


 Cite this: *RSC Adv.*, 2024, 14, 24874

Fabrication of a highly efficient CuO/ZnCo₂O₄/CNTs ternary composite for photocatalytic degradation of hazardous pollutants

 Norah Alomayrah,^a Mustabshira Ikram,^b Sonia Zulfiqar,^{cde} Sultan Alomairy,^f Mohammed Sultan Al-Buriahi,^g Imran Shakir,^h Muhammad Farooq Warsi^{ib}*^b and Eric W. Cochran^{ib}*^d

In the current study, CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs photocatalysts were prepared to remove crystal violet (CV) and colorless pollutants (diclofenac sodium and phenol) from wastewater. Herein, sol-gel and co-precipitation methods were used to synthesize CuO and ZnCo₂O₄, respectively. The sonication method was used to synthesize CuO/ZnCo₂O₄ and a CNTs-based composite (CuO/ZnCo₂O₄/CNTs). From the UV-Vis spectra of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs, the optical band gap value was calculated to be 2.11, 2.18, 1.71 and 1.63 eV respectively. The photocatalytic results revealed that CuO/ZnCo₂O₄/CNTs exhibited higher degradation of 87.7% against CV dye, 82% against diclofenac sodium, and 72% against phenol as compared to other prepared photocatalysts. The OH[•] radical is identified as the active species in the photocatalytic process over CuO/ZnCo₂O₄/CNTs. The impact of several parameters, such as pH, concentration, and catalyst dosage, has also been investigated. The better activity of the CNTs-based composite was due to the synergic effect of both CuO/ZnCo₂O₄ nanocomposite and carbon nanotubes. Therefore, the synthesized CuO/ZnCo₂O₄/CNTs photocatalyst has the potential to degrade organic wastewater effluents effectively.

 Received 15th June 2024
 Accepted 25th July 2024

DOI: 10.1039/d4ra04395b

rsc.li/rsc-advances

1. Introduction

Water is one of the essential substances for the existence of life on the surface of the Earth.¹ The fast growth of industries has resulted in the shortage of clean water, which poses a severe threat to living organisms.^{2,3} There are numerous causes of water pollution.^{4,5} As a consequence of different industrial processes, oils, organic solvents, heavy metals, textiles, mining, dyes, and harmful pollutants are discharged into the water.^{6,7} Dyes discharged in the water from industries have a large production cycle, slow decay, low discoloration, and toxic effects on human health and marine life. Therefore, dyes have

received a lot of interest during their discharge in industrial effluents.⁸ Various conventional techniques, including flocculation, adsorption, precipitation, sedimentation, chlorination, chemical oxidation, and photocatalytic degradation, have been employed to extract the harmful pigments from the industrial effluents.^{9–12} Among all the techniques, photocatalytic degradation has attracted the most attention because of its simple operation, low energy consumption, low cost, low secondary pollution, and high efficiency.¹³ Photocatalysis is a green, cutting-edge, quick, and affordable technology that uses semi-conducting materials as photocatalysts under irradiation of light to eliminate all industrial potentially contaminates and other hazardous chemicals from water.^{14,15} These materials are more effective, have a larger surface area, flexible band gaps, and require less energy to generate photo-excited states.^{16,17} Excited electrons and produced holes serve as the main reactants in photocatalytic processes.⁹ They interact with water and molecular oxygen to form secondary active species which interact with organic dyes and decompose them into simpler molecules.¹⁸

Metal oxide nanoparticles have several interesting characteristics, such as distinct electrical structures, as well as many phases, sizes, shapes, multiple oxidation states, and catalytic pollutant removal capabilities.^{19,20} Copper oxide (CuO) is one of the significant p-type semiconductors among the transition-metal oxides and has gained a lot of attention because of its

^aDepartment of Physics, College of Science, Princess Nourah bint Abdulrahman University, P. O. Box 84428, Riyadh 11671, Saudi Arabia

^bInstitute of Chemistry, Baghdad-ul-Jadeed Campus, The Islamia University of Bahawalpur, Bahawalpur-63100, Pakistan. E-mail: farooq.warsi@iub.edu.pk

^cDepartment of Physical Sciences, Lander University, 320 Stanley Ave, Greenwood, South Carolina 29649, USA

^dDepartment of Chemical and Biological Engineering, Iowa State University, Sweeney Hall, 618 Bissell Road, Ames, Iowa 50011, USA. E-mail: ecochran@iastate.edu

^eDepartment of Chemistry, Faculty of Science, University of Ostrava, 30. Dubna 22, Ostrava, 701 03, Czech Republic

^fDepartment of Physics, College of Science, Taif University, Taif 21944, Saudi Arabia

^gDepartment of Physics, Sakarya University, Sakarya, Turkey

^hDepartment of Physics, Faculty of Science, Islamic University of Madinah, Madinah, 42351, Saudi Arabia


narrow band gap.²¹ CuO is a transition metal oxide with a wide range of uses in different industries, including batteries, photoelectrochemical water splitting, photodetectors, supercapacitors, chemical and biosensors, and photovoltaic devices.²² CuO is closely related to high-Tc superconductors and has also been widely used as a potent heterogeneous catalyst to fully convert hydrocarbons into CO₂ and H₂O. CuO nanostructures have been employed in a wide range of settings, such as magnetic storage media, chemical and gas sensors, catalysis, in antitumor therapy, as biomedicine to prevent bacterial infection, and in photocatalysis to break down organic pollutants from wastewater.²³ Harish *et al.* synthesized a ZnO/CuO nanocomposite and found that the composite showed excellent efficiency for the removal of organic effluents.²⁴ Katal *et al.* prepared CuO films for photocatalytic degradation of MB dye.²⁵ Hossain *et al.* synthesized CuO/CdS by an ultrasound-assisted-wet-impregnation method and found that the nanocomposite exhibited excellent degradation capacity by degrading 75% of MB dye.²⁶ Atta ur Rehman *et al.* synthesized binary metal doped CuO nanocatalysts. The results revealed that the doping in CuO facilitates the excitation process and significantly increases the photocatalytic activity of the material.²⁷

Mixed metal oxides that have been extensively researched have a spinel structure and have the general formula of AB₂O₄.²⁸ Examples of these oxides are CuGa₂O₄,²⁹ CuFe₂O₄,³⁰ ZnFe₂O₄,³¹ CoFe₂O₄,³² MnCo₂O₄,³³ CoMn₂O₄,³⁴ and ZnCo₂O₄.³⁵ Among these, ZnCo₂O₄ is a typical spinel material and has attracted a lot of attention owing to its exceptional electronic structural properties and potential use as an anode material and gas sensor.^{36,37} The spinel ZnCo₂O₄ is a p-type semiconductor and has garnered significant interest due to its low cost, nontoxicity, earth-abundant nature, narrow energy band (E_g), and better electron conductivity as compared to single metal oxides like ZnO, Co₃O₄.³⁸ Because of its unique energy band structure (2.0 eV), the electrons within these bands show transition more readily. This lowers the rate of photogenerated electron-hole recombination.³⁹ Recent research on ZnO and other metal oxide-based nanocomposites has shown that a greater photocatalytic activity can be achieved because of the efficient transfer of charge carriers.⁴⁰ Taufique *et al.* synthesized a CuO–ZnO nanocomposite using hydrothermal approach. The results showed that the maximum photocatalytic activity achieved in the case of CuO–ZnO nanostructure.⁴¹ Goswami *et al.* synthesized heterostructured cation-doped ZnO–ZnCo₂O₄ nanocomposites. The results demonstrate heterojunction interfaces, which aid in the separation and transfer of electron-hole pairs, causing increased photocatalytic activity.⁴² Combinations of semiconductors, such as ZnO/ZnCo₂O₄,⁴² CaFe₂O₄/ZnCo₂O₄,⁴³ and SnO₂/ZnCo₂O₄,²⁸ have also been investigated in order to improve photo-efficiency of the prepared materials. The synergistic effect of copper, zinc and cobalt, metals as CuO/ZnCo₂O₄ increased the catalytic activity of nanocomposite as compared to pristine CuO and ZnCo₂O₄. It is a facile approach to form the CuO/ZnCo₂O₄ nanocomposite because the electrical band structures of the two materials match perfectly.⁴⁴ The interaction of these semiconductors generally results in the formation of an inherent potential that enhances the photocatalytic

effectiveness of the prepared composite. Moreover, the CuO/ZnCo₂O₄ nanocomposite exhibits effective separation of photogenerated electron–holes pairs because of the synergistic effects of the metals present in the composite. Zhu *et al.* synthesized a CuO/ZnO composite and found that the composite showed better photocatalytic activity as compared to pristine CuO and ZnO.⁴⁵ Jahanshahi *et al.* found that a ZnCo₂O₄/g-C₃N₄/Cu nanocomposite showed enhanced photocatalytic performance towards the MNZ degradation.⁴⁶

One way to overcome the limitations and to further improve the photocatalytic properties of CuO/ZnCo₂O₄ is to combine it with carbonaceous nanomaterials like carbon nanotubes (CNTs),⁴⁷ reduced-graphene oxide (rGO),⁴⁸ graphene,⁴⁹ and fullerenes.⁵⁰ Carbon nanotubes (CNTs) have attracted a lot of interest in photocatalytic research because of their excellent conductivity and large surface area.⁵¹ CNTs have been used in the synthesis of composites because of their special properties, including large specific surfaces, high tensile strength, corrosion resistance, and chemical stability. In the photocatalytic process, CNTs can separate charge carriers by capturing photoinduced electrons, thus extending their lifespan and accelerating the photocatalytic efficiency of prepared material, and leading to the effective breakdown of organic pollutants.⁵² Saravanakumar *et al.* reported the synthesis of CuO/ZnO/CNTs thin films and exhibited excellent degradation of Rhodamine-B.⁵³

To the best of our knowledge, no reports exist on the synthesis of a CuO/ZnCo₂O₄ and CuO/ZnCo₂O₄/CNTs composite using the sonication route and their application in photocatalytic degradation of pollutants presented in this study. Nonetheless, in the literature, there are several studies, including the synthesis of diamond-like ZnCo₂O₄,⁵⁴ CuO,¹⁹ Cu–In–Zn–S@ZnCo₂O₄@In₂O₃,⁵⁵ Cu-doped ZnO@CNTs,⁵⁶ and ZnO/ZnCo₂O₄.⁴² Herein, we provide an efficient method for synthesizing CuO/ZnCo₂O₄/CNTs composite to improve the photocatalytic activity by lowering the electron–hole pair recombination rate. Various physicochemical methods have been used to characterize all the synthesized materials. This research provides a pathway to comprehend the strategic effect of composite in visible light photocatalysis.

2. Experimental

2.1. Chemicals

Copper nitrate hemi(pentahydrate) (Cu(NO₃)₂·2.5H₂O, 99.5%), sodium hydroxide (NaOH), cobalt chloride hexahydrate (CoCl₂·6H₂O, 98.0%), zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O, 98%), oxalic acid (C₂H₂O₄, 99.9%), ethanol (C₂H₅OH, 96%), and carbon nanotubes (CNTs) were used for the synthesis of various photocatalysts. All chemicals were obtained from Sigma-Aldrich.

2.2. Synthesis of CuO

The sol–gel method was used for the synthesis of CuO nano-leaves. Firstly, 100 mL of 0.1 M solution of copper nitrate was prepared. The prepared solution was stirred to form a blue-colored homogenous solution. 0.2 M NaOH solution was then



added drop-wise. The solution was ultrasonicated at 80 °C for 2–3 h and then cooled at room temperature for several hours. This resulted in the formation of black-colored precipitates. Washing with ethanol was done to remove the impurities. The obtained product was calcined at 400 °C for 4 h.⁵⁷

2.3. Synthesis of ZnCo₂O₄

ZnCo₂O₄ nanoparticles were synthesized by a typical coprecipitation method. The cobalt chloride and zinc nitrate salts were used as starting materials, ethanol (C₂H₅OH) as solvent, and oxalic acid (C₂H₂O₄) as complex agent. In 30 mL C₂H₅OH solution, 9 mmol C₂H₂O₄, 6 mmol CoCl₂·6H₂O, and 3 mmol Zn(NO₃)₂·6H₂O were dissolved separately. The solutions were labeled A, B, and C respectively. Solution B and C were then added to solution A and stirred uniformly for an hour. This resulted in a turbid suspension. The pale pink precipitates were collected through centrifugation. This resultant slurry was then subjected to washing with ethanol. Drying was carried out at 120 °C for 8 h. The dried product was cooled at ambient temperature. Calcination was done at 500 °C for 2 h.⁵⁸

2.4. Synthesis of CuO/ZnCo₂O₄

CuO/ZnCo₂O₄ nanocomposite was synthesized using an ultrasonication technique. 30 mL of distilled water containing 0.5 g CuO and 0.5 g of ZnCo₂O₄ were subjected to sonication for two hours. Next, the product was dried in an oven for 5 h.

2.5. Synthesis of CuO/ZnCo₂O₄/CNTs composite

Fig. 1 shows the synthesis of CuO/ZnCo₂O₄/CNTs using a sonication technique, 0.4 g of CuO and 0.4 g of ZnCo₂O₄ were dissolved in 20 mL of CNTs suspension. The mixture was subjected to sonication for 1 h and then dried at 80 °C for 5 h. The dried product was ground and used for the photocatalytic experiments.

2.6. Characterization

The crystal structure and purity of the prepared samples were examined using a Bruker D8 Advance powder diffractometer. Morphological analysis and energy dispersive X-ray (EDX) were recorded using Hitachi SU4800 field emission scanning electron microscope (FESEM). XPS measurements were performed on a Kratos Analytical-Amicus. Photocatalytic measurements were performed using a dual-beam spectrophotometer (Cary-60).

2.7. Photocatalytic activity

The degradation of diclofenac sodium (drug), phenol and CV dye (pollutant) was carried out to assess the photocatalytic performance of the fabricated samples. The photocatalytic experiment was carried out using a 200 watt tungsten bulb. 7 ppm CV solution was prepared in a 1000 mL beaker. The pH of the prepared solution was kept at 6. Four beakers containing 70 mL of CV solution and 30 mg of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs were prepared respectively. The adsorption and desorption of photocatalysts and dye were

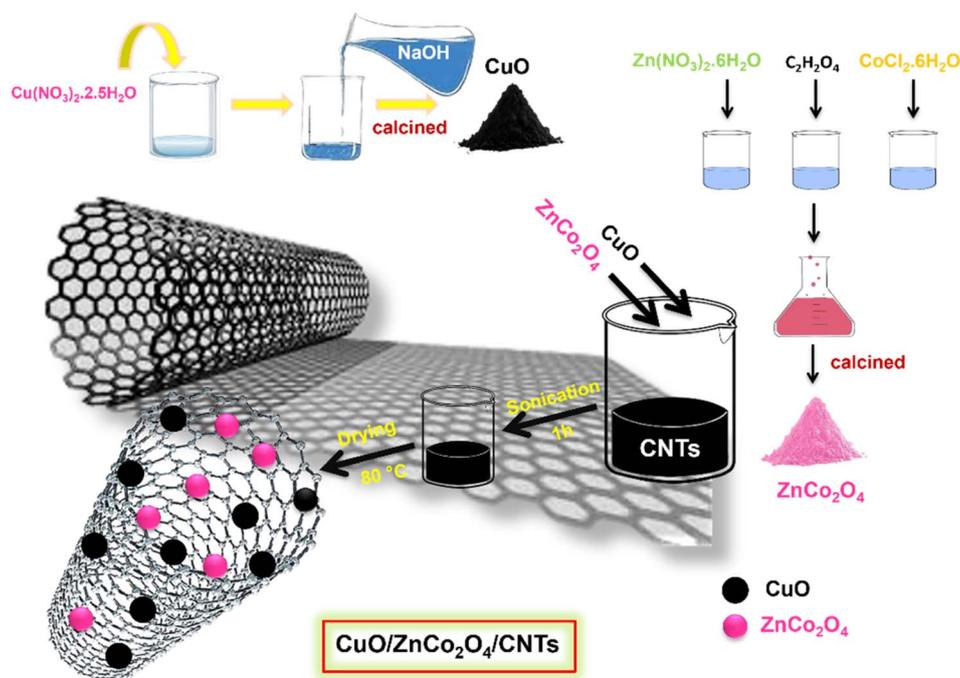


Fig. 1 Synthetic protocol for the preparation of CuO/ZnCo₂O₄/CNTs composite.



carried out by placing these beakers in the dark for about 30 min. Following the dark reaction, 4 mL of the homogenous mixture was taken out of each beaker. An Agilent Cary-60 UV spectrophotometer was used to measure the UV light absorption of the solutions after the reaction mixture was centrifuged in order to settle down the suspended photocatalyst. The solution was put under a 200 watt tungsten bulb irradiation for the subsequent experiment. After every 10 min, 4 mL of sample solutions were taken out, centrifuged and their absorbance was recorded. The procedure continued for 90 min. The diclofenac sodium and phenol photodegradation process followed the same procedure. The following eqn (1) was utilized to calculate the percentage degradation, in which A_0 represents the absorbance at zero minutes. A_t shows absorbance at various periods of time;

$$\text{Degradation (\%)} = 1 - \frac{A_t}{A_0} \times 100 \quad (1)$$

3. Results and discussion

3.1. X-ray diffraction (XRD) analysis

XRD analysis was used to assess the crystallinity and crystal phases of the synthesized materials.⁵⁹ Fig. 2 shows the diffraction pattern of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/

