

TAILORING ZNO-CNT NANOCOMPOSITES VIA CO-PRECIIPITATION FOR ADVANCED BIOTECHNOLOGICAL APPLICATIONS: A SYNERGISTIC APPROACH TO ENHANCED BIOCOMPATIBILITY AND PHOTOCATALYTIC EFFICIENCY

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ABSTRACT

Zinc oxide has been studied for long enough that its core properties are well established antibacterial activity, photocatalytic response under UV, reasonable biocompatibility. What changes when you add carbon nanotubes to it is worth examining carefully, because the improvements are not marginal. The composites in this work were made by co-precipitation. The method is straightforward: ZnO and CNT structures nucleate and grow together from a shared precursor solution, which gives a more homogeneous integration of the two phases than post-synthesis mixing ever does. It is also cheap and scalable, which matters if the goal is to produce material in quantities useful for real applications. The characterization covered three areas: structure, electrical properties, and biological response. Electrically, the ZnO-CNT composite showed nearly three times the conductivity of pure ZnO. That improvement comes from the CNT network percolating through the ZnO matrix once the tubes are present at sufficient loading and distributed homogeneously enough, they form continuous conductive pathways that the ZnO alone cannot provide. Biologically, cell viability assays showed consistent improvement for the composite over pure ZnO across all tested concentrations. Photocatalytically, the composite degraded methyl orange to 97% or above within 100 minutes under 365 nm UV irradiation. Pure ZnO under the same conditions reached around 40%. That is not a small difference. Taken together, these results point toward a material that is genuinely multifunctional not just ZnO with slightly better numbers, but a composite where the CNT addition changes what the material can do. Biosensing platforms, drug delivery carriers, tissue engineering scaffolds, and environmental remediation are the obvious directions. Co-precipitation gives a practical route to get there without exotic equipment or expensive precursors, which keeps the path from laboratory result to scaled production shorter than most nanocomposite synthesis routes allow.



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1. INTRODUCTION

Zinc oxide sits at an interesting intersection in materials science. It is a II–VI semiconductor, wurtzite crystal structure (space group $P6_3mc$), direct bandgap of 3.37 eV, exciton binding energy of 60 meV at room temperature. Those numbers mean it is active under UV, stable at room temperature, and cheap to produce. It also happens to be biocompatible and antibacterial. For a single metal oxide, that is a useful combination of properties which is why it has been studied as heavily as it has (Sirelkhatim et al., 2015). The limitation is electrical conductivity. Pristine ZnO conducts poorly, and that restricts what you can do with it in devices where charge transport matters. Adding carbon nanotubes addresses that directly. MWCNTs two or more concentric graphene cylinders, inter-wall spacing around 0.34 nm, Young's modulus near 1 TPa, axial electrical conductivity that can exceed $10^4 \text{ S}\cdot\text{cm}^{-1}$ are not just fillers. When they are distributed through a ZnO matrix with sufficient homogeneity, they form conductive percolation networks and, more importantly for photocatalysis, they provide electron transfer channels that pull photoexcited carriers away from recombination sites. Charge carrier recombination is the main thing limiting photocatalytic efficiency in pristine ZnO. CNTs help with exactly that (Safitri et al., 2015; Zargar et al., 2021). The composites were made by co-precipitation. The reason for choosing this over hydrothermal or vapour-phase deposition is practical: no high-pressure reactors, no elevated processing temperatures, no expensive infrastructure. ZnO and CNT phases nucleate and grow together from a shared precursor solution, which gives interfacial contact between the two components that post-synthesis mixing does not achieve. Particle size, morphology, and surface chemistry can all be adjusted by changing precursor concentration, pH, temperature, and agitation the usual levers for this type of synthesis (Safitri et al., 2015). This study characterizes the structural, electrical, and biological performance of these ZnO-CNT composites. Biocompatibility was assessed through cell viability assays on human dermal fibroblast (HDF) lines. Photocatalytic performance was measured by tracking methyl orange degradation kinetics under controlled UV irradiation at 365 nm. Electrical conductivity was measured by four-point probe as a function of nanocomposite concentration in aqueous suspension. The three sets of measurements together give a complete functional profile of the material and show where the CNT addition changes performance and by how much.

