

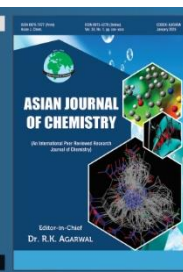


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Plant Mediated Green Synthesis of Zn–Ni–Se Nanocomposite Using *Moringa oleifera* Leaf Extract for Environmental Remediation and Antibacterial Applications

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A Zn–Ni–Se nanocomposite was synthesized through a green co-precipitation method using *Moringa oleifera* leaf extract as a natural reducing and stabilizing agent. The synthesized material was characterized by XRD, FT-IR, DRS, FE-SEM, EDS, HR-TEM, BET XPS to assess its crystal structure, morphology, elemental composition, surface area, optical properties chemical states. The photocatalytic activity of the nanocomposite was evaluated for the degradation of methylene blue (MB) and reactive red 120 (RR120) dyes under UV irradiation. Under optimized conditions of 50 ppm dye concentration and pH 7, approximately 98% degradation of MB was achieved within 150 min, while RR120 showed about 65% degradation. In addition, antibacterial activity was evaluated against *Staphylococcus aureus*, *Escherichia coli*, *Streptococcus pneumoniae* and *Pseudomonas aeruginosa* using the MIC assay. The nanocomposite exhibited antibacterial activity against the tested bacterial strains at 200 µg/mL. The enhanced multifunctional performance is attributed to the synergistic interaction among Zn, Ni and Se, promoting efficient charge separation, reactive oxygen species generation and antimicrobial activity. The green-synthesized Zn–Ni–Se nanocomposite demonstrates promising potential for dye degradation, antimicrobial applications and sustainable environmental remediation.

Keywords: *Moringa oleifera*, Photocatalytic degradation, Methylene blue, Reactive red 120, Sustainable water treatment.

INTRODUCTION

Rapid urbanization, population expansion and industrial development have placed increasing pressure on freshwater resources and contributed to the accumulation of persistent pollutants in aquatic environments. Industrial discharges may contain organic dyes, pharmaceutical residues and other chemical contaminants that can adversely affect human health, aquatic organisms ecosystem stability [1-3]. Many conventional wastewater treatment processes have limited effectiveness against chemically stable or poorly degradable pollutants, creating a need for treatment technologies capable of removing such contaminants more efficiently. In this context, photocatalysis has emerged as a promising approach in which

a semiconductor catalyst absorbs suitable light energy and generates reactive species capable of degrading organic pollutants [4-6].

Nanomaterials have been extensively explored for photocatalytic wastewater treatment due to their high specific surface area, tunable electronic properties and surface reactivity can facilitate pollutant adsorption and photocatalytic reactions [7]. Combining different components within a nanocomposite can further modify light absorption, charge transport and surface activity, providing opportunities to improve photocatalytic performance [8,9]. The method used to prepare these materials is equally important, since conventional synthesis routes may require hazardous chemicals and generate undesirable residues. Plant-assisted synthesis has gained attention as

an alternative route in which naturally occurring phytochemicals participate in the reduction and stabilization of precursor species [10].

Moringa oleifera leaves contain phenolic compounds, polyphenols and reducing polysaccharides that can participate in the formation and stabilization of nanomaterials [9]. In the present work, an aqueous *Moringa oleifera* leaf extract was employed to synthesize a Zn–Ni–Se nanocomposite. The synthesis conditions, particularly pH, temperature and calcination temperature, were optimized to obtain a crystalline and stable material suitable for photocatalytic applications [11,12]. Within the composite, the ZnO phase serves as the semiconductor component, Ni may promote electron trapping and charge separation, while Se incorporation can alter the electronic structure and optical response of the material. The resulting nanocomposite exhibited an effective band gap of 2.9 eV.

The photocatalytic behaviour of the Zn–Ni–Se nanocomposite was examined using methylene blue and reactive red 120 as representative cationic and anionic dyes, respectively. Its catalytic stability was assessed through repeated degradation cycles, while antibacterial activity was evaluated against *Staphylococcus aureus*, *Escherichia coli*, *Streptococcus pneumoniae* and *Pseudomonas aeruginosa*. The study therefore examines the relationship between plant-mediated synthesis, material characteristics, photocatalytic dye removal, catalyst reusability antibacterial activity within a single Zn–Ni–Se-based system.