Table 1 Structural parameters of CuO and ZnCo₂O₄

Sample	CuO	ZnCo ₂ O ₄
Crystal system	Monoclinic	Cubic
Lattice constant a (Å)	4.747	8.299
Lattice constant b (Å)	3.320	—
Lattice constant c (Å)	5.094	—
Cell volume V (Å ³)	78.67	571.58
Space group	$C2/c$	$Fd3m$

ZnCo₂O₄/CNTs. Fig. 2(a) shows the XRD pattern of CuO. All of the diffraction peaks are assigned to the CuO monoclinic phase (lattice constants $a = 4.74722$ Å, $b = 3.320797$ Å, and $c = 5.094737$ Å), which matches well with JCPDS Card No. 048-1548.⁶⁰ The diffraction peaks at 2θ values of 32.5°, 35.4°, 38.7°, 48.7°, 53.4°, 58.2°, 61.5°, 66.2°, 68.1°, 72.3°, and 75.2° correspond to (110), (002), (111), (202), (020), (202), and (113), (311), (220), (311), and (222) hkl planes. In Fig. 2(b), XRD data shows the diffraction planes of ZnCo₂O₄. The cubic phase of ZnCo₂O₄ is responsible for all the diffraction peaks. The diffraction peaks at 2θ values of 31.2°, 36.8°, 38.4°, 44.7°, 48.9°, 55.5°, 59.2°, 65.1°, and 77.2° correspond to (220), (311), (222), (400), (331), (422), (511), (440), and (553) hkl planes. These peaks are matched well with JCPDS 023-1390.⁶¹ There are some extra peaks and these remaining peaks exhibited the presence of

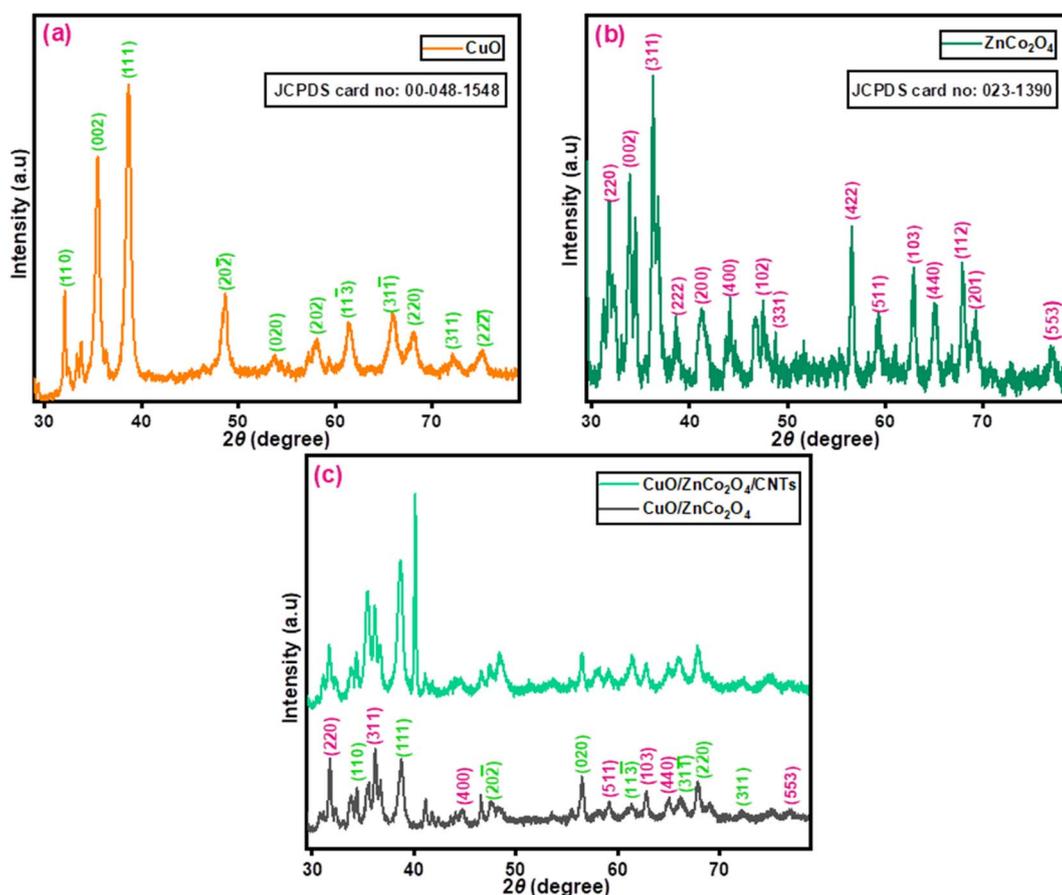


Fig. 2 XRD patterns of (a) CuO (b) ZnCo₂O₄ (c) CuO/ZnCo₂O₄ and CuO/ZnCo₂O₄/CNTs.



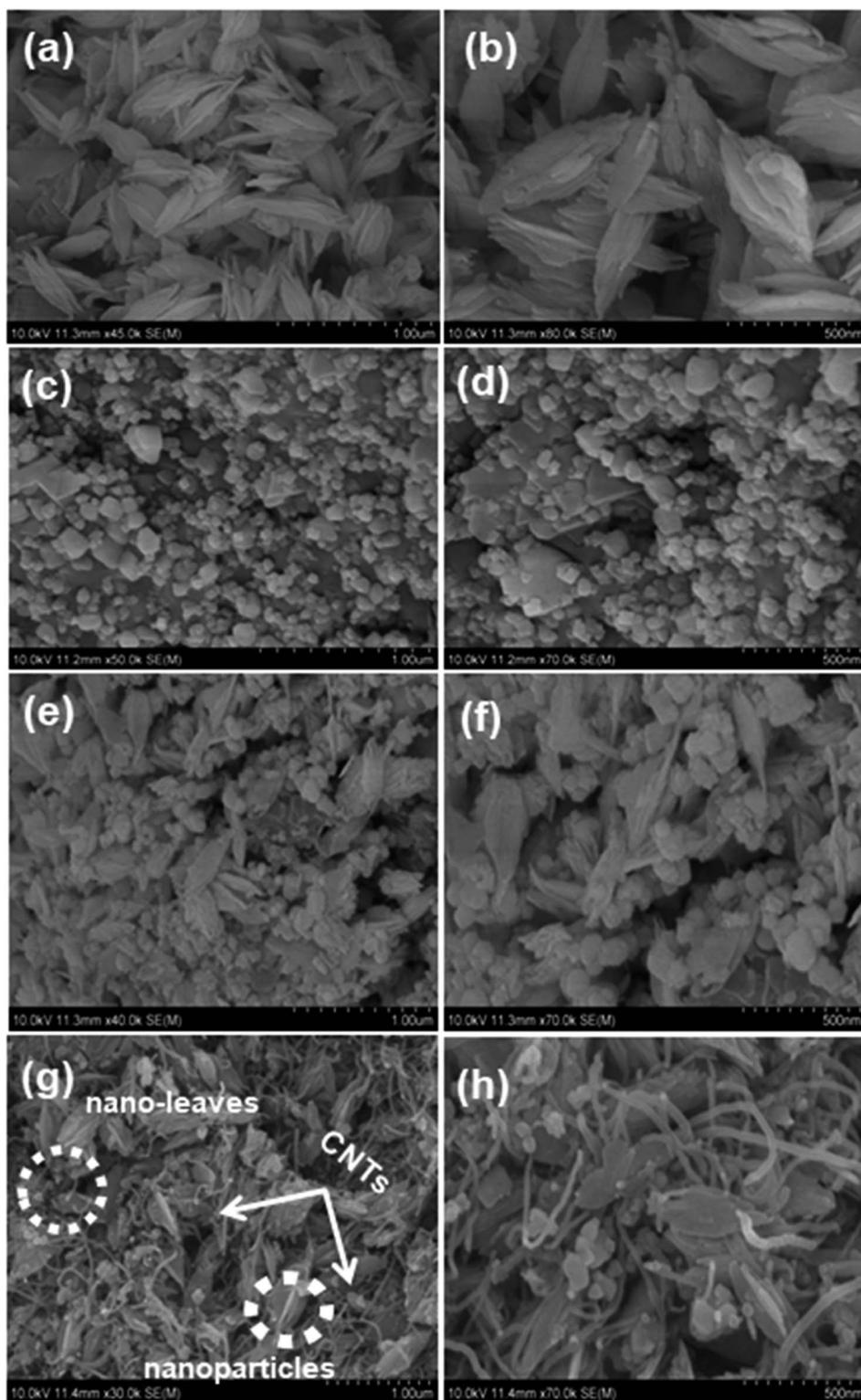


Fig. 3 FESEM images of (a and b) CuO (c and d) ZnCo₂O₄ (e and f) CuO/ZnCo₂O₄ and (g and h) CuO/ZnCo₂O₄/CNTs.

ZnO. These peaks are associated with the (002), (102), (103), (112), and (201) *hkl* planes (JCPDS 00-036-1451). These peaks are matched with the diffraction peaks at $2\theta = 34.4^\circ$, 47.5° , 62.8° , 67.9° , and 69.1° respectively. A peak at 41.2° corresponding to

(200) *hkl* plane is mainly because of CoO (JCPDS 48-1719).⁶² As in Fig. 2(c), the XRD spectrum of CuO/ZnCo₂O₄ includes combined peaks of both CuO and ZnCo₂O₄. The introduction of CNTs in CuO/ZnCo₂O₄ has no significant effect on the structure



of CuO/ZnCo₂O₄ as seen in Fig. 2(c). Peak shifting and intensity alteration was observed in the XRD pattern of CuO/ZnCo₂O₄/CNTs Fig. 2(c). Using the cell software, the lattice parameters of CuO and ZnCo₂O₄ were determined and presented in Table 1. The crystallite/grain sizes were calculated by using the following Debye-Scherrer eqn (2).⁶³

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (2)$$

where D represents the average particle size, λ corresponds to the X-ray wavelength, b is the full-width at half-maximum, θ represents the diffraction angle, and K is a constant (0.89), respectively. The grain sizes calculated using the aforementioned eqn (2), for CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs were found to be 12.9 nm, 19.1 nm, 9.8 nm, and

8.1 nm, respectively. The literature indicates that a sample with a smaller grain size has a greater ability for charges to flow across it.⁶⁴ Eqn (3) was used to calculate the surface area of CuO and ZnCo₂O₄.⁶⁵

$$\text{Surface area} = \frac{6000}{G.S \times \rho_x} \quad (3)$$

The extent to which grain boundaries are broken down affects surface area. The CuO and ZnCo₂O₄ had a surface area of 115 m² g⁻¹, 92.3 m² g⁻¹, with a grain size of 12.9 nm and 19.1 nm, respectively. Arun Kumar *et al.* synthesized nanocomposite and found that the nanocomposite had a small grain size of 0.50 nm as compared to pristine TiO₂ (4.74 nm) and SiO₂ (0.63 nm). Their

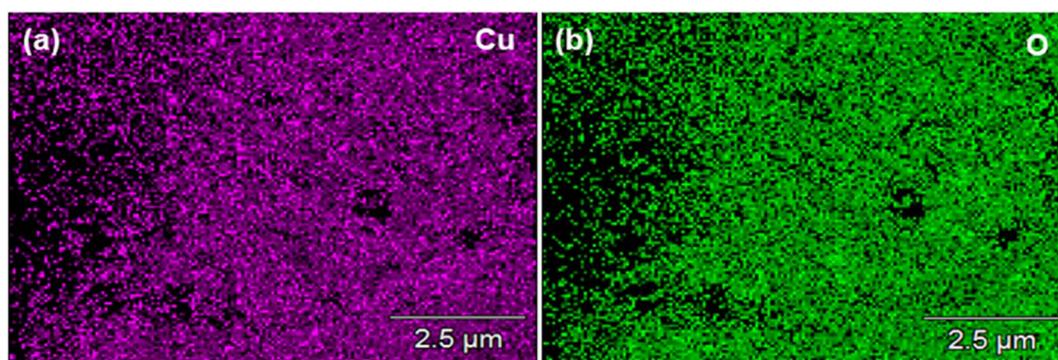


Fig. 4 Energy-dispersive X-ray elemental maps of CuO (a) Cu and (b) O.

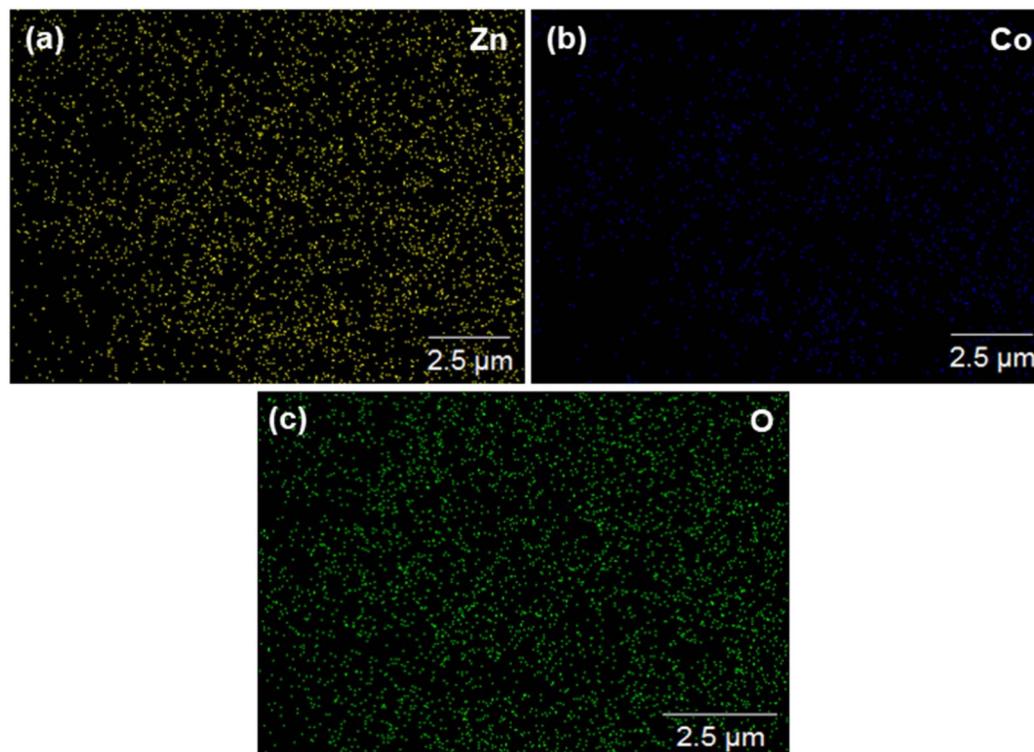


Fig. 5 Energy-dispersive X-ray elemental maps of ZnCo₂O₄ (a) Zn (b) Co and (c) O.



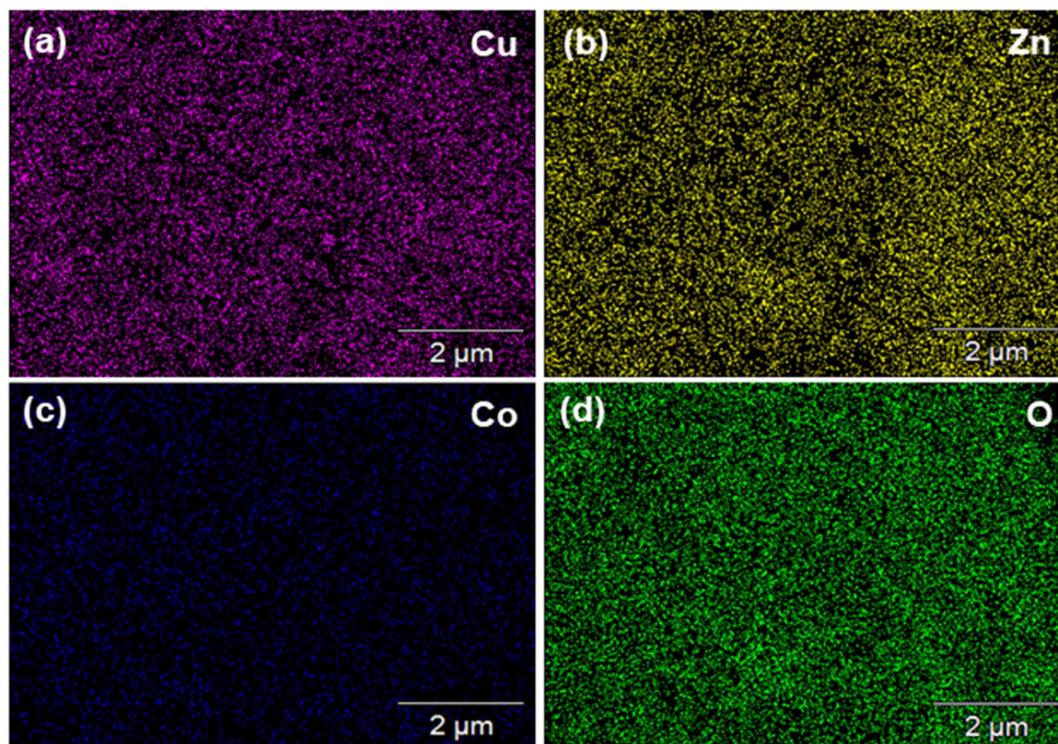


Fig. 6 Energy-dispersive X-ray elemental maps of CuO/ZnCo₂O₄ (a) Cu (b) Zn (c) Co and (d) O.