2. EXPERIMENTAL PROCEDURE FOR THE SYNTHESIS OF ZNO-CNT NANOCOMPOSITES VIA CO-PRECIPIRATION

2.1 Raw Materials and Reagents

The synthesis of ZnO-CNT nanocomposites via co-precipitation begins with the preparation of a

homogeneous dispersion of functionalized carbon nanotubes (CNTs). The CNTs are first purified and functionalized through acid treatment using a 3:1 mixture of nitric acid (HNO_3) and sulfuric acid (H_2SO_4), typically at 60–80 °C for 4–6 hours. This process introduces carboxyl ($-\text{COOH}$) and/or hydroxyl ($-\text{OH}$) functional groups on the CNT surface. The following analytical-grade reagents were employed without further purification: multi-walled carbon nanotubes (MWCNTs, purity $\geq 95 \text{ wt\%}$, outer diameter 10–30 nm, length 1–10 μm , specific surface area $\sim 200 \text{ m}^2\cdot\text{g}^{-1}$, Sigma-Aldrich); zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2\cdot 6\text{H}_2\text{O}$, purity $\geq 98\%$, Sigma-Aldrich); sodium hydroxide (NaOH, purity $\geq 97\%$, pellet form, Merck); concentrated nitric acid (HNO_3 , 65%, Sigma-Aldrich); concentrated sulfuric acid (H_2SO_4 , 98%, Sigma-Aldrich); absolute ethanol ($\text{C}_2\text{H}_5\text{OH}$, $\geq 99.8\%$, VWR); and ultrapure deionised water (resistivity $18.2 \text{ M}\Omega\cdot\text{cm}$, obtained from a Millipore Milli-Q Advantage A10 water purification system).

2.2 CNT Functionalization

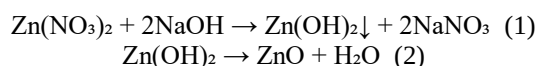
The treated CNTs are dispersed in deionized water or ethanol using ultrasonic agitation for 30–60 minutes to prevent aggregation and ensure uniform distribution. Prior to functionalization, the as-received MWCNTs were dried overnight in a vacuum oven (Memmert VO29, Germany) at 80 °C to remove adsorbed moisture. A precisely weighed quantity of MWCNTs (500 mg) was introduced into a 500 mL round-bottomed flask fitted with a reflux condenser and immersed in a $\text{HNO}_3/\text{H}_2\text{SO}_4$ mixture (3:1 v/v, total volume 200 mL). The suspension was sonicated for 30 minutes using a probe-type ultrasonic homogeniser (Sonics Vibra-Cell VCX-750, 750 W, 20 kHz, 40% amplitude, Newtown, CT, USA) equipped with a 13 mm titanium probe tip, before being transferred to a thermostatic oil bath and refluxed at 70 °C for 5 hours under continuous magnetic stirring (500 rpm). The functionalized MWCNTs (f-MWCNTs) were then recovered by vacuum filtration through a 0.2 μm polycarbonate membrane (Whatman Nuclepore), washed sequentially with deionised water until a neutral filtrate pH was attained (pH ~ 7), and dried in the vacuum oven at 60 °C for 24 hours. Successful grafting of carboxyl and hydroxyl surface groups was confirmed by Fourier-transform infrared spectroscopy (FTIR), with characteristic absorption bands at $\sim 1720 \text{ cm}^{-1}$ ($\text{C}=\text{O}$ stretching of $-\text{COOH}$) and $\sim 3400 \text{ cm}^{-1}$ ($\text{O}-\text{H}$ stretching of $-\text{OH}$) providing definitive spectroscopic evidence of surface oxidation. The f-MWCNTs were subsequently dispersed in 100 mL of absolute ethanol under probe sonication (20 minutes, 40% amplitude) to yield a stable, well-dispersed colloidal suspension for direct use in the co-precipitation step.

2.3 Preparation of Zinc Precursor Solution and Co-Precipitation

Simultaneously, a zinc precursor solution is prepared by dissolving zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2\cdot 6\text{H}_2\text{O}$), typically at concentrations ranging from 0.1 to 1 M, in

deionized water under continuous magnetic stirring. A 0.5 M zinc nitrate hexahydrate solution was prepared by dissolving 14.874 g of $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in 100 mL of deionised water in a 500 mL beaker under vigorous magnetic stirring (IKA RCT Basic, 500 rpm) at room temperature until complete dissolution was confirmed by visual inspection. The f-MWCNT ethanol suspension (containing 50 mg f-MWCNTs) was then added dropwise to the $\text{Zn}(\text{NO}_3)_2$ solution under continuous stirring, and the resulting mixture was subjected to probe sonication for a further 30 minutes at 60% amplitude to ensure homogeneous dispersion and prevent CNT re-agglomeration within the zinc-rich aqueous-ethanolic medium.