The work is relevant to SDG 6 through the development of a material for contaminated-water treatment and to SDG 12 through the use of a plant-mediated synthesis route. The combined photocatalytic and antibacterial properties of the nanocomposite provide a basis for further investigation of multifunctional materials for environmental remediation and water-quality improvement.

EXPERIMENTAL

Zinc nitrate hexahydrate [$\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$], nickel nitrate hexahydrate [$\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$], sodium selenite and sodium hydroxide were used as precursor materials for the synthesis of the nanocomposite. The concentrations of $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ were maintained at 0.25 M, while Na_2SeO_3 and NaOH solutions were prepared at 5% (w/v) and 0.1 M, respectively. Distilled water was used as the reaction medium throughout the synthesis process. All reagents were of analytical grade and used as received without further purification.

Preparation of plant extract: Fresh *M. oleifera* leaves were collected, authenticated and properly cleaned with distilled water to remove dust and other surface contaminants. The cleaned leaves were then shade-dried and coarsely chopped into little pieces. To promote the extraction of bioactive compounds, about 10 g of processed leaves were placed in 100 mL of distilled water and boiled for 15 min. The resultant solution was allowed to cool naturally to ambient temperature before filtering using Whatman No. 1 filter paper. The leaf extract was kept at 4 °C and used as a biogenic reducing and capping agent during the nanocomposite production.

Synthesis of Zn–Ni–Se nanocomposite: The Zn–Ni–Se nanocomposite was synthesized via a green co-precipitation

route employing *M. oleifera* plant leaf extract as a natural reducing and eco-friendly capping agent. Initially, zinc nitrate and nickel nitrate were dissolved in 100 mL of distilled water at equimolar concentrations (0.25 M each) under continuous magnetic stirring to obtain a homogeneous precursor solution. Subsequently, a 5% (w/v) sodium selenite solution was added dropwise to the precursor mixture and stirred for 15 min at ambient temperature to ensure uniform distribution of the selenium source. Thereafter, 5% (v/v) *M. oleifera* plant leaf extract was introduced into the reaction medium under constant stirring. The reaction solution was brought to a pH of around 9.0 by slowly introducing 0.1 M NaOH solution. The reaction combination was then maintained at 70 °C under continuous stirring for 150 min, promoting nucleation and growth of the nanocomposite and contributing to the formation of a gel-like precipitate. The resulting gel was collected and dried at 100 °C in a hot-air oven for 3 h to eliminate residual moisture and volatile impurities. Finally, the dried material was subjected to thermal treatment in a muffle furnace at 500 °C for 2 h, yielding the crystalline nanocomposite. This thermal treatment promoted the removal of residual organic species while improving the crystallinity and phase integrity of the synthesized nanocomposite.

Photocatalytic methodology: The photocatalytic degradation experiments for methylene blue (MB) and reactive red 120 (RR120) dyes were performed using a Heber multi-lamp photoreactor (model: HML-COPACT-LP-MP88). The aqueous dye solutions were contained in glass tubes (2.5 cm inner diameter, 37 cm length) and irradiated using four 8 W mercury UV lamps with a central wavelength of 365 nm. In a typical procedure, 50 mg of the synthesized Zn–Ni–Se photocatalyst was suspended in 100 mL of the respective dye solution (50 ppm). To establish an adsorption-desorption equilibrium between the dye molecules and the catalyst surface, the suspension was magnetically stirred in complete darkness for 30 min prior to irradiation. Control experiments were performed under identical conditions to verify the photocatalytic contribution to dye degradation. These experiments comprised a dye-only photolysis test under UV irradiation and a catalyst-in-the-dark adsorption test. During the photocatalytic reaction, 3 mL aliquots were withdrawn at regular time intervals and centrifuged (REMI-R-8C) to separate the catalyst powder. The clarified solutions were then analyzed using a Perkin-Elmer UV-Vis spectrometer to monitor the reduction in dye absorbance.