BET analysis showed that nanocomposite showed a large surface area of 303 m² g⁻¹ as compared to pristine samples.⁶⁶

These results revealed that surface area is correlated with grain size. The smaller the value of grain size, the greater the surface area. CuO/ZnCo₂O₄ and CuO/ZnCo₂O₄/CNTs have small grain sizes as compared to CuO and ZnCo₂O₄, so they will offer higher surface area and an increased number of sites where degradation of pollutants occur. It was further validated through Thakur *et al.* research on PANI/CNTs/MoS₂. It was found that the surface area of PANI was increased from 17.85 m² g⁻¹ to 23.14 m² g⁻¹ resulting from the incorporation of CNTs into the PANI matrix.⁶⁷ Guo *et al.* synthesized TiO₂-CNTs composite and found that CNTs-based composite has small crystallite size as compared to pristine TiO₂.⁶⁸

3.2. FESEM and EDX analysis

Field emission scanning electron microscopy (FESEM) was used to investigate the apparent morphology of the synthesized samples.⁶⁹ Fig. 3 shows the FESEM micrographs of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs that were taken at different magnifications. Fig. 3(a and b) shows the nano-leaves like morphology of CuO. Nanoparticles are clearly seen in the micrographs of ZnCo₂O₄ Fig. 3(c and d). The presence of both nano-leaves and nanoparticles in Fig. 3(e and f) suggests the successful synthesis of CuO/ZnCo₂O₄. Fig. 3(g and h) validates the successful integration of CNTs into the CuO/ZnCo₂O₄ matrix, leading to the synthesis of the CuO/ZnCo₂O₄/CNTs composite. The presence of nanotubes, nano-leaves, and nanoparticles can be clearly seen in Fig. 3(g and h). The

addition of carbon nanotubes into the CuO/ZnCo₂O₄ matrix further increases the surface area and number of active sites, thus improving the degradation of harmful pollutants.

EDX analysis further verified the purity and chemical structure of the prepared samples. The EDX elemental maps of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs are shown in Fig. 4–7, respectively. EDX elemental maps of CuO verified the presence of Cu and O elements. Whereas the EDX maps of ZnCo₂O₄ reveal the presence of Zn, Co, and O elements. The EDX results of CuO/ZnCo₂O₄ and CuO/ZnCo₂O₄/CNTs also confirm the formation of the synthesized materials. The elemental analysis of the prepared samples shows the prominent signals for Cu, Zn, Co, O, and additionally C in the case of CNTs composite. Table 2 shows the elemental data of all the prepared samples.

3.3. X-ray photoelectron spectroscopic (XPS) analysis

The chemical and surface constituents of the fabricated samples were identified by means of XPS analysis.⁷⁰ Fig. 8 (a–e) shows the XPS spectrum along with the binding energies and the presence of elements distributed on the surface of the sample. In the C 1s spectrum, three prominent peaks of sp² hybridized carbon (C_I), sp³ hybridized carbon (C_{II}), and -COO bond (C_{III}) appeared with the binding energies of 284.6 eV, 285.5 eV, and 288.7 eV. The XPS spectrum of the sample clearly indicates the presence of CNTs as shown in Fig. 8(a). Additionally, the O 1s XPS spectrum shows two peaks at 531.9 eV and 533.1 eV, which are assigned to the crystal lattice oxygen (O_I) and adsorbed oxygen (O_{II}), respectively, as can be seen in



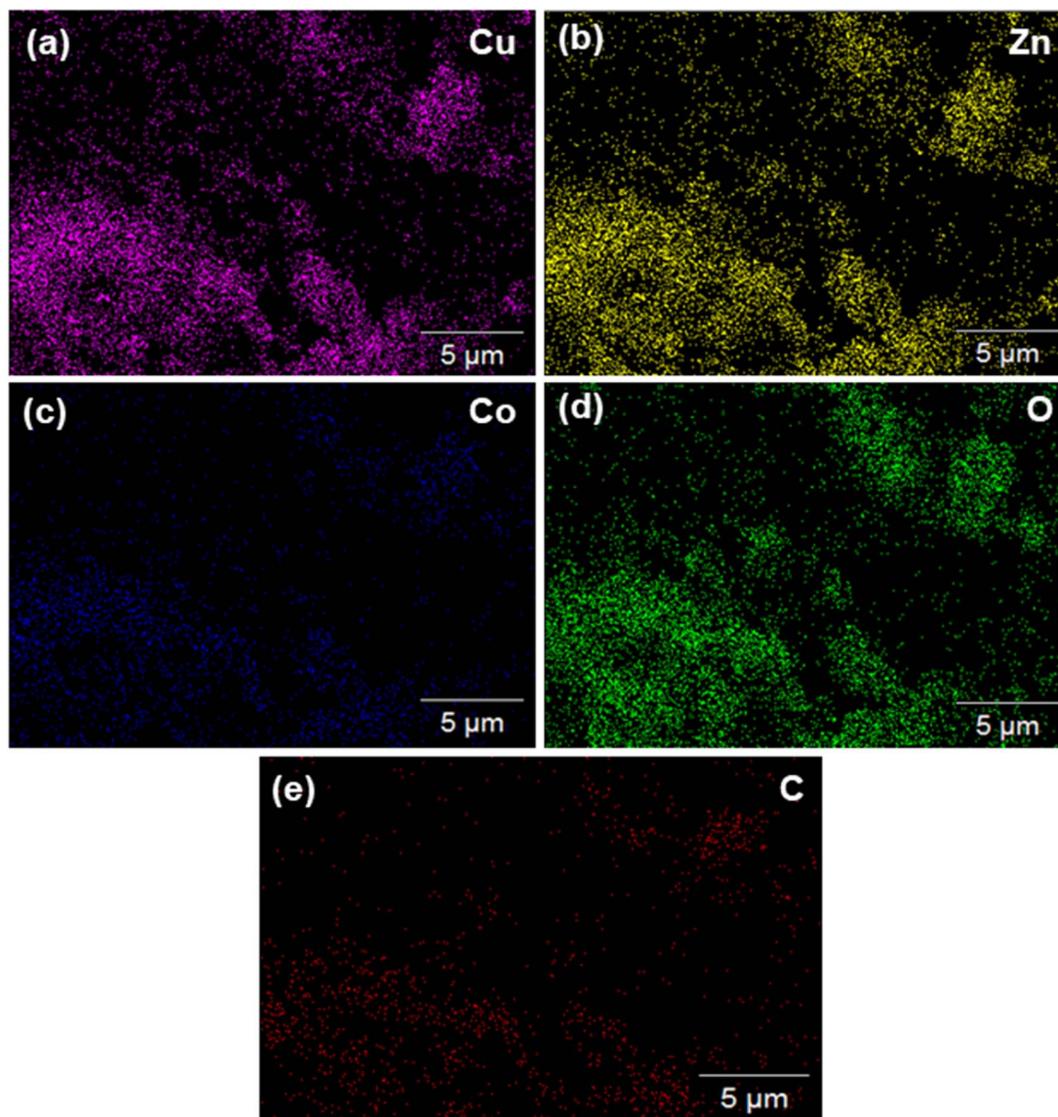


Fig. 7 Energy-dispersive X-ray elemental maps of CuO/ZnCo₂O₄/CNTs (a) Cu (b) Zn (c) Co (d) O and (e) C.

Table 2 Elemental data of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs photocatalysts

Sr. no.	Sample name	Elements	Atom%	wt%
1	CuO	Cu	40.86	73.30
		O	59.14	26.70
2	ZnCo ₂ O ₄	Zn	29.02	52.97
		Co	12.78	21.03
3	CuO/ZnCo ₂ O ₄	O	58.20	26.00
		Cu	8.43	16.61
		Zn	21.15	42.85
		Co	4.22	7.71
4	CuO/ZnCo ₂ O ₄ @CNTs	O	66.20	32.83
		Cu	14.29	29.98
		Zn	14.67	31.66
		Co	2.79	5.43
		O	44.55	23.53
		C	23.70	9.40

Fig. 8(b).⁷¹ In the Co 2p spectrum, two distinctive peaks at 781 eV and 796.4 eV correspond to the Co 2p_{3/2} and Co 2p_{1/2} with two satellite peaks having the binding energies of 782.6 eV and 797 eV, respectively, as shown in Fig. 8(c).⁷² Moreover, two peaks of Cu 2p_{3/2} and Cu 2p_{1/2} with the binding energies of 934.4 eV and 954.2 eV were seen in the XPS spectrum of Cu 2p as seen in Fig. 8(d). In addition, two satellite peaks appeared at 943.2 eV and 962.6 eV in Cu 2p spectra. In Fig. 8(e) Zn 2p indicates two peaks of 2p_{3/2} and 2p_{1/2} having the binding energy of 1022.2 eV and 1045.4 eV respectively.

3.4. Optical analysis

The optical spectra of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs are shown in Fig. 9(a–d), respectively. Within the 200–300 nm range, the produced samples displayed the highest absorption. The following eqn (4) was used to determine the band gap;



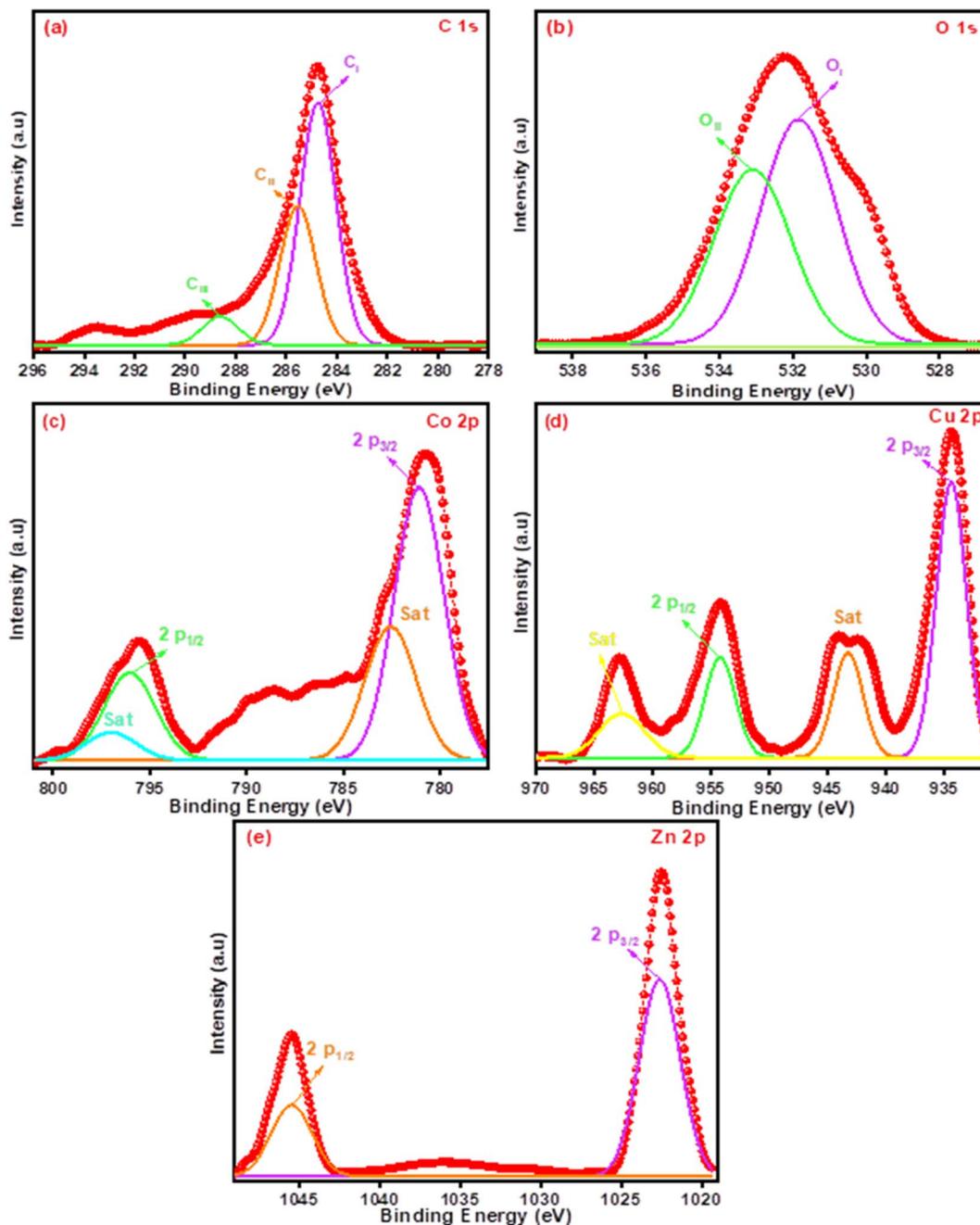


Fig. 8 High-resolution XPS spectra of (a) C 1s, (b) O 1s, (c) Co 2p, (d) Cu 2p, and (e) Zn 2p in CuO/ZnCo₂O₄@CNTs.

$$(\alpha h\nu)^{1/m} = A(h\nu - E_g) \quad (4)$$

where α represents the absorption coefficient, ν is the energy of the photon, and A demonstrates constant of proportionality. The band gap energy of the synthesized photocatalysts was analyzed to determine the effectiveness of the catalysts in dye degradation.⁷³ In the literature, the band gap energy ranging from 1.23 to 3.26 eV is required for photocatalysts to function effectively.⁷⁴ A graph is plotted between $h\nu$ and $(\alpha h\nu)^2$. The optical band gap energies obtained from the Tauc plots by extrapolating the curves in the direction of the x -axis are

displayed in Fig. 10. It was observed that CuO, ZnCo₂O₄, CuO/ZnCo₂O₄ and CuO/ZnCo₂O₄/CNTs have band gap energies of 2.11, 2.18, 1.71 and 1.63 eV respectively.

3.5. Electrochemical impedance spectroscopic (EIS) analysis

Electrochemical impedance spectroscopy (EIS) was used to study the R_{ct} and R_s values of the prepared samples. Using the potentiostat half-cell structure and an alkaline electrolyte (1 M KOH), the value of R_s was determined. Nyquist plot (Fig. 11) generally displays the resistance of the interface layer at the electrode surface, where Z' denotes actual resistance and Z''



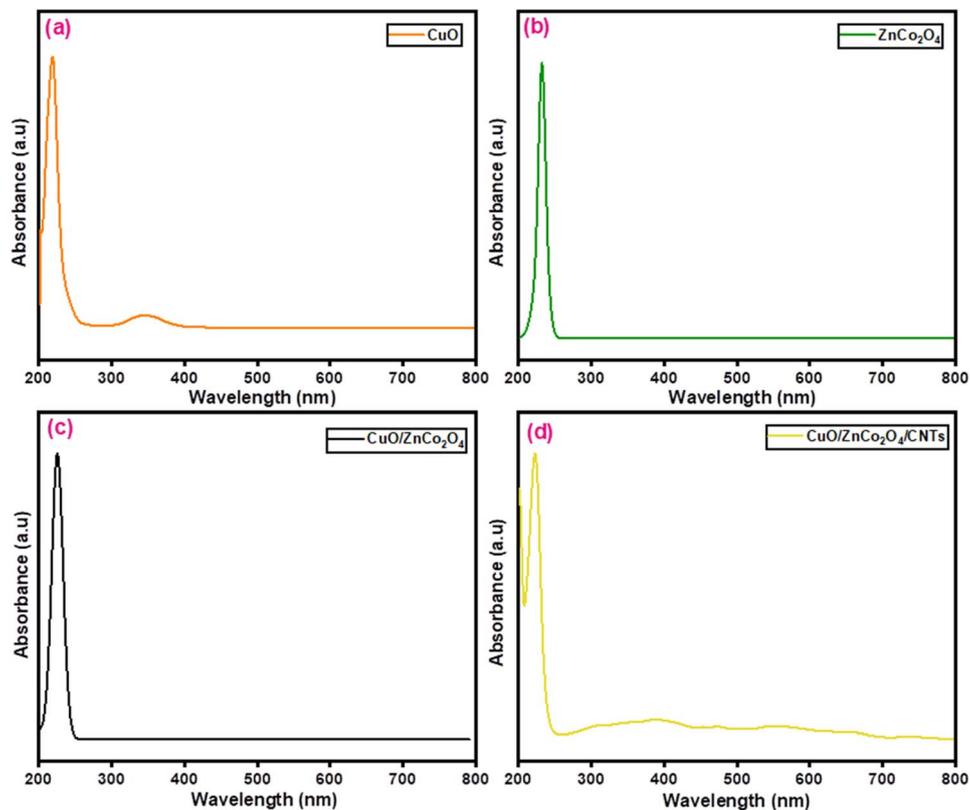


Fig. 9 The UV-Visible spectral profiles of (a) CuO (b) ZnCo₂O₄, (c) CuO/ZnCo₂O₄ and (d) CuO/ZnCo₂O₄/CNTs.