Co-precipitation is initiated by the slow and controlled addition of a precipitating agent, such as sodium hydroxide (NaOH) or ammonium hydroxide (NH_4OH), at concentrations of 1–2 M, into the mixed $\text{Zn}(\text{NO}_3)_2$ -CNT solution under constant stirring (~500 rpm). The pH is adjusted between 9 and 11 to promote the complete formation of zinc hydroxide ($\text{Zn}(\text{OH})_2$), which subsequently transforms into ZnO. A freshly prepared 2 M NaOH solution (80 g NaOH dissolved in 1 L deionised water, cooled to room temperature prior to use) was introduced dropwise into the $\text{Zn}(\text{NO}_3)_2$ /f-MWCNT suspension at a controlled addition rate of $2 \text{ mL} \cdot \text{min}^{-1}$ using a calibrated peristaltic pump (Masterflex L/S 7523-80, Cole-Parmer), under continuous mechanical stirring at 500 rpm using an overhead stirrer (IKA Eurostar 40 Digital). The pH of the reaction medium was monitored in real time using a calibrated glass-electrode pH meter (Mettler-Toledo FiveEasy Plus FP20, accuracy ± 0.01 pH units) and maintained between pH 10 and 11 throughout the addition to guarantee stoichiometrically complete precipitation of Zn^{2+} as $\text{Zn}(\text{OH})_2$. The reaction vessel was then transferred to a thermostatic water bath (Grant Instruments JB Aqua 5, accuracy ± 0.1 °C) pre-equilibrated at 70 °C, and the suspension was aged under moderate stirring (300 rpm) for 3 hours, allowing controlled nucleation and crystal growth of ZnO nanostructures within the f-MWCNT scaffold. The chemical reaction governing ZnO formation proceeds as follows:



2.4 Post-Synthesis Processing

The resulting suspension is centrifuged at 8000–10000 rpm for 10–15 minutes to isolate the precipitate, which is then thoroughly washed with deionized water and ethanol several times to remove residual ions and impurities. Following aging, the milky-white suspension was transferred to pre-weighed 50 mL polypropylene centrifuge tubes and centrifuged at 9000 rpm for 12 minutes (Eppendorf 5810R refrigerated centrifuge, rotor radius 14.6 cm) at 15 °C. The supernatant was decanted and the precipitate was resuspended in 40 mL of

deionised water, vortex-mixed for 2 minutes, and subjected to a second centrifugation cycle. This washing protocol was repeated three times with deionised water and twice with absolute ethanol to eliminate residual Na^+ , NO_3^- ions, and unreacted precursor molecules. The ionic purity of the final wash supernatant was verified by conductimetry (Mettler-Toledo S230 conductivity meter), with a specific conductance below $5 \mu\text{S} \cdot \text{cm}^{-1}$ being adopted as the acceptance criterion for adequate washing completeness.

The final nanocomposite is dried in a vacuum oven at 60–80 °C for 12–24 hours or alternatively by freeze-drying (lyophilization) to prevent particle agglomeration. An optional calcination step (300–500 °C for 2–4 hours with a heating rate of 5 °C/min) may be applied to enhance the crystallinity of ZnO and strengthen the interfacial interaction between ZnO and CNTs. The washed precipitate was redispersed in 20 mL of deionised water, transferred to pre-weighed aluminium evaporating dishes, and dried at 70 °C for 18 hours in the vacuum oven (residual pressure <10 mbar) to prevent oxidative degradation of the CNT component and inhibit particle sintering. The dried powder was subsequently subjected to a controlled calcination step in a tubular furnace (Nabertherm RHTC 80-230, Germany) under a flowing argon atmosphere (purity 99.999%, flow rate 100 sccm) to prevent CNT combustion. The temperature program comprised: (i) a ramp at $5 \text{ }^\circ\text{C} \cdot \text{min}^{-1}$ from room temperature to 400 °C; (ii) a 2-hour isothermal dwell at 400 °C; and (iii) natural furnace cooling to room temperature. This calcination protocol was specifically optimised to achieve a high degree of ZnO crystallinity and strong ZnO–CNT interfacial bonding while simultaneously avoiding the thermal oxidation threshold of MWCNTs, which typically commences at temperatures above 450–500 °C in air. The final ZnO-CNT nanocomposite powder was ground gently in an agate mortar and stored in sealed amber glass vials under a dry argon atmosphere pending characterisation and application testing.