Minimum inhibitory concentration (MIC): The antibacterial activity of the synthesized nanomaterial was evaluated against *S. aureus*, *E. coli*, *S. pneumoniae* and *P. aeruginosa* at different concentrations ranging from 5 to 200 µg/mL. The samples were evaluated and the bacterial growth response was monitored after incubation. All culture tubes were then incubated at a controlled room temperature of 32 °C for 24 h. Following incubation, the antibacterial efficacy was determined by observing the visual appearance of the growth pattern and measuring the optical density of the broth to quantify bacterial inhibition

RESULTS AND DISCUSSION

Structural analysis: The crystallographic structure, phase composition crystallinity of the biosynthesized Zn–Ni–Se

nanocomposite were investigated by X-ray diffraction (XRD). The diffraction pattern in Fig. 1 confirms the coexistence of NiSe and ZnSe phases, which indicate the formation of a multi-phase nanocomposite. The diffraction peaks at $2\theta = 28.57^\circ, 32.88^\circ, 43.24^\circ, 48.94^\circ, 59.06^\circ, 60.23^\circ, 68.49^\circ$ and 70.38° were assigned to the (111), (101), (102), (110), (103), (201), (202) (004) planes of NiSe, respectively (JCPDS No. 01-075-0610) [13]. The peaks at $27.41^\circ, 45.45^\circ, 53.13^\circ, 56.74^\circ, 65.12^\circ$ and 75.25° correspond to the (111), (220), (311), (222), (400) (420) planes of cubic ZnSe, respectively (JCPDS No. 00-005-0522) [14]. The presence of reflections from both phases confirms the incorporation of NiSe and ZnSe within the composite.

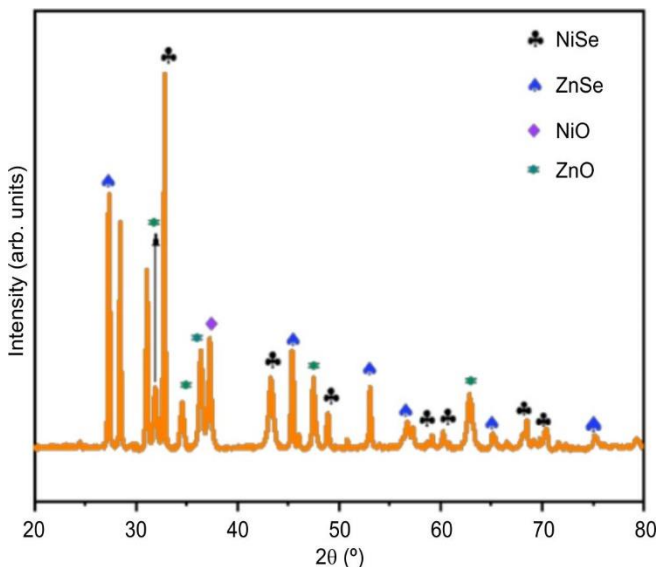


Fig. 1. XRD pattern of synthesized Zn–Ni–Se nanocomposite

Additional reflections at $31.83^\circ, 34.51^\circ, 36.49^\circ, 47.55^\circ$ and 62.91° were indexed to ZnO (JCPDS No. 36-1451) [15], while the reflection at 37.42° was assigned to NiO (JCPDS No. 01-078-0643) [16]. These minor oxide phases may arise from partial oxidation during thermal treatment and incomplete selenization under limited selenium availability. The XRD pattern therefore indicates a predominantly NiSe/ZnSe crystalline composite with minor ZnO and NiO phases. Microstructural parameters, namely crystallite size, dislocation density and microstrain, were calculated using eqns. 1-3 to assess crystallite dimensions, lattice defects and structural strain within the synthesized material [17].

$$D = \frac{0.9\lambda}{\beta \cos \theta} \quad (1)$$

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

$$\varepsilon = \frac{\beta \cos \theta}{4} \quad (3)$$

In this context, D signifies the crystallite size, λ indicates the wavelength of the X-ray employed, K represents the crystallite shape factor, which is 0.94, β refers to the peak width at half maximum height and θ denotes the Bragg angle. The calculated mean crystallite size, lattice strain and dislocation density of the Zn–Ni–Se nanocomposite, derived from the

prominent peaks, were found to be 41.01 nm, 0.0039 and $2.08 \times 10^{15} \text{ cm}^{-2}$, respectively.

FTIR analysis: FT-IR analysis was performed over the $4000\text{--}400 \text{ cm}^{-1}$ range to identify functional groups associated with the green synthesis and stabilization of the Zn–Ni–Se nanocomposite (Fig. 2). The broad band at $3600\text{--}3200 \text{ cm}^{-1}$ can be assigned to O–H stretching vibrations from phenolic compounds and adsorbed water, which is due to the hydrogen-bonded phytochemical constituents [18]. The absorption band at 2920.64 cm^{-1} corresponds to the aliphatic C–H stretching vibrations [19]. The band near 1353 cm^{-1} is associated with O–H bending of polyphenolic and flavonoid compounds, while the bands at 1117 and 1042 cm^{-1} are attributed to C–O stretching vibrations of alcohols and other oxygen-containing constituents present in the *M. oleifera* extract [20–22].