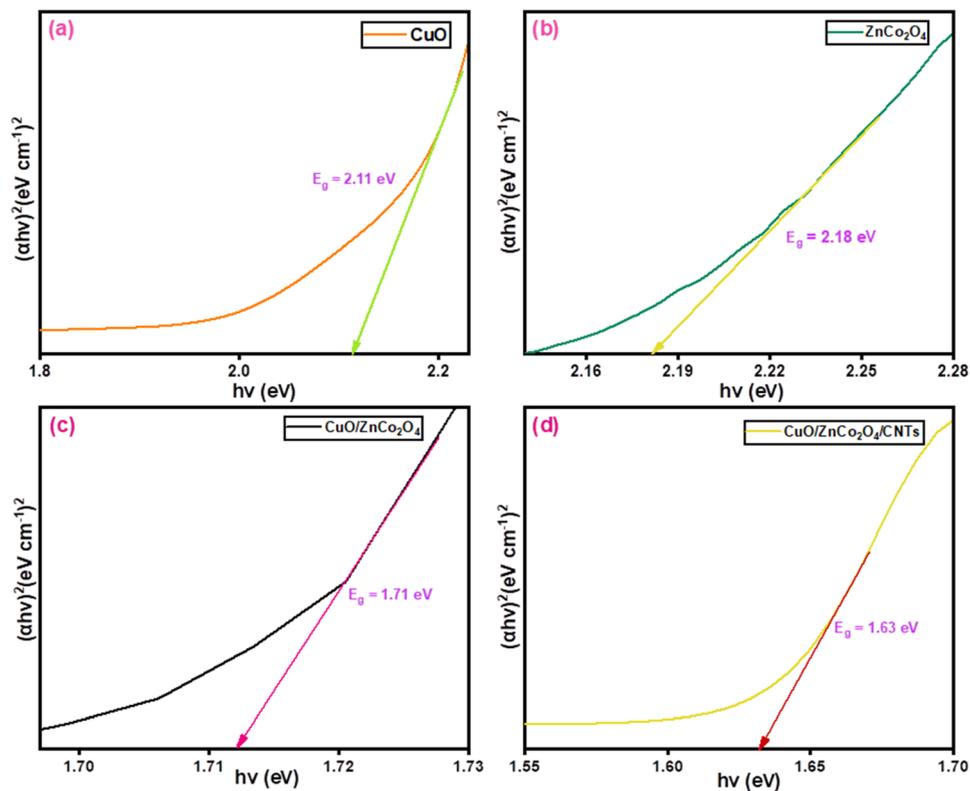


Fig. 10 Tauc plots for (a) CuO (b) ZnCo₂O₄, (c) CuO/ZnCo₂O₄ and (d) CuO/ZnCo₂O₄/CNTs.



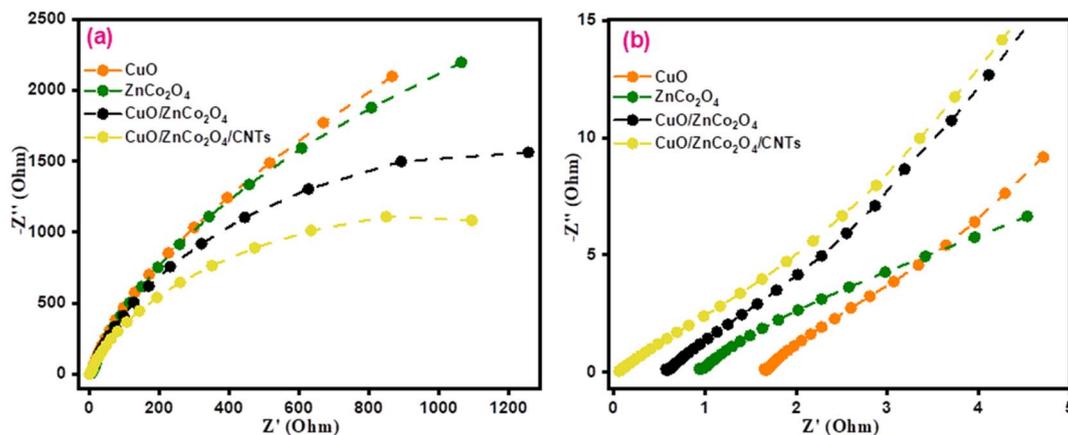


Fig. 11 EIS measurements: (a) Nyquist plots for all fabricated photocatalysts. (b) Magnified high-frequency region of Nyquist plots.

denotes imaginary resistance. For CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs, the R_s values are 1.68 Ω , 0.94 Ω , 0.56 Ω , and 0.04 Ω respectively. In EIS spectra, the arc radius depicts the charge transfer rate. A smaller arc radius of CuO/ZnCo₂O₄/CNTs shows a higher charge-transfer process because photogenerated electrons and holes are effectively separated, which enhances the electron transfer during the redox reaction. Therefore, the low R_s value of CuO/ZnCo₂O₄/

CNTs, as compared to other electrode materials, exhibits high conductance and allows the degradation of organic contaminants more effectively by photocatalysis.

3.6. Mott-Schottky analysis

In order to enhance our understanding of the electrical nature and intrinsic characteristics of semiconductor materials, Mott-Schottky technique was used. This analysis was used to examine

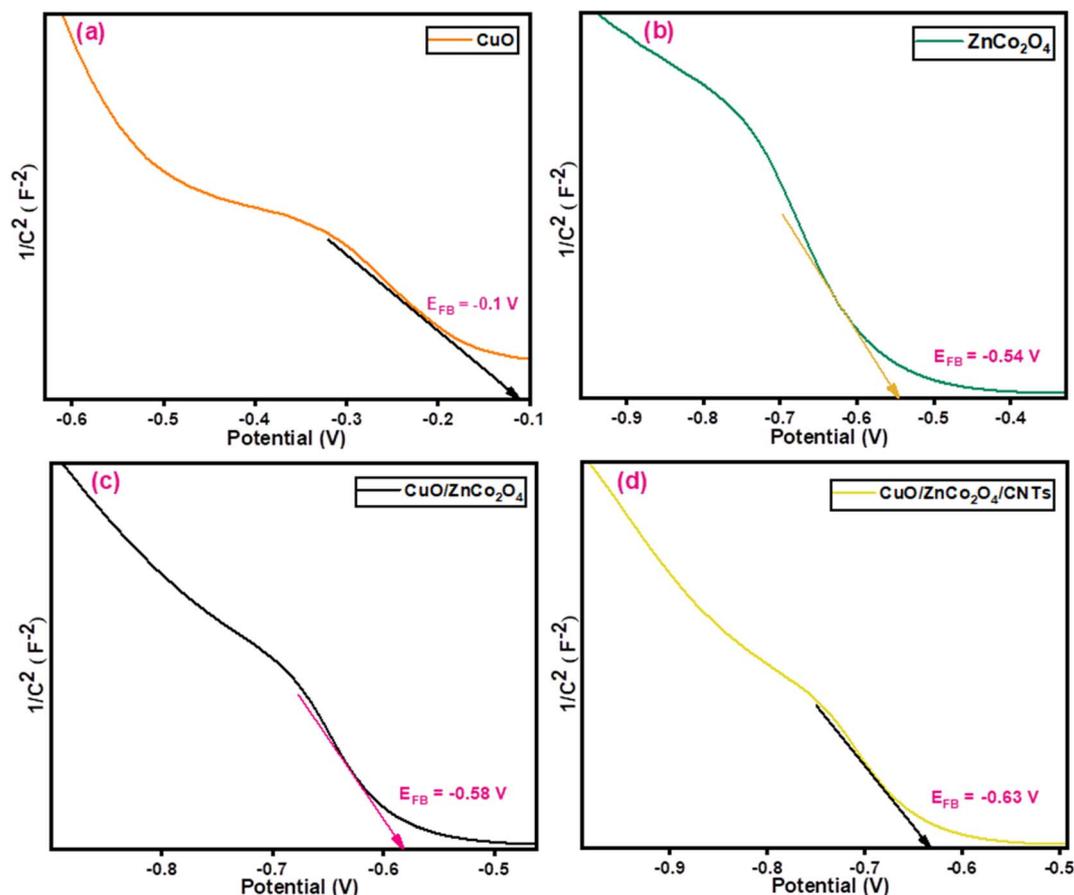


Fig. 12 Mott-Schottky diagrams of (a) CuO (b) ZnCo₂O₄ (c) CuO/ZnCo₂O₄, and (d) CuO/ZnCo₂O₄/CNTs.



the type of semiconductor (p-type or n-type). A GAMRY Interface 5000 E was used to conduct the measurements. The potential $vs. 1/C^2$ provides the value of the flat band potential for CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs electrodes (Fig. 12). The following formula (5) was used to calculate the flat band potential (E_{FB}):

$$\frac{1}{C^2} = \frac{2}{\epsilon\epsilon_0 N_D \left(E - E_{FB} - \frac{K_b T}{q} \right)} \quad (5)$$

Fig. 12 illustrates the negative slopes for CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs, demonstrating that they are p-type semiconducting materials. The values of flat band potential (E_{FB}) for CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs are -0.10 , -0.54 , -0.58 , and -0.63 V respectively. In comparison to other synthesized nanocatalysts, the CuO/ZnCo₂O₄/CNTs has a higher negative flat band potential value as shown in Fig. 12. This negative flat band potential value promotes rapid charge movement in the semiconducting material and greatly inhibits charge carrier recombination as compared to other electrode materials. E_{FB} affects redox processes, kinetics, and alignment of energy levels. A higher negative E_{FB} value indicates a faster redox reaction. Therefore, CuO/ZnCo₂O₄/CNTs show a faster redox process as compared to CuO, ZnCo₂O₄, and CuO/ZnCo₂O₄.

4. Photocatalytic studies

4.1. Photodegradation of crystal violet

The photodegradation activity of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs was investigated using crystal violet, a colored organic pollutant. Fig. 13 shows the absorption spectra of the fabricated samples. Fig. 14(a and b) shows the kinetics plots for the photodegradation of crystal violet by various photocatalysts. CuO/ZnCo₂O₄/CNTs, CuO/ZnCo₂O₄, ZnCo₂O₄, and CuO were able to degrade 87.7%, 78%, 61.5%, and 45.6% of the crystal violet dye, respectively. Among the other photocatalysts, CuO/ZnCo₂O₄/CNTs has the highest photocatalytic efficiency as shown in Fig. 14(c). The rate constants for crystal violet dye degradation by CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs are shown in Fig. 14(d) as 0.006, 0.009, 0.016, and 0.022 min⁻¹, respectively. The highest value of rate constant in the case of CNTs-based composite is mainly because of the synergetic effect of both CNTs and CuO/ZnCo₂O₄ that increase the effectiveness of this photocatalyst compared to CuO/ZnCo₂O₄ that has low photodegradation efficiency. Introduction of CNTs offers enhanced surface area and active sites to maximize adsorption while lowering the rate at which photogenerated species recombine. By forming a composite of CuO with ZnCo₂O₄, the band gap was reduced as compared to pure CuO and ZnCo₂O₄. Table 3 shows various parameters for CV degradation by the prepared photocatalysts.

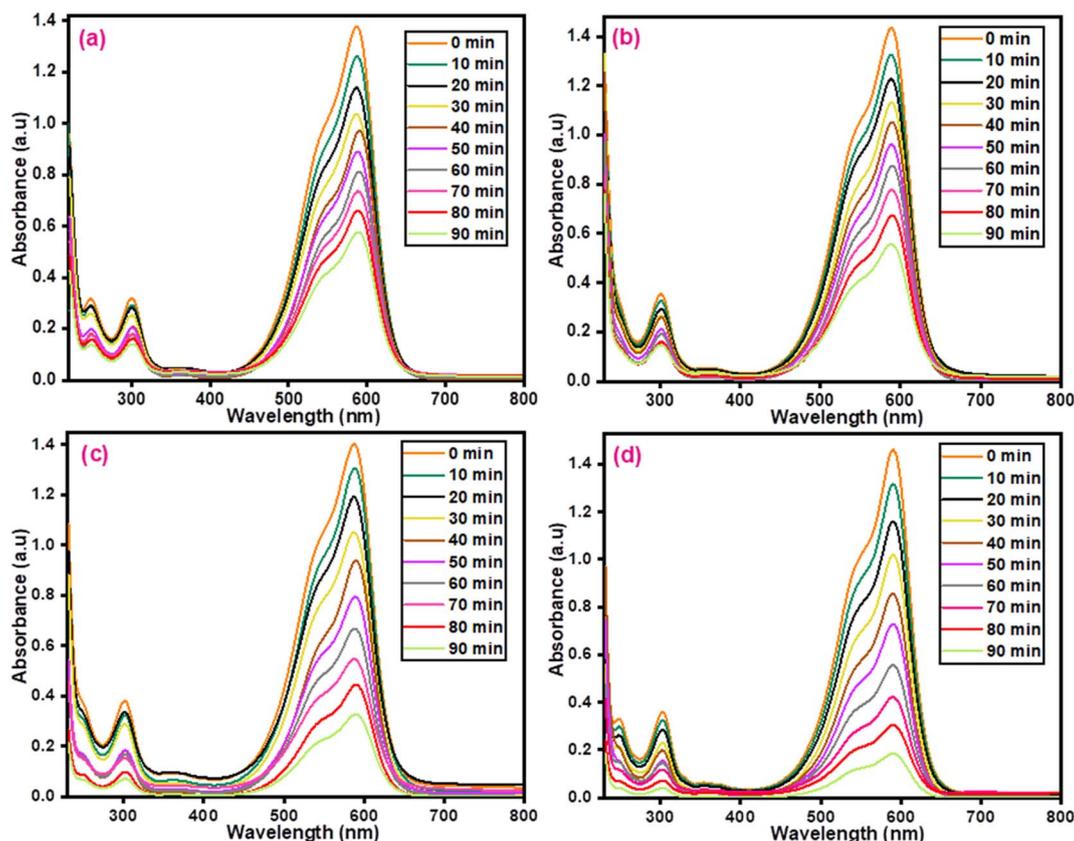


Fig. 13 Absorption spectra of (a) CuO (b) ZnCo₂O₄ (c) CuO/ZnCo₂O₄, and (d) CuO/ZnCo₂O₄/CNTs for CV dye degradation.



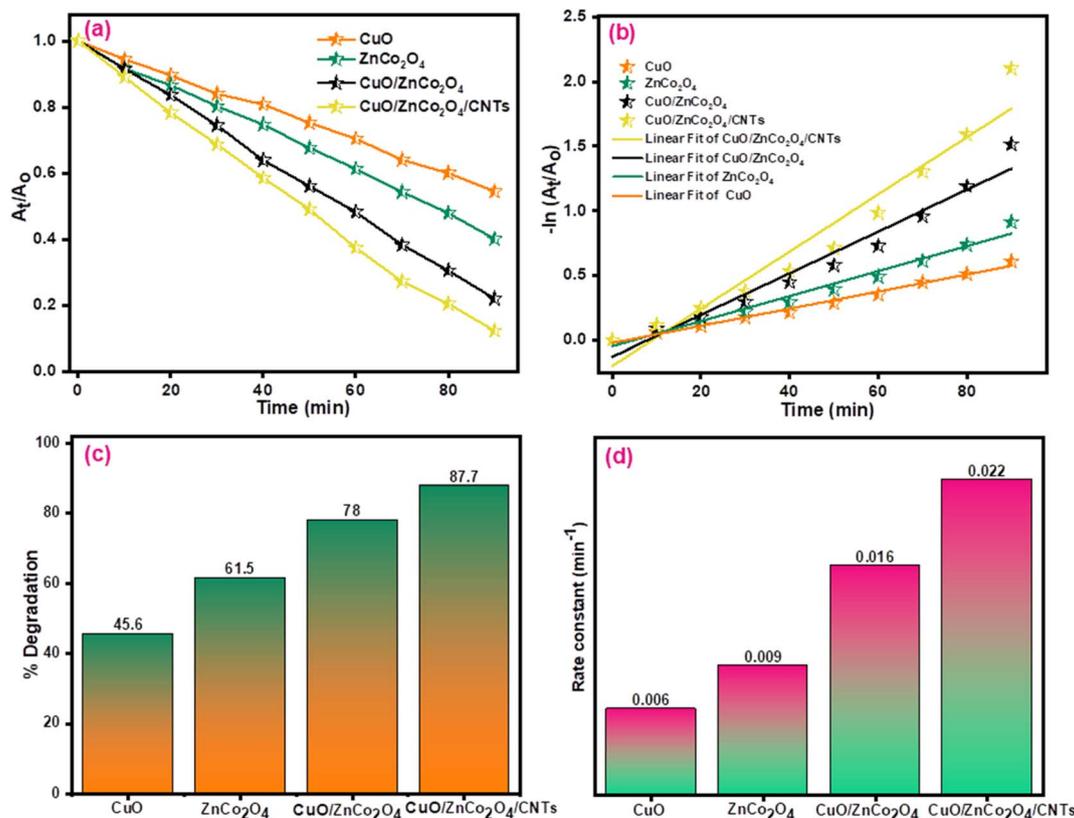


Fig. 14 (a and b) Kinetic plots (c) % degradation and (d) rate constant plot for CV dye degradation using CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs.