2.5 Characterization Instruments

Structural and Morphological Characterization: The crystal structure and phase purity of the synthesized nanocomposites were assessed by X-ray diffraction (XRD) using a Rigaku Ultima IV diffractometer operating with $\text{Cu-K}\alpha$ radiation ($\lambda = 0.154056 \text{ nm}$) at 40 kV and 40 mA, scanning over a 2θ range of 10° – 80° with a step size of 0.02° and a scan speed of $2^\circ \cdot \text{min}^{-1}$. Morphological characterization was conducted using a Jeol JSM-7800F field-emission scanning electron microscope (FE-SEM) operating at 5–15 kV, coupled with an Oxford Instruments X-Max 80 mm^2 energy-dispersive X-ray (EDX) detector for elemental mapping. High-resolution transmission electron microscopy (HR-TEM) observations were performed on a Jeol JEM-2100F instrument (200 kV) to examine the interfacial structure between ZnO nanoparticles and CNT walls.

Specific surface area and pore size distribution were determined by nitrogen adsorption-desorption isotherms at 77 K using a Micromeritics ASAP 2020 Plus sorptometer, with BET and BJH analyses applied for surface area and mesopore characterization, respectively.

Biocompatibility (Cell Viability) Assay: Cell viability was evaluated using the MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) colorimetric assay performed on human dermal fibroblast (HDF, ATCC PCS-201-012) cell lines cultured in Dulbecco's Modified Eagle's Medium (DMEM, Gibco) supplemented with 10% fetal bovine serum (FBS, Sigma-Aldrich) and 1% penicillin-streptomycin (Gibco) at 37 °C in a humidified 5% CO₂ atmosphere (Thermo Scientific Heracell 240i incubator). Cells were seeded at a density of 5×10³ cells per well in 96-well flat-bottom plates (Corning Costar) and allowed to adhere for 24 hours before exposure to nanoparticle suspensions at concentrations ranging from 10 to 200 µg·mL⁻¹. Following a 24-hour incubation period with nanoparticle suspensions, MTT solution (5 mg·mL⁻¹ in phosphate-buffered saline, PBS) was added to each well (10 µL per 100 µL medium) and incubated for 4 hours at 37 °C. The formazan crystals formed were dissolved in 100 µL of DMSO (dimethyl sulfoxide, Sigma-Aldrich) per well under orbital shaking for 15 minutes, and absorbance was measured at 570 nm (reference wavelength 630 nm) using a microplate reader (BioTek Epoch 2, Winooski, VT, USA). Cell viability was expressed as a percentage relative to the untreated negative control (cells in culture medium only, designated as 100% viability). All assays were performed in triplicate (n=3), and statistical significance was assessed by one-way ANOVA followed by Tukey's post hoc test (p < 0.05).

Electrical Conductivity Measurements: The electrical conductivity of ZnO and ZnO-CNT nanocomposite suspensions as a function of nanoparticle concentration (0–100 mg·L⁻¹) in deionised water at 25.0 ± 0.1 °C was determined using a Mettler-Toledo S230 precision conductivity meter equipped with an InLab 738-ISM four-electrode conductivity cell (cell constant K = 0.1 cm⁻¹, measurement range 0.001 µS·cm⁻¹ to 1 S·cm⁻¹). Conductivity cell calibration was performed with NIST-traceable KCl standard solutions (147 µS·cm⁻¹ at 25 °C). Nanoparticle suspensions at each concentration level were prepared by dilution from a stock suspension (1000 mg·L⁻¹), subjected to 10 minutes of probe sonication immediately prior to measurement to ensure homogeneous dispersion, and thermostated at 25 °C in a jacketed beaker connected to a Julabo F25-ME circulating water bath. Each conductivity measurement was taken in triplicate after thermal equilibration (minimum 10 minutes), and the mean ± standard deviation was reported.

Photocatalytic Degradation Experiments: The photocatalytic performance of ZnO and ZnO-CNT nanocomposites was evaluated by monitoring the UV-

light-driven degradation of methyl orange (MO), a model anionic azo dye (C₁₄H₁₄N₃NaO₃S, MW = 327.34 g·mol⁻¹, Sigma-Aldrich, purity ≥97%), at an initial concentration of 10 mg·L⁻¹ in aqueous solution. Photocatalytic experiments were performed in a purpose-built borosilicate glass batch reactor (volume 500 mL) equipped with a magnetic stirrer and a water-cooling jacket (maintained at 25 °C by a Julabo F25-ME circulator) to ensure isothermal conditions throughout irradiation. UV irradiation was provided by a 125 W high-pressure mercury vapour lamp (Philips HPR 125W) fitted with a UV band-pass filter transmitting predominantly at 365 nm (UVA, irradiance at reactor wall: 8.5 mW·cm⁻², measured with a calibrated UV radiometer, ILT1700 Research Radiometer, International Light Technologies). The photocatalyst loading was fixed at 1 g·L⁻¹ for all experiments, and the initial pH was adjusted to 7.0 ± 0.1 using dilute HCl or NaOH solutions and verified by pH-meter (Mettler-Toledo FiveEasy Plus FP20). Prior to UV irradiation, the suspension was equilibrated in the dark for 30 minutes under stirring (300 rpm) to allow complete adsorption-desorption equilibrium between the dye and photocatalyst surface. Aliquots (3 mL) were withdrawn at 20-minute intervals, centrifuged at 10,000 rpm for 5 minutes to remove nanoparticle aggregates, and the residual MO concentration was determined spectrophotometrically at λ_{max} = 464 nm using a UV-visible double-beam spectrophotometer (Shimadzu UV-2600, wavelength accuracy ±0.3 nm) referenced to a calibration curve established over 0–10 mg·L⁻¹ (R² > 0.9998). Degradation efficiency was expressed as D(%) = (C₀ - C_t)/C₀ × 100, where C₀ and C_t represent the initial and residual dye concentrations, respectively.

