong Song, Hai Lu, and Xiaoyan Wang. 2023. “A Review of the Photocatalytic Degradation of Organic Pollutants in Water by Modified TiO(2).” *Water science and technology : a journal of the International Association on Water Pollution Research* 88(6): 1495–1507. doi:[10.2166/wst.2023.288](https://doi.org/10.2166/wst.2023.288).
48. Nie, Yu-Chun, Fan Yu, Lai-Chun Wang, Qiu-Ju Xing, Xia Liu, Yong Pei, Jian-Ping Zou, et al. 2018. “Photocatalytic Degradation of Organic Pollutants Coupled with Simultaneous Photocatalytic H₂ Evolution over Graphene Quantum Dots/Mn-N-TiO₂/g-C₃N₄ Composite Catalysts: Performance and Mechanism.” *Applied Catalysis B: Environmental* 227: 312–21. doi:<https://doi.org/10.1016/j.apcatb.2018.01.033>.
49. Onoriode-Afunzie, Maria-Anthoniette Oghenetjiro, Povilas Urbanskis, Inga Urniežaitė, and Agnė Šulčiūtė. 2025. “Optimized TiO(2) Coatings on AISI 316 Steel for Advanced Photocatalytic Wastewater Treatment: Mechanism and Performance.” *ACS omega* 10(31): 34666–82. doi:[10.1021/acsomega.5c03565](https://doi.org/10.1021/acsomega.5c03565).
50. Paul, Ruhit Kumar. 2025. “Advanced Photocatalytic Degradation of POPs and Other Contaminants : A Comprehensive Review on Nanocomposites and Heterojunctions.” : 31313–59. doi:[10.1039/d5ra04336k](https://doi.org/10.1039/d5ra04336k).
51. Piriälä, Minna, Mohammed Saouabe, Satu Ojala, Buddhika Rathnayake, Fabien Drault,

- Anna Valtanen, Mika Huuhtanen, Rachid Brahmi, and Riitta L Keiski. 2015. "Photocatalytic Degradation of Organic Pollutants in Wastewater." *Topics in Catalysis* 58(14): 1085–99. doi:10.1007/s11244-015-0477-7.
52. Rani, Manviri, Keshu, and Uma Shanker. 2021. "Sunlight-Induced Photocatalytic Degradation of Organic Pollutants by Biosynthesized Hetrometallic Oxides Nanoparticles." *Environmental Science and Pollution Research* 28(43): 61760–80. doi:10.1007/s11356-021-15003-0.
 53. Remediation, Environmental, Nahal Goodarzi, Zahra Ashrafi-peyman, Elahe Khani, and Alireza Z Moshfegh. 2023. "Recent Progress on Semiconductor Heterogeneous Photocatalysts in Clean Energy Production And."
 54. Rostami, Mojtaba, Alireza Badiei, Mohammad Reza Ganjali, Mehdi Rahimi-Nasrabadi, Mastoureh Naddafi, and Hassan Karimi-Maleh. 2022. "Nano-Architectural Design of TiO(2) for High Performance Photocatalytic Degradation of Organic Pollutant: A Review." *Environmental research* 212(Pt D): 113347. doi:10.1016/j.envres.2022.113347.
 55. Sadiq, Alia. 2014. "Qualitative and Quantitative Determination of Secondary Metabolites and Antioxidant Potential of Eruca Sativa." *Natural Products Chemistry & Research* 2(4). doi:10.4172/2329-6836.1000137.
 56. Sahu, Raj Kumar. 2023. "Photocatalytic Degradation of Organic Pollutants : Mechanisms and Material Innovations." 10(1).
 57. Sak, Gamze. 2026. "Organic Pollutant Degradation Through Photocatalysis : Progress , Challenges , and Sustainable Solutions (Mini Review)."
 58. Schwarze, Michael, Steffen Borchardt, Marvin L Frisch, Jason Collis, Carsten Walter, Prashanth W Menezes, Peter Strasser, Matthias Driess, and Minoo Tasbihi. 2023. "Degradation of Phenol via an Advanced Oxidation Process (AOP) with Immobilized Commercial Titanium Dioxide (TiO(2)) Photocatalysts." *Nanomaterials (Basel, Switzerland)* 13(7). doi:10.3390/nano13071249.
 59. Mohan, N.S., Arulraj, A., Mangalaraja, R.V. et al. A facile one-pot synthesis of highly efficient ZnO nanoparticles with enhanced photocatalytic and antibacterial performance. *J Mater Sci: Mater Electron* 35, 2126 (2024). <https://doi.org/10.1007/s10854-024-13825-5>
 60. Sinha, Rupal, and Partha Sarathi Ghosal. 2023. "A Comprehensive Appraisal on Status and Management of Remediation of DBPs by TiO(2) Based-Photocatalysts: Insights of Technology, Performance and Energy Efficiency." *Journal of environmental*

management 328: 117011. doi:10.1016/j.jenvman.2022.117011.

61. Wang, Xueqin, Siow Hwa Teo, Mohd Razali Shamsuddin, and Newati Wid. 2024. "Photocatalytic Degradation of Organic Pollutants and Microplastics Using Ag/TiO₂: Recent Advances in Mechanism, Synthesis and Properties." *Water, Air, & Soil Pollution* 236(1): 30. doi:10.1007/s11270-024-07669-2.