Table 3 Calculated parameters for CV dye degradation using various photocatalysts

Photocatalyst	Degradation (%)	k (min ⁻¹)	$t_{1/2}$ (min)	R^2
CuO	45.6	0.006	115.5	0.945
ZnCo ₂ O ₄	61.5	0.009	77.0	0.960
CuO/ZnCo ₂ O ₄	78	0.016	43.3	0.976
CuO/ZnCo ₂ O ₄ /CNTs	87.7	0.022	31.5	0.989

Table 4 shows the comparison of the photocatalytic activity of already reported catalysts with the materials synthesized in this work.

The kinetics was examined using the eqn (6);

$$-\ln[A_t/A_0] = kt \quad (6)$$

Eqn (7) was used to calculate the half-life;

Table 4 Comparison of photocatalytic activity of already reported catalysts with current study

Sr. no.	Photocatalysts	Pollutant	Light source	Degradation (%)	References
1	CuO	4-Nitrophenol	Visible light	72%	75
2	ZnCo ₂ O ₄	MB	Sunlight	41.97%	76
3	Ag-ZnCo ₂ O ₄	MB	Sunlight	58.02%	76
4	ZnCo ₂ O ₄	CV	Visible light	84.3%	77
5	Ti ₂ C/ZnCo ₂ O ₄	CR	Visible light	78%	78
6	CNTs/Cu _x O	MB	LED light	84%	79
7	ZnO/CuO	CV	Hg-vapor lamp	90%	80
8	ZnO/CuO/Ag	MO	Xe/Hg 1000W	52.34%	81
9	CuO	CV	Tungsten bulb	45.6%	Current work
10	ZnCo ₂ O ₄	CV	Tungsten bulb	61.5%	Current work
11	CuO/ZnCo ₂ O ₄	CV	Tungsten bulb	78%	Current work
12	CuO/ZnCo ₂ O ₄ /CNTs	CV	Tungsten bulb	87.7%	Current work



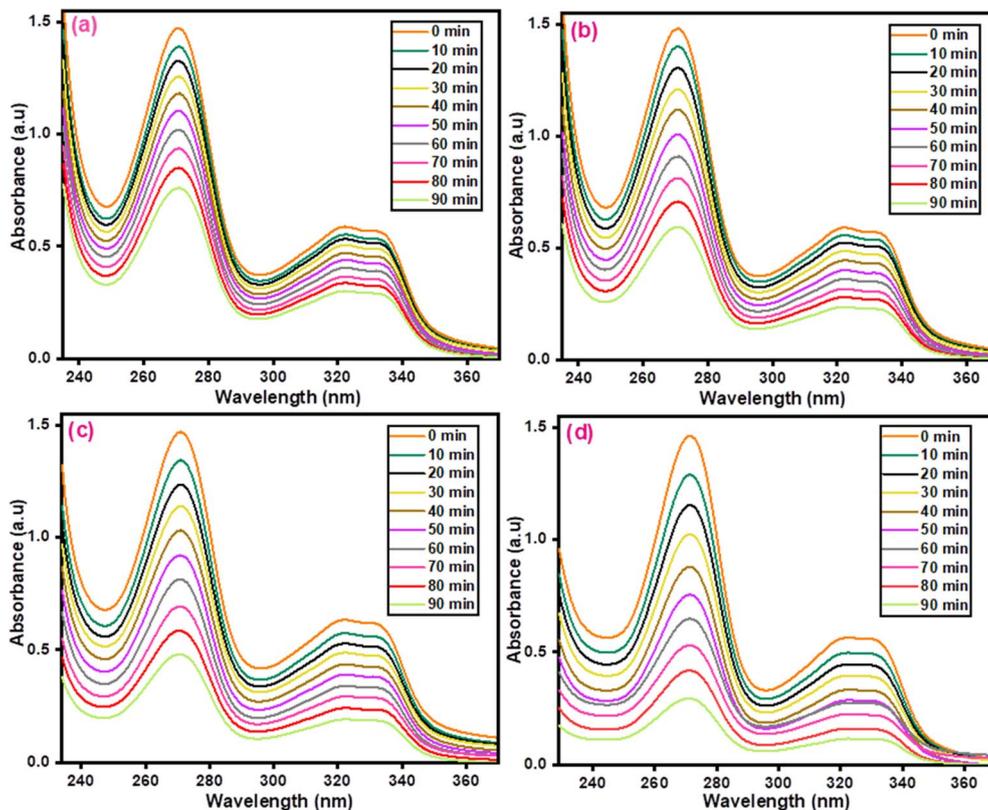


Fig. 15 Absorption spectra of (a) CuO (b) ZnCo₂O₄ (c) CuO/ZnCo₂O₄, and (d) CuO/ZnCo₂O₄/CNTs for diclofenac sodium degradation.

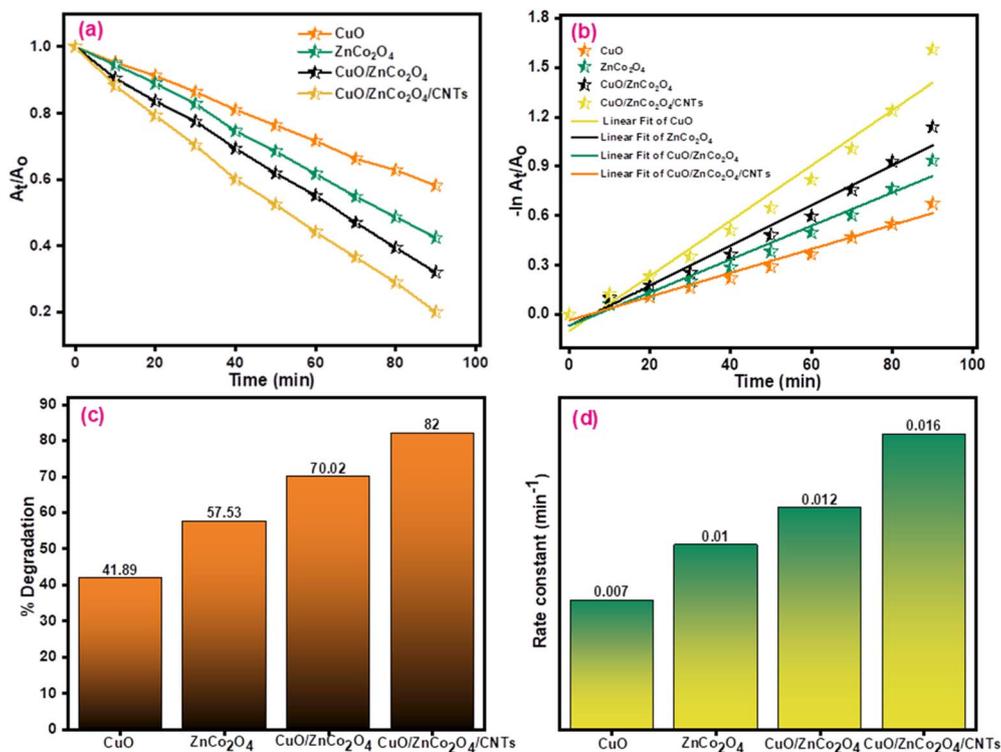


Fig. 16 (a and b) Kinetic plots (c) % degradation, and (d) rate constant plot for diclofenac sodium degradation using CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs.



Table 5 Calculated parameters for diclofenac sodium degradation using various photocatalysts

Photocatalyst	Degradation (%)	k (min^{-1})	$t_{1/2}$ (min)	R^2
CuO	41.89	0.007	99.01	0.979
ZnCo ₂ O ₄	57.53	0.010	69.3	0.971
CuO/ZnCo ₂ O ₄	70.02	0.012	57.75	0.973
CuO/ZnCo ₂ O ₄ /CNTs	82	0.016	43.31	0.966

$$t_{1/2} = \frac{\ln 2}{k} = \frac{0.6931}{k} \quad (7)$$

4.2. Photodegradation of diclofenac sodium

The photocatalytic performance of the prepared photocatalysts was investigated for the degradation of diclofenac sodium. Absorption plots are shown in Fig. 15(a–d). Fig. 16(a and b) shows the kinetics profiles for the diclofenac sodium degradation. The rate constant values in the case of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs photocatalysts were found to be 0.007, 0.01, 0.012, and 0.016 min^{-1} . The % degradation values using the prepared photocatalysts are shown in Fig. 16(c). The maximum degradation of diclofenac sodium was

found to be 82% using CuO/ZnCo₂O₄/CNTs photocatalyst, respectively. Composite with CNTs shows higher degradation as compared to other prepared catalysts. The degradation parameters for diclofenac sodium are displayed in Table 5.

4.3. Photodegradation of phenol

The photocatalytic activity of the as-prepared CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs photocatalysts was investigated through the degradation of colorless pollutant such as phenol. The absorption plots of prepared photocatalysts are shown in Fig. 17. The rate constant for each prepared photocatalyst was determined using the linear plots, and the results are shown in Fig. 18(d) and Table 6. The rate constants for the photodegradation of phenol in the presence of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs photocatalysts were found to be 0.007, 0.009, 0.010, and 0.014, respectively. Fig. 18(a and b) shows the kinetics plots for the degradation of phenol. The removal percentage of phenol in the presence of CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs photocatalysts was calculated as 51%, 57.8%, 64.3%, and 72%, respectively (Fig. 18(c)).

4.4. Recyclability experiment

A recyclability experiment was conducted to assess the stability of the fabricated photocatalyst (CuO/ZnCo₂O₄/CNTs) towards

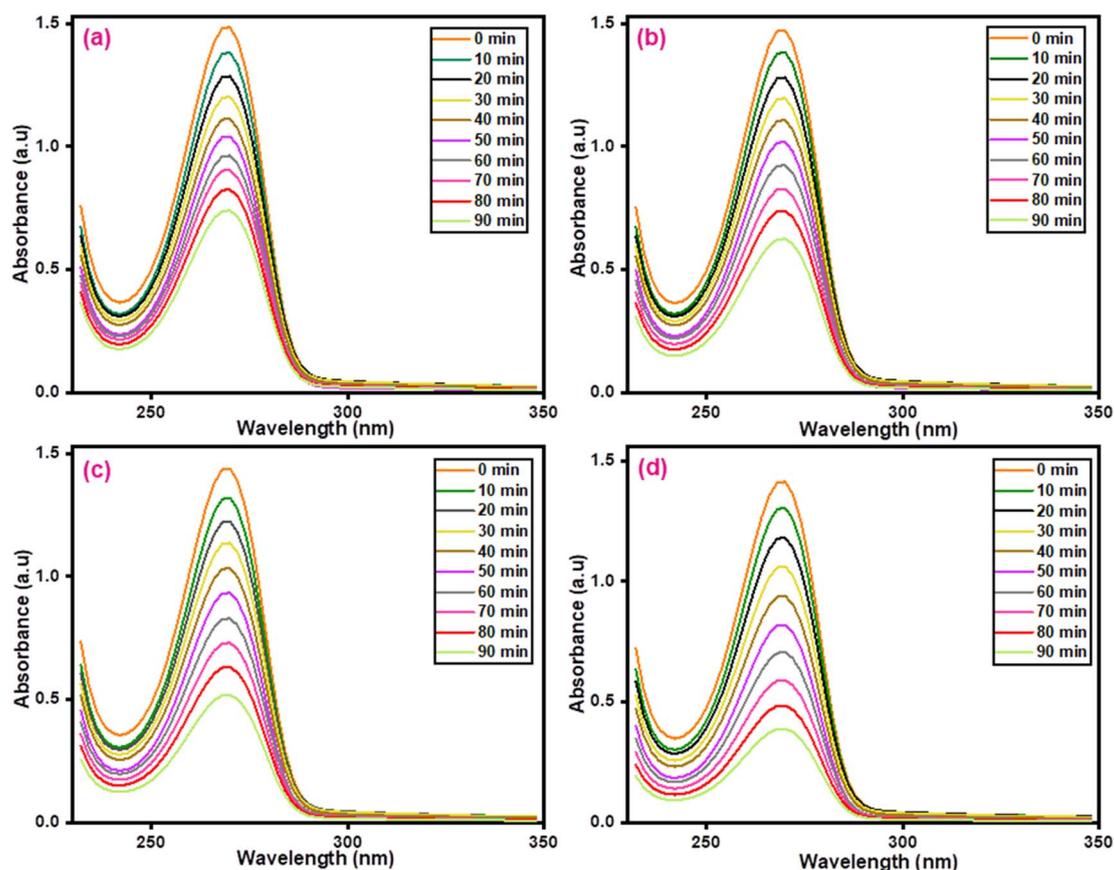


Fig. 17 Absorption spectra of (a) CuO (b) ZnCo₂O₄ (c) CuO/ZnCo₂O₄, and (d) CuO/ZnCo₂O₄/CNTs for phenol degradation.



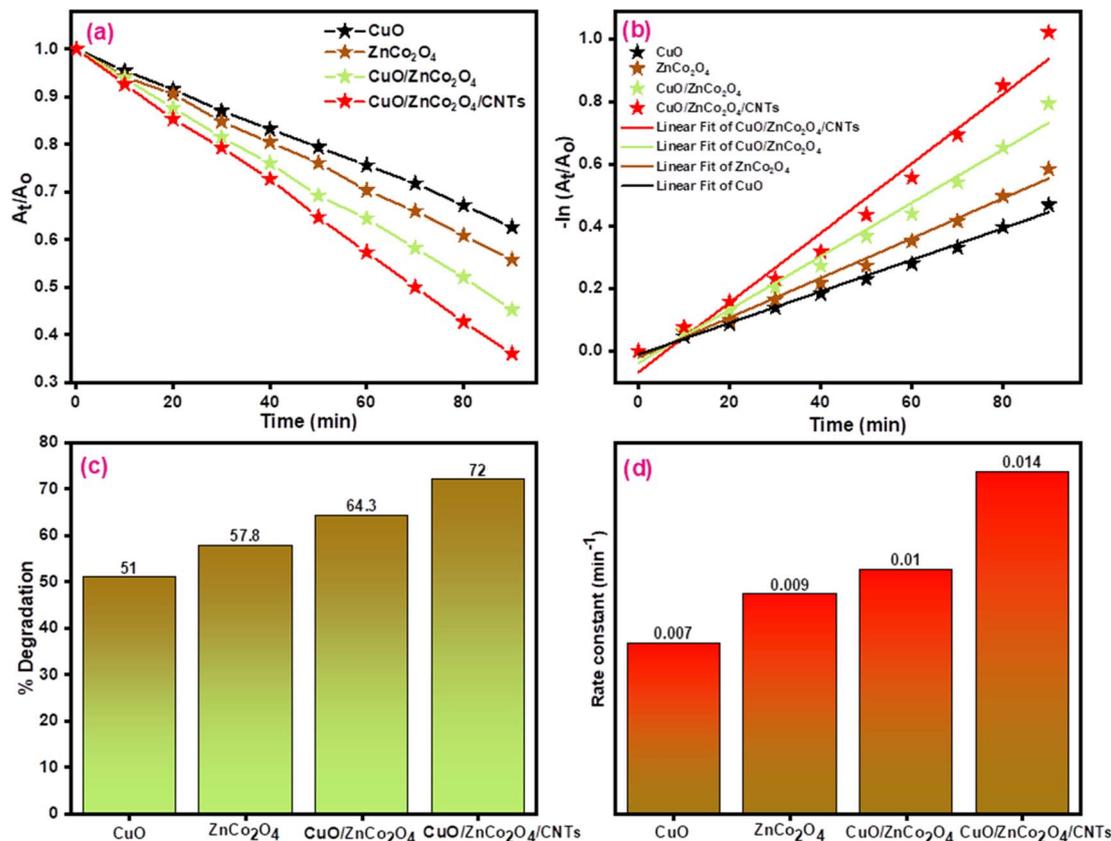


Fig. 18 (a and b) Kinetic plots (c) % degradation, and (d) rate constant plot for phenol degradation using CuO, ZnCo₂O₄, CuO/ZnCo₂O₄, and CuO/ZnCo₂O₄/CNTs.