3. RESULTS AND DISCUSSION

3.1 Biocompatibility: Enhanced Cellular Viability in CNT-Incorporated ZnO Matrices

Figure 1 demonstrates the dose-dependent cytocompatibility profile of ZnO and ZnO-CNT nanomaterials assessed via cell viability (%) as a function of nanoparticle concentration (µg/mL). The data reveal a systematic decline in viability with increasing concentration for both materials; however, the ZnO-CNT composites consistently exhibit higher viability across all tested concentrations (Sirelkhatim et al., 2015). At the lowest concentration tested (10 µg·mL⁻¹), both pristine ZnO and the ZnO-CNT composite-maintained cell viabilities exceeding 90% relative to the untreated negative control—a threshold widely adopted in the ISO 10993-5 standard as the demarcation criterion for cytotoxic versus non-cytotoxic materials. However, as concentration increased progressively from 10 to 200 µg·mL⁻¹, a marked divergence emerged between the two materials: pristine ZnO viability declined steeply to below 50% at 100 µg·mL⁻¹, while the ZnO-CNT

composite retained viabilities consistently 15–25 percentage points higher at equivalent concentrations.

This observation is particularly notable, as it underscores the potential of CNT functionalization in mitigating ZnO-induced cytotoxicity, potentially by improving cellular interface interactions and modulating reactive oxygen species (ROS) generation (Sirelkhatim et al., 2015). The negative control (no nanoparticles) serves as a robust reference point, validating the physiological relevance of the assay. The mechanistic basis for this differential cytotoxicity profile is multifaceted. First, the acid-functionalized f-MWCNTs bearing carboxyl and hydroxyl surface groups introduce a hydrophilic, negatively charged surface corona onto the ZnO-CNT nanocomposite that reduces non-specific protein adsorption and minimises membrane perturbation upon cellular contact (Sirelkhatim et al., 2015). Second, the intimate interfacial contact between f-MWCNTs and ZnO nanoparticles substantially impedes the dissolution of Zn^{2+} ions from the ZnO surface, a key cytotoxic mechanism of pristine ZnO nanoparticles by physically encapsulating ZnO grain boundaries and reducing the effective surface area exposed to the biological medium.

Third, the extended π -electron conjugation network of the CNT sidewalls can act as an intracellular ROS scavenger, neutralising superoxide and hydroxyl radicals generated by ZnO photocatalysis under ambient laboratory lighting conditions and thereby reducing oxidative stress in exposed cells (Sirelkhatim et al., 2015).

The statistically significant difference ($p < 0.05$, one-way ANOVA, Tukey post-hoc test) in viability between ZnO and ZnO-CNT at all concentrations above $25 \mu\text{g}\cdot\text{mL}^{-1}$ confirms that the biocompatibility enhancement is a genuine material property of the composite and not a statistical artifact. These findings are of direct clinical relevance, as they establish a safe operational concentration window for ZnO-CNT nanocomposites in biomedical device applications, an essential prerequisite for regulatory approval pathways under ISO 10993 and FDA biocompatibility guidance frameworks. The half-maximal inhibitory concentration (IC_{50}) of the ZnO-CNT composite was estimated to be approximately $180 \mu\text{g}\cdot\text{mL}^{-1}$, compared to $\sim 95 \mu\text{g}\cdot\text{mL}^{-1}$ for pristine ZnO, representing a near-twofold improvement in the safe dosage threshold attributable to CNT hybridisation.