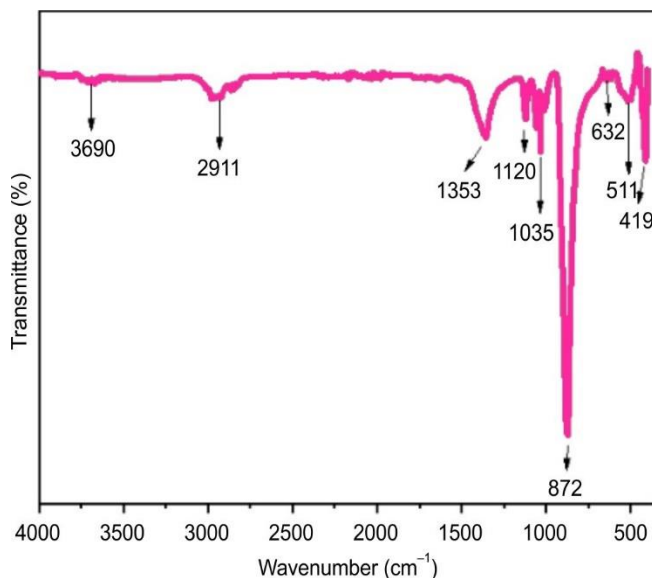


Fig. 2. FT-IR spectrum of synthesized Zn–Ni–Se nanocomposite

A band near 885 cm^{-1} may be assigned to Se–O stretching vibrations, whereas the feature around 855 cm^{-1} corresponds to out-of-plane C–H bending of alkene groups. The absorption region at $627\text{--}631 \text{ cm}^{-1}$ is attributed to Zn–Se vibrations. Bands near 500 and 400 cm^{-1} are assigned to Ni–Se vibrational modes, thus confirmed the incorporation of Ni and Se into the nanocomposite structure [23–26]. The FT-IR profile suggests that phytochemical constituents of *M. oleifera* participate in the reduction of precursor ions and remain associated with the nanocomposite surface, where they can act as capping or stabilizing species during material formation [27].

Optical analysis: The optical absorption spectrum of the Zn–Ni–Se nanocomposite was recorded over the $300\text{--}700 \text{ nm}$ wavelength range using a UV-Vis spectrometer (Fig. 3). The nanocomposite exhibited pronounced absorption in the UV region, with a distinct band near 300 nm that can be associated with near-band-edge electronic transitions. A broad absorption tail extended toward approximately 500 nm , which may arise from sub-band-gap defect states, such as oxygen vacancies, within the nanocomposite. The bandgap energy of the films adjacent to the absorption edge was ascertained via the Tauc method in accordance with the following formula:

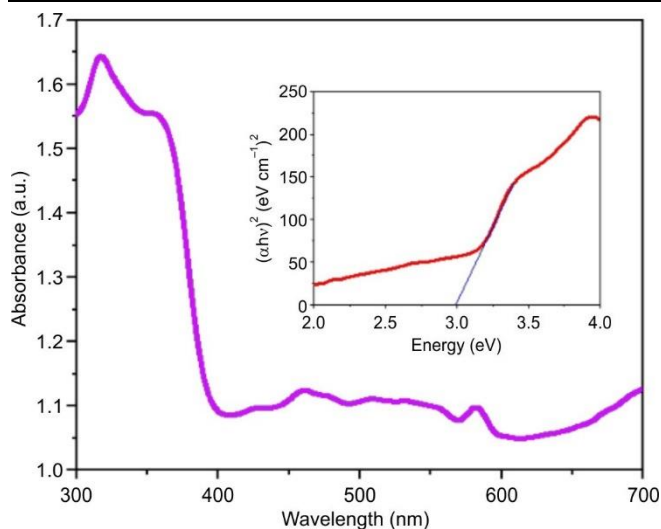


Fig. 3. DRS spectrum of the synthesized Zn-Ni-Se nanocomposite with Tauc plot (inset)