Table 6 Calculated parameters for phenol degradation using various photocatalysts

Photocatalyst	Degradation (%)	k (min ⁻¹)	$t_{1/2}$ (min)	R^2
CuO	51	0.007	99.0	0.995
ZnCo ₂ O ₄	57.8	0.009	77	0.979
CuO/ZnCo ₂ O ₄	64.3	0.010	69.31	0.974
CuO/ZnCo ₂ O ₄ /CNTs	72	0.014	49.5	0.977

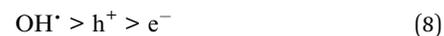
the CV decolorization. Four photocatalytic cycles were used to test the reusability of the material. Fig. 19(a) shows the recyclability plot of CuO/ZnCo₂O₄/CNTs photocatalyst for the removal of CV dye. After each cycle, there was a very small decrease in the % photodegradation using CuO/ZnCo₂O₄/CNTs (Fig. 19b). After the first cycle, the photocatalyst degrades 87.7% of CV dye. The result demonstrated that even after four cycles, the CuO/ZnCo₂O₄/CNTs retained 80% degrading efficiency. Actually, the total catalyst efficiency was reduced by the adsorption of organic intermediates and during the process of washing after every cycle run.⁸²

4.5. Trapping tests

A scavenging mechanism was employed to examine the roles of various photo-active species in the photocatalytic degradation of CV dye using CuO/ZnCo₂O₄/CNTs, with different quenchers

present. Salicylic acid and 2-propanol were used to quench hydroxyl radicals.⁸³ While ethylenediaminetetraacetic acid (EDTA) and silver nitrate (AgNO₃) were used to quench holes and electrons respectively. The trapping experiment was examined using the same photocatalytic process (Fig. 20).

The results demonstrate that OH[•] is the main active species in the degradation of crystal violet because it represents the minimum degradation as compared to other scavengers. CuO/ZnCo₂O₄/CNTs degrade, 55.1% of CV dye in the presence of 2-propanol and 51.7% in the presence of salicylic acid. CV dye shows degradation of 76.5% in the presence of EDTA and 84.2% in the presence of silver nitrate. Table 7 shows the parameters calculated for CV degradation in the presence of scavengers. The activity displayed by photo-reactive species in the degradation of CV dye follows the following order.



5. Photodegradation mechanism

The pollutant degradation pathway using CuO/ZnCo₂O₄/CNTs is shown in Fig. 21. Eqn (9) and (10) were used to determine the values of the valence band potential (E_{VB}) and conduction band potential (E_{CB}).



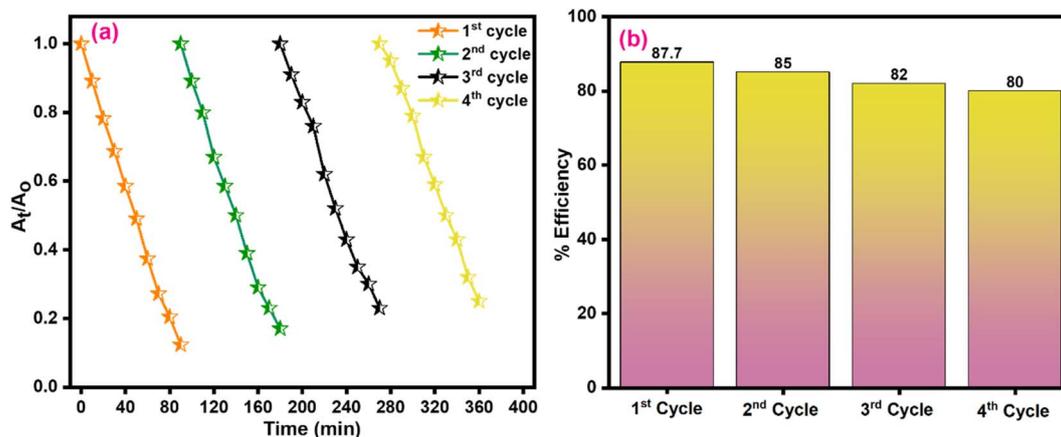


Fig. 19 (a) A_t/A_0 vs. time plot of CV dye degradation by CuO/ZnCo₂O₄/CNTs and (b) % efficiency shown by the CuO/ZnCo₂O₄/CNTs for the removal of CV dye for four consecutive cycles.

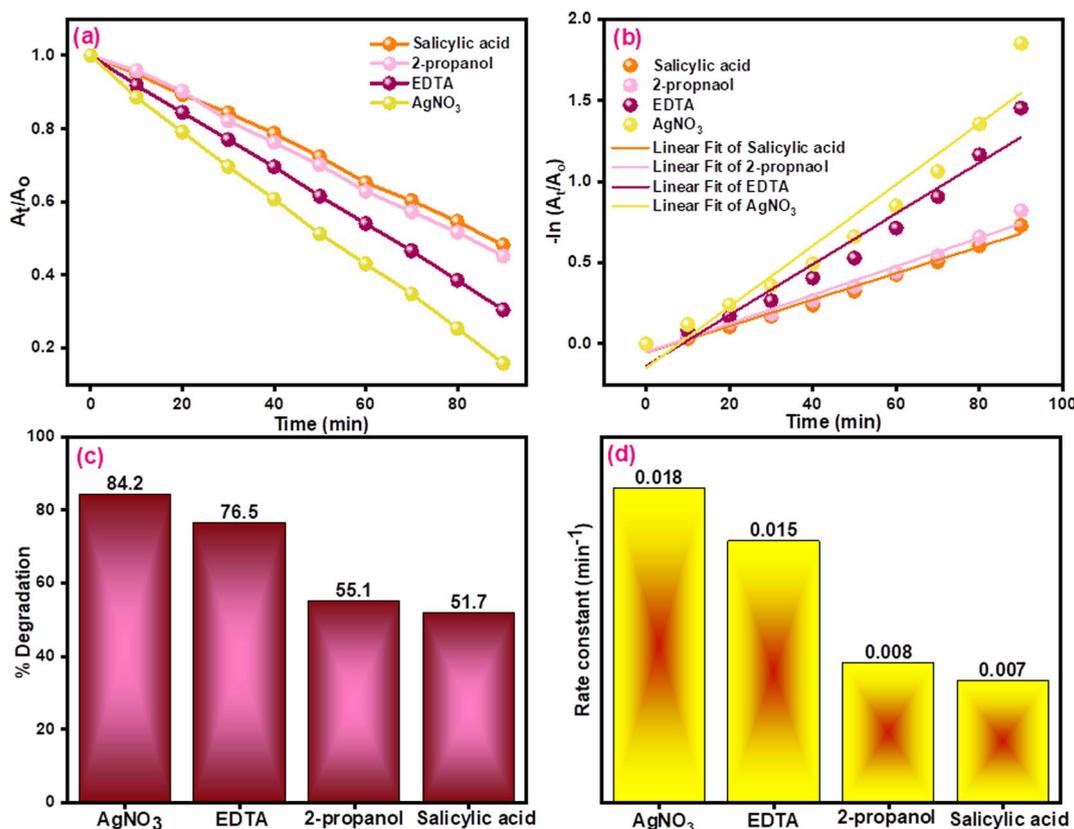


Fig. 20 Scavenging plots for CV dye degradation (a) A_t/A_0 vs. time (b) $-\ln(A_t/A_0)$ vs. time (c) % degradation, and (d) rate constant plot in the presence of different quenchers using CuO/ZnCo₂O₄/CNTs.

$$E_{CB} = \chi - E^e - 0.5E_g \quad (9)$$

$$E_{VB} = E_g + E_{CB} \quad (10)$$

In this case, χ denotes absolute electronegativity, E^e is the energy of free electrons, E_g is the band gap energy.

When the CuO/ZnCo₂O₄/CNTs photocatalyst is exposed to visible light, the excited electrons move from the valence band

Table 7 Calculated parameters for CV degradation in the presence of scavengers

Photocatalyst	% degradation	k (min ⁻¹)	$t_{1/2}$ (min)	R^2
Salicylic acid	51.7	0.007	99.01	0.984
2-Propanol	55.1	0.008	86.63	0.979
EDTA	76.5	0.015	46.20	0.956
AgNO ₃	84.2	0.018	38.50	0.941



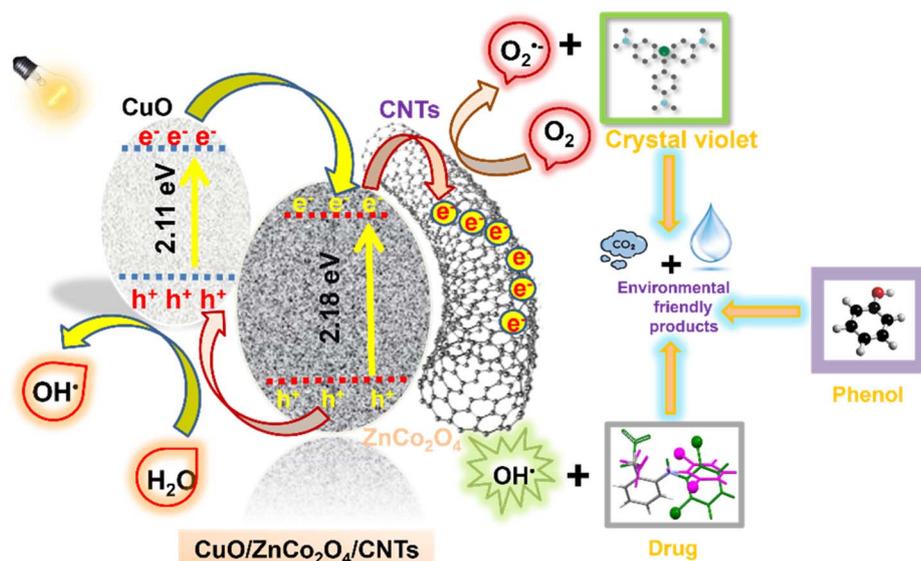


Fig. 21 Mechanism of degradation of pollutants by CuO/ZnCo₂O₄/CNTs.

to the conduction band, leaving holes behind. Subsequently, the photoexcited electrons transfer from the conduction band (CB) of CuO to the CB of ZnCo₂O₄. This causes the abundance of electrons in ZnCo₂O₄. These electrons are then trapped by

CNTs. Meanwhile, VB of CuO became hole-rich. These photo-generated electrons react with O₂ to form O₂^{·-}, which then contributes to the degradation of pollutants through a series of reactions. On the surface of the CuO/ZnCo₂O₄/CNTs, holes and

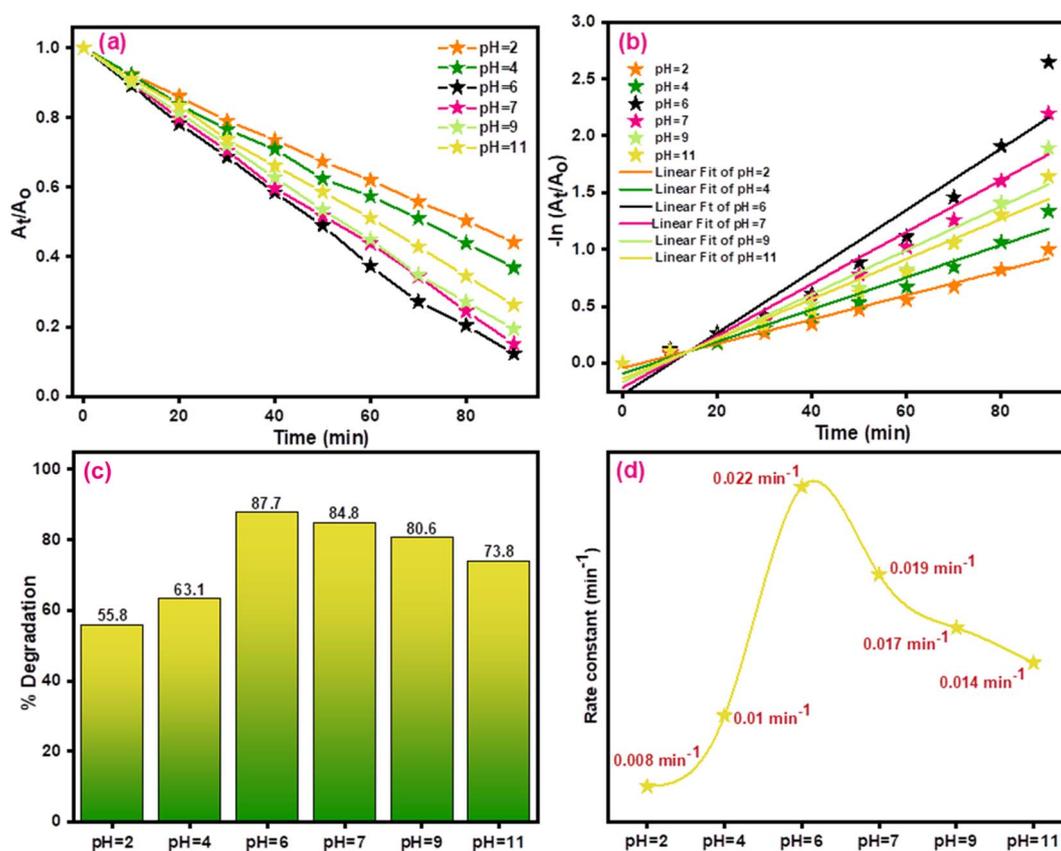
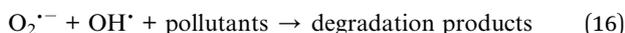
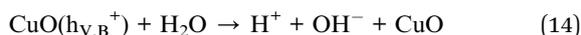
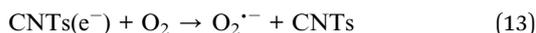
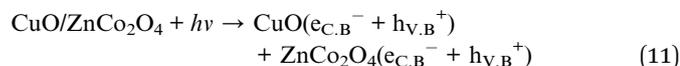


Fig. 22 Effect of pH on CV dye degradation (a and b) kinetics plots, (c) % degradation and (d) rate constant under CuO/ZnCo₂O₄/CNTs.



electrons cause oxidation–reduction reactions. These reactions produced hydroxyl radicals. When these $O_2^{\cdot-}$ and OH^{\cdot} degrade the pollutants, environmentally safe byproducts (CO_2 and H_2O) are produced. The following equations illustrate the photocatalytic mechanism.



6. Effect of pH

The photo-oxidation of organic dyes is significantly impacted by the wide range of pH levels of the wastewater from different industries. Solutions with varying pH values (2, 4, 6, 7, 9, and 11) were used to examine the impact of the initial pH of the CV dye. The pH was maintained by using solutions of sodium hydroxide

(0.2 M) and hydrochloric acid (0.2 M). Fig. 22(a–d) shows the behavior of CV dye solutions of various pH in the presence of $CuO/ZnCo_2O_4/CNTs$. The results showed that the CV dye degradation rate was higher at pH values between 6 and 11 as compared pH 2 and 4. This trend suggests that the rate of dye degradation onto the surface of the $CuO/ZnCo_2O_4/CNTs$ is maximum at pH = 6. CV dye was found to degrade at a maximal rate of $k = 0.022 \text{ min}^{-1}$, which drops sharply to 0.019 min^{-1} at pH 7. The electrostatic connection between the substrate and photocatalyst surfaces was linked to the degradation patterns at basic and acidic pH levels.⁸⁴ The percentage of dye degradation was low at acidic pH. This could be because of the increased development of H^+ ions on the surface of the photocatalyst, which reduced the rate of degradation and the adsorption of molecules. Higher pH values resulted in increased degradation efficiency because more hydroxyl radicals were generated owing to the greater concentration of OH^- ions in the alkaline medium.

7. Effect of dye concentration

In order to further investigate the efficiency of the prepared $CuO/ZnCo_2O_4/CNTs$, the effect of dye concentration was examined. The degree of photocatalytic reaction rate at the surface of the photocatalyst can be influenced by the initial dye concentration. When the concentration of dye is high, there will be

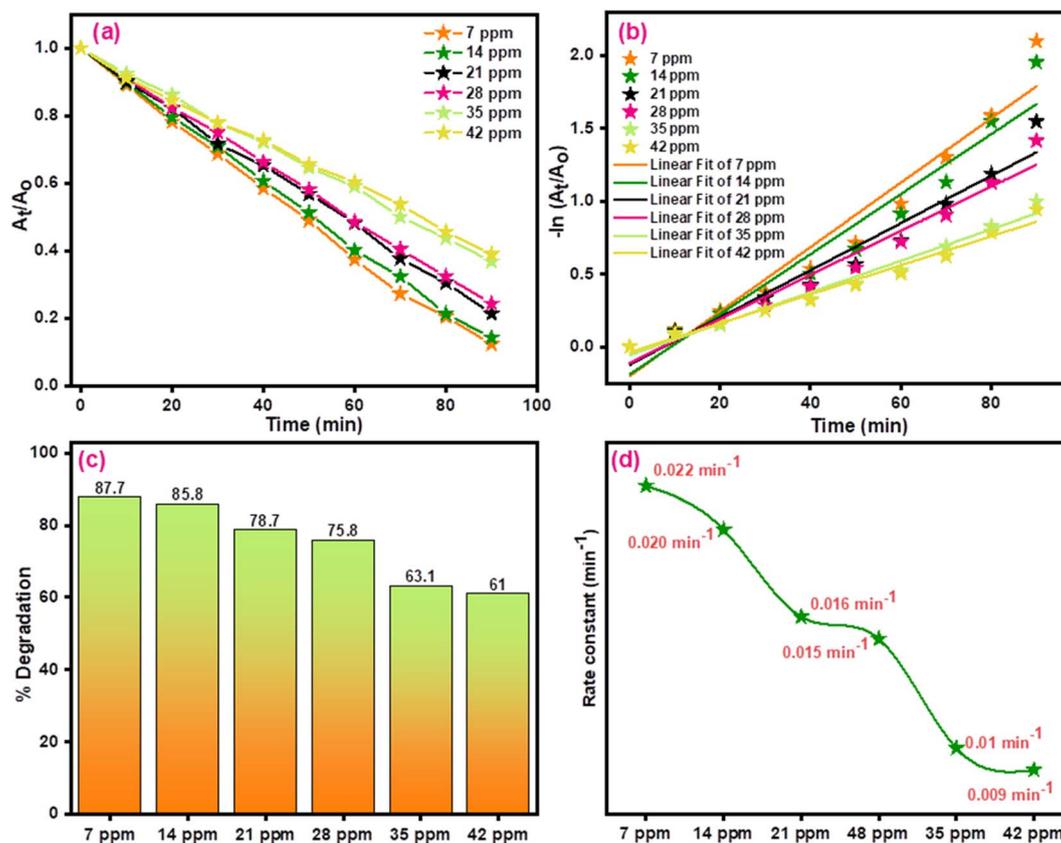


Fig. 23 Effect of dye concentration on (a and b) kinetics plots of CV dye, (c) % degradation and (d) rate constant under $CuO/ZnCo_2O_4/CNTs$.



intense competition among the dye molecules to become adsorbed on the photocatalyst surface.⁸⁵ The process of photodegradation finally slows down or stops. Therefore, the experiments were conducted under CuO/ZnCo₂O₄/CNTs with varying dye (CV) concentrations to investigate the concentration effect. The findings are shown in Fig. 23(a–d).