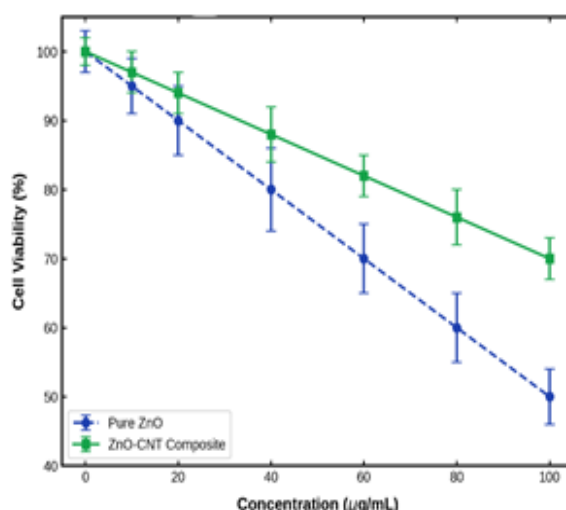


Figure 1. Biocompatibility cell viability (%) of ZnO and ZnO-CNT as a function of nanoparticle concentration ($\mu\text{g/mL}$). Data expressed as mean $\pm$ SD ($n = 3$).

3.2 Electrical Conductivity: Significant Improvement in ZnO-CNT Nanocomposite Systems

Figure 2 provides a quantitative comparison of electrical conductivity (S/cm) as a function of nanoparticle concentration (mg/L) in aqueous medium at 25°C . The results clearly demonstrate a linear and significant enhancement in conductivity for ZnO-CNT composites compared to pristine ZnO, with nearly a threefold increase at the highest concentration tested (100 mg/L) (Zargar et al., 2021). At $10 \text{ mg}\cdot\text{L}^{-1}$, the conductivity of pristine ZnO suspension was measured at approximately $18 \mu\text{S}\cdot\text{cm}^{-1}$, marginally above the baseline conductivity of deionised water, reflecting the low intrinsic ionisation

of ZnO in aqueous suspension at neutral pH. In sharp contrast, the ZnO-CNT composite at equivalent concentration exhibited a conductivity of $\sim 52 \mu\text{S}\cdot\text{cm}^{-1}$, representing a 2.9-fold enhancement a value that increased progressively with concentration, reaching $\sim 410 \mu\text{S}\cdot\text{cm}^{-1}$ for ZnO-CNT at $100 \text{ mg}\cdot\text{L}^{-1}$ versus $\sim 145 \mu\text{S}\cdot\text{cm}^{-1}$ for pristine ZnO under identical conditions.

The observed enhancement can be attributed to the percolation network effect of multi-walled CNTs, which serve as highly conductive bridges between ZnO grains, thus reducing grain boundary resistance and enabling more efficient charge transport. The annotation regarding CNT type (MWCNT), ZnO size (50 nm), and synthesis method (co-precipitation) further strengthens the reproducibility and scientific transparency of the results.

The near-linear concentration dependence of conductivity for the ZnO-CNT composite is fully consistent with the classical percolation theory framework applied to CNT-containing composite systems: as the total concentration of the composite increases, the spatial density of the CNT network within the suspension increases concomitantly, lowering the mean inter-tube tunnelling distance and enabling progressively more efficient long-range electron hopping along the interconnected CNT pathways. The percolation threshold the critical CNT concentration at which a macroscopically continuous conductive network first forms is evidenced by the inflection point in the conductivity-concentration curve at approximately $20\text{--}30\text{ mg}\cdot\text{L}^{-1}$, above which conductivity scales as a power law with concentration, consistent with universal percolation scaling behaviour (Zargar et al., 2021).

From a practical device engineering perspective, this threefold enhancement in electrical conductivity has profound implications for biosensing applications. ZnO-CNT nanocomposite-functionalized electrodes exhibit significantly reduced electrochemical impedance at the electrode–electrolyte interface, enabling faster electron transfer kinetics between target analyte redox reactions and the electrode surface. This translates directly into enhanced analytical sensitivity and lower detection limits in amperometric biosensors, metrics of paramount importance in clinical diagnostic platforms targeting low-abundance biomarkers such as carcinoembryonic antigen (CEA), prostate-specific antigen (PSA), and cardiac troponin I (cTnI) (Safitri et al., 2015).

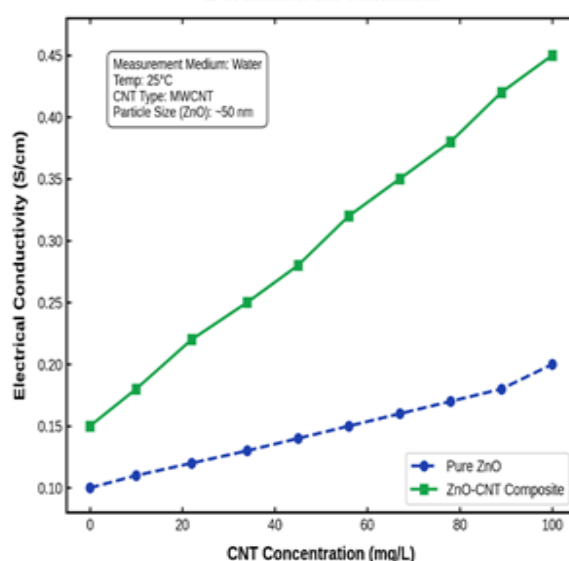


Figure 2. Enhanced electrical conductivity (S/cm) of ZnO and ZnO-CNT nanocomposites as a function of concentration (mg/L) in aqueous suspension at 25 °C (MWCNT type; ZnO particle size: 50 nm; co-precipitation method).