The rate and degradation of the dye decreased as the concentration of CV increased. For 7 ppm, the degradation percentage was 87.7% and for 42 ppm, the degradation dropped to 61%. The obtained results showed that increasing dye concentration provides a larger number of dye molecules, which in turn enhances competition for the adsorption process. The active sites are coated with dye molecules, which lower the percentage of degradation.

8. Effect of catalyst dosage

The photocatalyst dosage affects the surface area, light absorption efficiency, and photo-removal process for organic dyes.^{82,86} Photocatalytic tests were conducted with varying concentrations of CuO/ZnCo₂O₄/CNTs (5–40 mg) in order to examine the dosage effect on CV dye degradation. The outcomes are shown in Fig. 24(a–d).

It is evident from the results that an increase in catalyst concentration is correlated with a rise in the photodegradation percentage. When the dosage of photocatalyst was increased

from 5 mg to 30 mg, the rate of CV dye degradation increased as well. The percentage degradation of CV dye did not significantly change with an additional increase in catalyst dosage. At a catalytic dosage of 30 mg, the highest degradation rate of 87.7% was noted. Actually, more light exposure increases the capacity of the CuO/ZnCo₂O₄/CNTs to absorb photons and ultimately enhances photocatalytic efficiency. The availability of a higher surface area for the adsorption of additional dye molecules and the rise in the mass to volume ratio of photocatalyst are both credited with the increase in the rate of CV dye degradation.

9. Conclusions

In this work, CNTs were introduced into CuO/ZnCo₂O₄ using a sonication technique to synthesize CuO/ZnCo₂O₄/CNTs nanocomposite. Various physicochemical aspects of the prepared photocatalysts, such as phase identification, morphology, purity, and optical properties, were identified through XRD, FESEM, EDS, and UV-Vis spectroscopy. The band gap values of the prepared photocatalysts followed the order ZnCo₂O₄ > CuO > CuO/ZnCo₂O₄ > CuO/ZnCo₂O₄/CNTs. The rate constant value for the degradation of CV dye, diclofenac sodium, and phenol using CuO/ZnCo₂O₄/CNTs was found to be 0.022, 0.016, and 0.014 min⁻¹ respectively. After being exposed to visible light, CuO/ZnCo₂O₄/CNTs showed high percentage

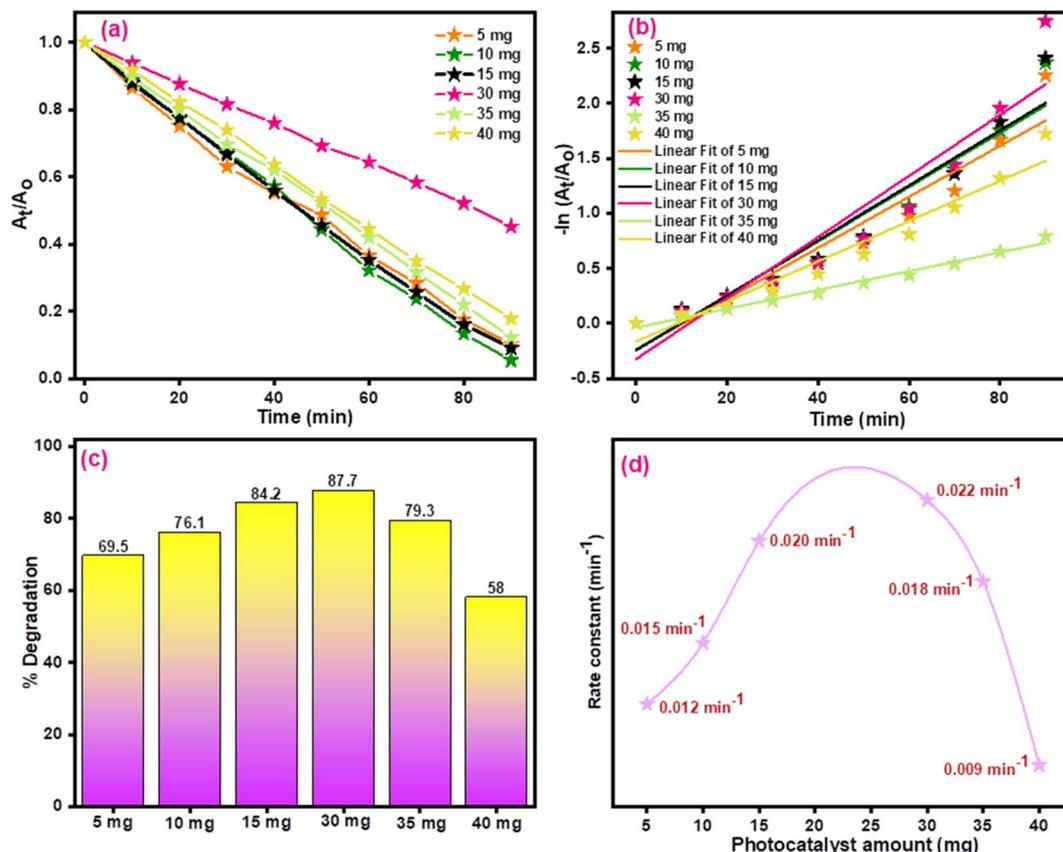


Fig. 24 Effect of catalyst dosage on (a and b) kinetics plots of CV dye, (c) % degradation and (d) rate constant under CuO/ZnCo₂O₄/CNTs.



degradation of 87.7% of the CV dye, whereas the % degradation of diclofenac sodium and phenol were found to be 82% and 72% respectively. Among all the photocatalysts, the highest degradation efficiency was achieved with CuO/ZnCo₂O₄/CNTs for all pollutants examined in this study, owing to the presence of CNTs in the composite that offers enhanced surface area and active sites for the rapid and efficient breakdown of organic contaminants.

Data availability

All data generated or analyzed during this study are included in this article.

Conflicts of interest

The authors declare that there is no conflict of interest.

Acknowledgements

The authors express their gratitude to Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2024R450), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia. Prof. Dr Sonia Zulfiqar extends her heartfelt thanks to the Statutory City of Ostrava, Czechia, for their support through the Research Grant "Global Experts". Prof. Cochran and Zulfiqar express their gratitude to the National Science Foundation for financial support through research grants NSF-2113695, NSF-2218070 and NSF-2242763. The authors are also thankful to the Deanship of Scientific Research, Islamic University of Madinah, Madinah (Saudi Arabia) for support *via* post publishing program.

References

- 1 P. Rajasulochana and V. Preethy, Comparison on efficiency of various techniques in treatment of waste and sewage water—A comprehensive review, *Resour.-Effic. Technol.*, 2016, **2**, 175–184.
- 2 M. F. Abou Taleb, M. Afaq, H. A. Albalwi, F. I. Abou El Fadl, A. Irshad and M. M. Ibrahim, Tb-doped BiFeO₃ nanostructure and its composite with CNTs to improve the light-harvesting properties, *Mater. Sci. Eng., B*, 2024, **299**, 116916.
- 3 L. Schweitzer and J. Noblet, Water contamination and pollution, *Green Chem.*, 2018, 261–290.
- 4 K. M. Katubi, S. Akbar, A. Habib, Z. Alrowaili, M. Al-Buriahi, A. Irshad and M. F. Warsi, Fabrication of CNTs supported CuCo₂O₄/Co₃S₄ composite for advanced photocatalytic application, *Optik*, 2024, **300**, 171653.
- 5 S. Sohrabnezhad, A. Pourahmad and E. Radaee, Photocatalytic degradation of basic blue 9 by CoS nanoparticles supported on AlMCM-41 material as a catalyst, *J. Hazard. Mater.*, 2009, **170**, 184–190.
- 6 A. Singh, S. S. Shah, C. Sharma, V. Gupta, A. K. Sundramoorthy, P. Kumar and S. Arya, An approach towards different techniques for detection of heavy metal ions and their removal from wastewater, *J. Environ. Chem. Eng.*, 2024, 113032.
- 7 A. Ahmed, A. Singh, B. Padha, A. K. Sundramoorthy, A. Tomar and S. Arya, UV-vis spectroscopic method for detection and removal of heavy metal ions in water using Ag doped ZnO nanoparticles, *Chemosphere*, 2022, **303**, 135208.
- 8 J. Arshad, F. M. A. Alzahrani, M. F. Warsi, U. Younis, M. Anwar, Z. Alrowaili, M. Al-Buriahi and A. Manzoor, Copper substituted spinel Co–Cr spinel Ferrites@ Graphitic carbon nitride nanocomposite as a visible light active photocatalytic material, *Opt. Mater.*, 2024, **148**, 114906.
- 9 N. Alfryyan, M. Ikram, A. Manzoor, A. Jamil, Z. Alrowaili, M. Al-Buriahi, A. Irshad and M. I. Din, Synthesis of Cd-substituted NiCoPrFe₂O₄@ CNTs via sol-gel method: Investigating the structural and photocatalytic properties, *Phys. B*, 2023, **660**, 414885.
- 10 D. Lu, Y. Zhang, S. Lin, L. Wang and C. Wang, Synthesis of magnetic ZnFe₂O₄/graphene composite and its application in photocatalytic degradation of dyes, *J. Alloys Compd.*, 2013, **579**, 336–342.
- 11 R. V. Prihod'ko and N. M. Soboleva, Photocatalysis: Oxidative processes in water treatment, *J. Chem.*, 2013, **2013**, 168701.
- 12 K. Kannan, D. Radhika, D. Gnanasangeetha, S. K. Lakkaboyana, K. K. Sadasivuni, K. Gurushankar and M. M. Hanafiah, Photocatalytic and antimicrobial properties of microwave synthesized mixed metal oxide nanocomposite, *Inorg. Chem. Commun.*, 2021, **125**, 108429.
- 13 A. Singh, A. Ahmed, A. Sharma, C. Sharma, S. Paul, A. Khosla, V. Gupta and S. Arya, Promising photocatalytic degradation of methyl orange dye via sol-gel synthesized Ag–CdS@ Pr-TiO₂ core/shell nanoparticles, *Phys. B*, 2021, **616**, 413121.
- 14 D. Ravelli, D. Dondi, M. Fagnoni and A. Albini, Photocatalysis. A multi-faceted concept for green chemistry, *Chem. Soc. Rev.*, 2009, **38**, 1999–2011.
- 15 M. Kumar, B. Abebe, H. Nagaswarupa, H. Murthy, C. Ravikumar and F. Sabir, Enhanced photocatalytic and electrochemical performance of TiO₂–Fe₂O₃ nanocomposite: its applications in dye decolorization and as supercapacitors, *Sci. Rep.*, 2020, **10**, 1249.
- 16 A. Shabbir, S. Ajmal, M. Shahid, I. Shakir, P. O. Agboola and M. F. Warsi, Zirconium substituted spinel nano-ferrite Mg_{0.2}Co_{0.8}Fe₂O₄ particles and their hybrids with reduced graphene oxide for photocatalytic and other potential applications, *Ceram. Int.*, 2019, **45**, 16121–16129.
- 17 K. Nakata and A. Fujishima, TiO₂ photocatalysis: Design and applications, *J. Photochem. Photobiol., C*, 2012, **13**, 169–189.
- 18 M. F. Warsi, B. Bashir, S. Zulfiqar, M. Aadil, M. U. Khalid, P. O. Agboola, I. Shakir, M. A. Yousuf and M. Shahid, Mn_{1-x}Cu_xO₂/reduced graphene oxide nanocomposites: synthesis, characterization, and evaluation of visible light mediated catalytic studies, *Ceram. Int.*, 2021, **47**, 5044–5053.
- 19 A. K. Sibhatu, G. K. Weldegebrerial, S. Sagadevan, N. N. Tran and V. Hessel, Photocatalytic activity of CuO nanoparticles