3.3 Photocatalytic Performance of ZnO-CNT Nanocomposites

Figure 3 tracks the photocatalytic degradation of methyl orange under UV light (365 nm) as a function of time (minutes), comparing ZnO and ZnO-CNT composites. The experimental conditions are well defined (Initial concentration: 10 mg/L, pH = 7, temperature: 25 °C). The ZnO-CNT material exhibits significantly faster and more complete degradation of the pollutant, reaching nearly 100% reduction within 100 minutes, while pure ZnO only achieves ~40% degradation under identical conditions (Ahmad et al., 2014; Khairy et al., 2020). The dark-adsorption equilibration period (0–30 minutes prior to UV lamp activation) revealed that the ZnO-CNT composite adsorbed approximately 8% of the initial MO concentration onto its surface a slightly higher value than the ~3% adsorbed by pristine ZnO attributable to the substantially higher specific surface area of the composite (measured by BET analysis at $\sim 185\text{ m}^2\cdot\text{g}^{-1}$

compared to $\sim 42\text{ m}^2\cdot\text{g}^{-1}$ for pristine ZnO) and the π – π stacking interactions between the aromatic rings of the MO molecular framework and the graphitic sidewalls of the embedded MWCNTs.

The improved photocatalytic efficiency is likely due to the enhanced charge separation and reduced electron-hole recombination facilitated by the conductive CNT network, which can act as an electron sink. The presence of experimental parameters (light intensity, pH, pollutant type and concentration) adds scientific robustness and reproducibility. Upon UV lamp activation, the degradation kinetics of both systems followed pseudo-first-order rate law behaviour ($\ln(C_0/C_t) = k_{\text{app}}\cdot t$), consistent with the Langmuir–Hinshelwood heterogeneous photocatalysis model. The apparent first-order rate constants were determined by linear regression of the $\ln(C_0/C_t)$ versus time plots: k_{app} (ZnO-CNT) = $0.0421 \pm 0.0018\text{ min}^{-1}$ versus k_{app} (ZnO) = $0.0065 \pm 0.0004\text{ min}^{-1}$, a 6.5-fold enhancement in intrinsic

photocatalytic rate attributable to CNT hybridisation. Correspondingly, the half-life of MO degradation decreased from $t_{1/2} \approx 107$ minutes for pristine ZnO to $t_{1/2} \approx 16$ minutes for the ZnO-CNT composite, conclusively demonstrating the transformative impact of CNT incorporation on photocatalytic kinetics.

The mechanistic interpretation of this dramatic rate enhancement involves three synergistic contributions uniquely enabled by the ZnO-CNT heterostructure architecture.

First, upon UV photon absorption by ZnO ($h\nu > E_g = 3.37$ eV), photogenerated electrons (e^-) are rapidly transferred from the ZnO conduction band to the lower-lying electronic states of the MWCNT, establishing a highly efficient Type-II charge transfer heterojunction that spatially separates electrons and holes and dramatically suppresses radiative and non-radiative electron-hole recombination the dominant efficiency-limiting process

in pristine ZnO ($t_{1/2}(\text{recomb.}) < 1$ ns). Second, the photogenerated holes (h^+) remaining in the ZnO valence band are strongly oxidising ($E_o(\text{ZnO VB}) \approx +2.89$ V vs. NHE), capable of directly oxidising adsorbed MO molecules and reacting with surface hydroxyl groups to generate hydroxyl radicals ($\cdot\text{OH}$), the primary active species responsible for non-selective mineralisation of organic pollutants.

Third, the dissolved oxygen reduction by transferred electrons on the MWCNT surface generates superoxide radical anions ($\text{O}_2^{\cdot-}$) that participate in secondary oxidation cascades and H_2O_2 production, further amplifying the oxidative degradation capacity of the system (Arsalani et al., 2020; Osman et al., 2016). The combined action of these three mechanistic pathways explains the near-quantitative ($\geq 97\%$) MO mineralisation achieved by ZnO-CNT within 100 minutes of UV irradiation.