- for organic and inorganic pollutants removal in wastewater remediation, *Chemosphere*, 2022, **300**, 134623.
- 20 Y. Al-Douri, S. Abdulateef, A. A. Odeh, C. Voon and N. Badi, GaNO colloidal nanoparticles synthesis by nanosecond pulsed laser ablation: Laser fluence dependent optical absorption and structural properties, *Powder Technol.*, 2017, **320**, 457–461.
 - 21 J.-P. Jolivet, M. Henry and J. Livage, *Metal Oxide Chemistry and Synthesis: From Solution to Solid State*, 2000.
 - 22 A.-Z. Warsi, O. K. Hussien, A. Iftikhar, F. Aziz, D. Alhashmialameer, S. F. Mahmoud, M. F. Warsi and D. I. Saleh, Co-precipitation assisted preparation of Ag₂O, CuO and Ag₂O/CuO nanocomposite: characterization and improved solar irradiated degradation of colored and colourless organic effluents, *Ceram. Int.*, 2022, **48**, 19056–19067.
 - 23 A. Tadjarodi, O. Akhavan and K. Bijanzad, Photocatalytic activity of CuO nanoparticles incorporated in mesoporous structure prepared from bis (2-aminonicotinato) copper (II) microflakes, *Trans. Nonferrous Met. Soc. China*, 2015, **25**, 3634–3642.
 - 24 S. Harish, J. Archana, M. Sabarinathan, M. Navaneethan, K. Nisha, S. Ponnusamy, C. Muthamizhchelvan, H. Ikeda, D. Aswal and Y. Hayakawa, Controlled structural and compositional characteristic of visible light active ZnO/CuO photocatalyst for the degradation of organic pollutant, *Appl. Surf. Sci.*, 2017, **418**, 103–112.
 - 25 R. Katal, S. Masudy-panah, E. Y.-J. Kong, N. D. Khiavi, M. H. D. A. Farahani and X. Gong, Nanocrystal-engineered thin CuO film photocatalyst for visible-light-driven photocatalytic degradation of organic pollutant in aqueous solution, *Catal. Today*, 2020, **340**, 236–244.
 - 26 S. S. Hossain, M. Tarek, T. D. Munusamy, K. M. R. Karim, S. M. Roopan, S. M. Sarkar, C. K. Cheng and M. M. R. Khan, Facile synthesis of CuO/CdS heterostructure photocatalyst for the effective degradation of dye under visible light, *Environ. Res.*, 2020, **188**, 109803.
 - 27 A. ur Rehman, M. Aadil, S. Zulfiqar, P. O. Agboola, I. Shakir, M. F. A. Aboud, S. Haider and M. F. Warsi, Fabrication of binary metal doped CuO nanocatalyst and their application for the industrial effluents treatment, *Ceram. Int.*, 2021, **47**, 5929–5937.
 - 28 H. Benhebal, C. Wolfs, S. Kadi, R. G. Tilkin, B. Allouche, R. Belabid, V. Collard, A. Felten, P. Louette and S. D. Lambert, Visible light sensitive SnO₂/ZnCo₂O₄ material for the photocatalytic removal of organic pollutants in water, *Inorganics*, 2019, **7**, 77.
 - 29 K. Gurunathan, J.-O. Baeg, S. M. Lee, E. Subramanian, S.-J. Moon and K.-j. Kong, Visible light active pristine and Fe³⁺ doped CuGa₂O₄ spinel photocatalysts for solar hydrogen production, *Int. J. Hydrogen Energy*, 2008, **33**, 2646–2652.
 - 30 Y. Yao, F. Lu, Y. Zhu, F. Wei, X. Liu, C. Lian and S. Wang, Magnetic core-shell CuFe₂O₄@ C₃N₄ hybrids for visible light photocatalysis of Orange II, *J. Hazard. Mater.*, 2015, **297**, 224–233.
 - 31 S. Sharma, V. Dutta, P. Raizada, A. Hosseini-Bandegharai, V. Thakur, V.-H. Nguyen, Q. VanLe and P. Singh, An overview of heterojunctioned ZnFe₂O₄ photocatalyst for enhanced oxidative water purification, *J. Environ. Chem. Eng.*, 2021, **9**, 105812.
 - 32 B. Basha, M. Ikram, Z. Alrowaili, M. Al-Buriahi, M. Anwar and M. Suleman, Wet chemical route synthesis of Cr doped CoFe₂O₄@ rGO nanocomposite for photodegradation of organic effluents present in drinking water, *Ceram. Int.*, 2023, **49**, 30049–30059.
 - 33 I. A. Mkhalid, A. A. Ismail, M. A. Hussein and R. H. Al Thomali, Nanoheterojunctions MnCo₂O₄ nanoparticles anchored on mesoporous TiO₂ networks for superior photocatalytic ability, *Mater. Res. Bull.*, 2023, **167**, 112439.
 - 34 L. Liu, L. Zuo, R. Li, T. Xi, H. Fan, B. Li and L. Wang, Novel CoMn₂O₄-ZnIn₂S₄ hollow heterostructure cage for efficient photocatalytic hydrogen evolution, *Appl. Surf. Sci.*, 2023, **635**, 157646.
 - 35 H. Guo, J. Chen, W. Weng, Q. Wang and S. Li, Facile template-free one-pot fabrication of ZnCo₂O₄ microspheres with enhanced photocatalytic activities under visible-light illumination, *Chem. Eng. J.*, 2014, **239**, 192–199.
 - 36 G.-Y. Zhang, B. Guo and J. Chen, MCo₂O₄ (M= Ni, Cu, Zn) nanotubes: template synthesis and application in gas sensors, *Sens. Actuators, B*, 2006, **114**, 402–409.
 - 37 Y. Sharma, N. Sharma, G. Subba Rao and B. Chowdari, Nanophase ZnCo₂O₄ as a high performance anode material for Li-ion batteries, *Adv. Funct. Mater.*, 2007, **17**, 2855–2861.
 - 38 H. Jung, T.-T. Pham and E. W. Shin, Effect of g-C₃N₄ precursors on the morphological structures of g-C₃N₄/ZnO composite photocatalysts, *J. Alloys Compd.*, 2019, **788**, 1084–1092.
 - 39 B. Cui, H. Lin, X.-C. Zhao, J.-B. Li and W.-D. Li, Visible light induced photocatalytic activity of ZnCo₂O₄ nanoparticles, *Acta Phys.-Chim. Sin.*, 2011, **27**, 2411–2415.
 - 40 T. Chang, Z. Li, G. Yun, Y. Jia and H. Yang, Enhanced photocatalytic activity of ZnO/CuO nanocomposites synthesized by hydrothermal method, *Nanomicro Lett.*, 2013, **5**, 163–168.
 - 41 M. Taufique, A. Haque, P. Karnati and K. Ghosh, ZnO–CuO nanocomposites with improved photocatalytic activity for environmental and energy applications, *J. Electron. Mater.*, 2018, **47**, 6731–6745.
 - 42 K. Goswami, R. Ananthkrishnan and S. Mandal, Facile synthesis of cation doped ZnO-ZnCo₂O₄ hetero-nanocomposites for photocatalytic decomposition of aqueous organics under visible light, *Mater. Chem. Phys.*, 2018, **206**, 174–185.
 - 43 B. Tan, Y. Fang, Q. Chen, X. Ao and Y. Cao, Preparation of a CaFe₂O₄/ZnCo₂O₄ composite material and its photocatalytic degradation of tetracycline, *Opt. Mater.*, 2020, **109**, 110470.
 - 44 D. Upadhaya and D. D. Purkayastha, Self-cleaning activity of CuO/ZnO heterostructure: A synergy of photocatalysis and hydrophilicity, *J. Taiwan Inst. Chem. Eng.*, 2022, **132**, 104216.



- 45 L. Zhu, H. Li, Z. Liu, P. Xia, Y. Xie and D. Xiong, Synthesis of the 0D/3D CuO/ZnO heterojunction with enhanced photocatalytic activity, *J. Phys. Chem. C*, 2018, **122**, 9531–9539.
- 46 R. Jahanshahi, A. Mohammadi, M. Doosti, S. Sobhani and J. M. Sansano, ZnCo₂O₄/g-C₃N₄/Cu nanocomposite as a new efficient and recyclable heterogeneous photocatalyst with enhanced photocatalytic activity towards the metronidazole degradation under the solar light irradiation, *Environ. Sci. Pollut. Res.*, 2022, **29**, 65043–65060.
- 47 Z. Li, B. Gao, G. Z. Chen, R. Mokaya, S. Sotiropoulos and G. L. Puma, Carbon nanotube/titanium dioxide (CNT/TiO₂) core-shell nanocomposites with tailored shell thickness, CNT content and photocatalytic/photoelectrocatalytic properties, *Appl. Catal., B*, 2011, **110**, 50–57.
- 48 S. Song, B. Cheng, N. Wu, A. Meng, S. Cao and J. Yu, Structure effect of graphene on the photocatalytic performance of plasmonic Ag/Ag₂CO₃-rGO for photocatalytic elimination of pollutants, *Appl. Catal., B*, 2016, **181**, 71–78.
- 49 X. An and C. Y. Jimmy, Graphene-based photocatalytic composites, *RSC Adv.*, 2011, **1**, 1426–1434.
- 50 Y. Pan, X. Liu, W. Zhang, Z. Liu, G. Zeng, B. Shao, Q. Liang, Q. He, X. Yuan and D. Huang, Advances in photocatalysis based on fullerene C60 and its derivatives: Properties, mechanism, synthesis, and applications, *Appl. Catal., B*, 2020, **265**, 118579.
- 51 M. Aadil, S. Zulfiqar, M. Shahid, P. O. Agboola, S. Haider, M. F. Warsi and I. Shakir, Fabrication of rationally designed CNTs supported binary nanohybrid with multiple approaches to boost electrochemical performance, *J. Electroanal. Chem.*, 2021, **884**, 115070.
- 52 M. Ahmad, I. Ahmad, E. Ahmed, M. S. Akhtar and N. Khalid, Facile and inexpensive synthesis of Ag doped ZnO/CNTs composite: Study on the efficient photocatalytic activity and photocatalytic mechanism, *J. Mol. Liq.*, 2020, **311**, 113326.
- 53 D. Saravanakumar, H. Abou Oualid, Y. Brahmi, A. Ayeshamariam, M. Karunanaithy, A. M. Saleem, K. Kaviyarasu, S. Sivaranjani and M. Jayachandran, Synthesis and characterization of CuO/ZnO/CNTs thin films on copper substrate and its photocatalytic applications, *OpenNano*, 2019, **4**, 100025.
- 54 M. Priya, S. Udhayan, P. Vasantharani and G. Sivakumar, Energy storage performance and photocatalytic activity of Diamond-like ZnCo₂O₄ nanostructure, *Inor. Chem. Commun.*, 2023, **153**, 110762.
- 55 C. Wang, H. Wang, L. Li, R. Zhao, J. Han and L. Wang, Hollow rod-shaped Cu-In-Zn-S@ ZnCo₂O₄@ In₂O₃ tandem heterojunction for efficient visible light-induced photocatalytic hydrogen production, *Fuel*, 2024, **355**, 129537.
- 56 M. Ahmad, E. Ahmed, Z. Hong, X. Jiao, T. Abbas and N. Khalid, Enhancement in visible light-responsive photocatalytic activity by embedding Cu-doped ZnO nanoparticles on multi-walled carbon nanotubes, *Appl. Surf. Sci.*, 2013, **285**, 702–712.
- 57 A. Muthuvel, M. Jothibas and C. Manoharan, Synthesis of copper oxide nanoparticles by chemical and biogenic methods: photocatalytic degradation and in vitro antioxidant activity, *Nanotechnol. Environ. Eng.*, 2020, **5**, 14.
- 58 X. Song, Q. Ru, B. Zhang, S. Hu and B. An, Flake-by-flake ZnCo₂O₄ as a high capacity anode material for lithium-ion battery, *J. Alloys Compd.*, 2014, **585**, 518–522.
- 59 M. Ikram, M. M. Baig, I. Shakir, A. Irshad, Z. A. AlOthman, M. F. Warsi and S. G. Lee, Boosting the electrochemical properties of MoO₃/MnFe₂O₄/MXene for high-performance supercapacitor applications, *J. Energy Storage*, 2024, **90**, 111746.
- 60 S. H. Kim, A. Umar and S.-W. Hwang, Rose-like CuO nanostructures for highly sensitive glucose chemical sensor application, *Ceram. Int.*, 2015, **41**, 9468–9475.
- 61 S. S. Abdullaev, Y. F. Breesam, A. A. AlZubaidi, A. K. Tripathi, A. Kareem, S. V. Kuznetsov, T. Alawsi and R. S. Zabibah, ZnO@ ZnCo₂O₄ core-shell: a novel high electrocatalytic nanostructure to replace platinum as the counter electrode in dye-sensitized solar cells, *Mater. Sci. Semicond. Process.*, 2023, **165**, 107709.
- 62 A. Sivakumar, S. Soundarya, S. S. Jude Dhas, K. K. Bharathi and S. M. B. Dhas, Shock wave driven solid state phase transformation of Co₃O₄ to CoO nanoparticles, *J. Phys. Chem. C*, 2020, **124**, 10755–10763.
- 63 S. Li, Z. Hou, Z. Cheng, H. Lian, C. Li and J. Lin, Enhanced near-infrared quantum cutting luminescence in 1, 2, 4, 5-benzenetetracarboxylic acid/NaYF₄: Tb³⁺, Yb³⁺ hybrid nanoparticles, *RSC Adv.*, 2013, **3**, 5491–5497.
- 64 M. U. Khalid, K. M. Katubi, S. Zulfiqar, Z. Alrowaili, M. Aadil, M. Al-Buriahi, M. Shahid and M. F. Warsi, Boosting the electrochemical activities of MnO₂ for next-generation supercapacitor application: adaptation of multiple approaches, *Fuel*, 2023, **343**, 127946.
- 65 M. Aadil, A. G. Taki, S. Zulfiqar, A. Rahman, M. Shahid, M. F. Warsi, Z. Ahmad, A. A. AlOthman and S. Mohammad, Gadolinium doped zinc ferrite nanoarchitecture reinforced with a carbonaceous matrix: a novel hybrid material for next-generation flexible capacitors, *RSC Adv.*, 2023, **13**, 28063–28075.
- 66 D. Arun Kumar, J. Merline Shyla and F. P. Xavier, Synthesis and characterization of TiO₂/SiO₂ nano composites for solar cell applications, *Appl. Nanosci.*, 2012, **2**, 429–436.
- 67 A. K. Thakur, A. B. Deshmukh, R. B. Choudhary, I. Karbhal, M. Majumder and M. V. Shelke, Facile synthesis and electrochemical evaluation of PANI/CNT/MoS₂ ternary composite as an electrode material for high performance supercapacitor, *Mater. Sci. Eng. B*, 2017, **223**, 24–34.
- 68 M. Y. Guo, F. Liu, Y. H. Leung, A. M. C. Ng, A. B. Djurišić and W. K. Chan, TiO₂-carbon nanotube composites for visible photocatalysts—Influence of TiO₂ crystal structure, *Curr. Appl. Phys.*, 2013, **13**, 1280–1287.
- 69 M. Ikram, A. Irshad, K. M. Katubi, Z. Alrowaili, M. Al-Buriahi and M. F. Warsi, Enhanced electrochemical activity of chemically engineered rGO-decorated NiO/CoFe₂O₄ for supercapacitor applications, *Ceram. Int.*, 2024, **50**, 19578–19591.



- 70 B. Singh, A. Singh, A. Sharma, P. Mahajan, S. Verma, B. Padha, A. Ahmed and S. Arya, Electrochemical sensing and photocatalytic degradation of 2, 4-dinitrophenol via bismuth (III) oxide nanowires, *J. Mol. Struct.*, 2022, **1255**, 132379.
- 71 H. Chen, J. Wang, X. Han, F. Liao, Y. Zhang, L. Gao and C. Xu, Facile synthesis of mesoporous ZnCo₂O₄ hierarchical microspheres and their excellent supercapacitor performance, *Ceram. Int.*, 2019, **45**, 8577–8584.
- 72 L. Xie, Y. Liu, H. Bai, C. Li, B. Mao, L. Sun and W. Shi, Core-shell structured ZnCo₂O₄@ ZnWO₄ nanowire arrays on nickel foam for advanced asymmetric supercapacitors, *J. Colloid Interface Sci.*, 2018, **531**, 64–73.
- 73 S. Khan, A. Noor, I. Khan, M. Muhammad, M. Sadiq and N. Muhammad, Photocatalytic degradation of organic dyes contaminated aqueous solution using binary CdTiO₂ and ternary NiCdTiO₂ nanocomposites, *Catalysts*, 2022, **13**, 44.
- 74 A. Farooq, M. Anwar, H. Somaily, S. Zulfiqar, M. F. Warsi, M. I. Din, A. Muhammad and A. Irshad, Fabrication of Ag-doped magnesium aluminate/rGO composite: a highly efficient photocatalyst for visible light-driven photodegradation of crystal violet and phenol, *Phys. B*, 2023, **650**, 414508.
- 75 S. M. Botsa and K. Basavaiah, Removal of Nitrophenols from wastewater by monoclinic CuO/RGO nanocomposite, *Nanotechnol. Environ. Eng.*, 2019, **4**, 1–7.
- 76 H. M. Abo-Dief, S. M. El-Bahy, O. K. Hussein, Z. M. El-Bahy, M. Shahid and I. Shakir, Synthesis and characterization of rGO supported silver doped bimetallic ZnCo₂O₄ spinel oxides for enhanced photocatalytic degradation of industrial effluents, *J. Alloys Compd.*, 2022, **913**, 165164.
- 77 N. Kitchamsetti, D. Narsimulu, A. Chinthakuntla, C. S. Chakra and A. L. de Barros, Bimetallic MOF derived ZnCo₂O₄ nanocages as a novel class of high performance photocatalyst for the removal of organic pollutants, *Inorg. Chem. Commun.*, 2022, **144**, 109946.
- 78 J. Fatima, M. B. Tahir, M. S. Tahir and M. Sagir, Solar driven photocatalytic dye degradation through the novel Ti₂C–ZnCo₂O₄/MXenes nanocomposite, *Opt. Mater.*, 2022, **133**, 113034.
- 79 A. Dana and S. Sheibani, CNTs-copper oxide nanocomposite photocatalyst with high visible light degradation efficiency, *Adv. Powder Technol.*, 2021, **32**, 3760–3769.
- 80 R. S. Shinde, S. D. Khairnar, M. R. Patil, V. A. Adole, P. B. Koli, V. V. Deshmane, D. K. Halwar, R. A. Shinde, T. B. Pawar and B. S. Jagdale, Synthesis and characterization of ZnO/CuO nanocomposites as an effective photocatalyst and gas sensor for environmental remediation, *J. Inorg. Organomet. Polym. Mater.*, 2022, 1–22.
- 81 F. A. Cataño, G. Cáceres, A. Burgos and R. S. Schrebler, Synthesis and characterization of a ZnO/CuO/Ag composite and its application as a photocatalyst for methyl orange degradation, *Int. J. Electrochem. Sci.*, 2018, **13**, 9242–9256.
- 82 N. Shaheen, M. F. Warsi, S. Zulfiqar, J. T. Althakafy, A. K. Alanazi, M. I. Din, H. M. Abo-Dief and M. Shahid, La-doped WO₃@ gCN Nanocomposite for Efficient degradation of cationic dyes, *Ceram. Int.*, 2023, **49**, 15507–15526.
- 83 Y. Chen, C. Chen, Y. Liu and L. Yu, Probing the effect of nitrate anion in CAN: An additional opportunity to reduce the catalyst loading for aerobic oxidations, *Chin. Chem. Lett.*, 2023, **34**, 108489.
- 84 O. Bechambi, S. Sayadi and W. Najjar, Photocatalytic degradation of bisphenol A in the presence of C-doped ZnO: effect of operational parameters and photodegradation mechanism, *J. Ind. Eng. Chem.*, 2015, **32**, 201–210.
- 85 S.-M. Lam, J.-C. Sin, A. Z. Abdullah and A. R. Mohamed, Degradation of wastewaters containing organic dyes photocatalysed by zinc oxide: a review, *Desalin. Water Treat.*, 2012, **41**, 131–169.
- 86 A. Rahman, M. Aadil, M. Akhtar, M. F. Warsi, A. Jamil, I. Shakir and M. Shahid, Magnetically recyclable Ni_{1-x}Cd_xCe_yFe_{2-y}O₄-rGO nanocomposite photocatalyst for visible light driven photocatalysis, *Ceram. Int.*, 2020, **46**, 13517–13526.