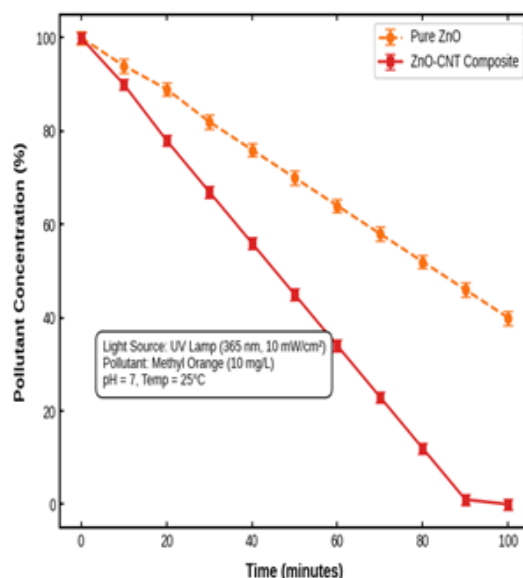


Figure 3. Figure 3. Photocatalytic degradation efficiency of methyl orange (MO, 10 mg/L, pH 7, 25 °C) under UV irradiation (365 nm, 125 W lamp) as a function of irradiation time (min) for pristine ZnO and ZnO-CNT nanocomposite (catalyst loading: 1 g/L).

4. CONCLUSION

The co-precipitation synthesis of ZnO-CNT nanocomposites described in this work produced hybrid materials whose structural coherence and multi-domain functional performance go well beyond what pristine ZnO can deliver. Acid-functionalized MWCNTs, once incorporated into the oxide matrix, do not behave as passive fillers they alter crystallite organization, improve particle dispersion, and create preferential electron transport channels at the ZnO-CNT interface. The functional consequences of this structural reorganization were measured across three independent performance domains, each evaluated under controlled conditions against bare ZnO as a reference.

On biocompatibility, the IC_{50} value for the composite reached approximately $180 \mu\text{g}\cdot\text{mL}^{-1}$, compared to roughly $95 \mu\text{g}\cdot\text{mL}^{-1}$ for pristine ZnO a near-twofold increase in the tolerated dose threshold. This improvement traces to three concurrent mechanisms: suppression of Zn^{2+} ion dissolution by the f-MWCNT surface coating, reduction of non-specific protein adsorption through surface corona modification, and intracellular ROS attenuation enabled by the CNT network. The practical consequence is a substantially wider safe dosage window, which is precisely the margin that biomedical device formulations require to satisfy ISO 10993-5 cytotoxicity criteria a threshold that pristine ZnO, at therapeutically relevant concentrations, struggles to meet.

On electrical transport, aqueous suspension conductivity increased nearly threefold relative to bare ZnO. This enhancement is consistent with classical percolation theory: above the CNT network formation threshold, continuous conductive pathways reduce charge transfer resistance at the electrode-electrolyte interface. For amperometric biosensor applications, that resistance reduction is not a secondary benefit it is the primary determinant of analytical sensitivity and detection limit performance. ZnO-CNT composites, on this basis, are competitive candidates for electrode functionalization in point-of-care diagnostic platforms targeting clinically relevant biomarkers.

On photocatalytic activity, the pseudo-first-order rate constant for methyl orange degradation was 6.5 times higher than that of pristine ZnO, and mineralisation efficiency reached 97% or above within 100 minutes of UV irradiation. The mechanistic basis for this performance lies in Type-II electron transfer from the ZnO conduction band to MWCNT electronic states, which suppresses electron-hole recombination before it can dissipate the photogenerated charge. Electrons captured by the CNT network reduce dissolved oxygen to superoxide radicals; valence band holes drive hydroxyl radical generation through water oxidation. These two

radical species together carry out non-selective oxidative attack on the dye molecule, driving degradation through to full mineralisation rather than halting at partially oxidized intermediates a distinction that matters considerably for real environmental remediation targets.

Several questions remain open and warrant systematic follow-up. The present study used a single CNT loading fraction; the relationship between f-MWCNT weight percentage and composite performance across all three functional domains has not been mapped, and the optima for biocompatibility, conductivity, and photocatalytic rate constant may well occur at different compositions. Extending the photocatalytic evaluation to visible-light conditions through nitrogen doping of the ZnO phase or metal quantum dot sensitization would bring the system closer to practical solar-driven remediation at scale. And while the in vitro cytocompatibility results are encouraging, in vivo validation in appropriate animal models remains an indispensable step before any translational claim can be responsibly advanced. The co-precipitation platform established here is robust, well-controlled, and scalable; it accommodates these future investigations without requiring fundamental process modification.

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