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad (4)$$

where A represents a material-dependent proportionality constant, $h\nu$ denotes the incident photon energy (eV) and E_g corresponds to the optical band gap energy of the material. The exponent n is determined by the type of electronic transition involved. Values of $n = 2$ and $n = 1/2$ are assigned to direct and indirect allowed transitions, respectively, whereas $n = 2/3$ and $n = 1/3$ correspond to direct and indirect forbidden transitions. The optical band gap energy was estimated by extrapolating the linear portion of the $(\alpha h\nu)^2$ versus $h\nu$ plot to the photon energy axis. The calculated optical band gap value of the nanocomposite is 2.9 eV, as determined by the linear extrapolation of the Tauc plot (inset of Fig. 3).

This band gap energy corresponds to an intrinsic absorption edge near 427 nm, which aligns well with the strong absorption observed in the UV region. This wide band gap confirms that the material generates electron-hole pairs efficiently under ultraviolet excitation, making it highly suitable for the UV-light-driven photocatalytic applications investigated in this study. Moreover, the structural and vibrational properties of Zn-Ni-Se nanocomposite were systematically examined using Raman spectroscopy, as depicted in Fig. 4. The Raman spectrum of the Zn-Ni-Se nanocomposite displays distinct bands at 187, 215, 261 and 540 cm^{-1} , corresponding to vibrational modes of its constituent phases. The bands at 187 and 261 cm^{-1} are assigned to the TO and LO phonon modes of Zn-Se, respectively, while the intense band at 540 cm^{-1} is associated with the LO phonon mode of Ni-Se. The band at 215 cm^{-1} can be attributed to Se-Se bond stretching. These vibrational features support the formation of Zn-Se and Ni-Se phases within the nanocomposite and are consistent with its crystalline structure.

Morphological and elemental characterization: The surface morphology and topography of the Zn-Ni-Se nanocomposite synthesized by *M. oleifera* leaf extract-mediated co-precipitation were examined using FE-SEM. The micrographs in Fig. 5a-b show nanoparticles anchored within the phytochemical matrix, along with noticeable particle agglomeration.

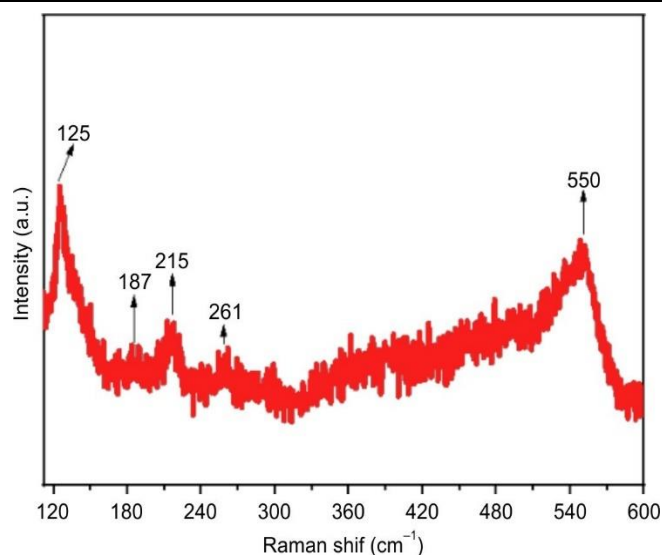


Fig. 4. Raman spectrum of synthesized Zn-Ni-Se nanocomposite

Such aggregation may arise from the high surface energy of nanosized particles and interactions between phytochemical residues adsorbed on their surfaces, which favour particle clustering during growth [28]. These surface-bound compounds may also act as capping and stabilizing agents, helping to control nanoparticle growth.

The elemental composition was examined by energy-dispersive X-ray spectroscopy (EDX) (Fig. 5c), which detected Zn, Ni, Se O in the synthesized material. Elemental mapping (Fig. 5d) showed the spatial distribution of these elements throughout the analyzed region. The presence and distribution of the constituent elements support the formation of the Zn-Ni-Se nanocomposite.

HR-TEM analysis (Fig. 5e) revealed predominantly quasi-spherical nanoparticles with some variation in particle size, consistent with the FE-SEM observations. ImageJ analysis gave a particle-size range of 10-22 nm, with an average equivalent diameter of approximately 15 nm. The corresponding SAED pattern exhibited diffraction rings characteristic of a polycrystalline material, which is consistent with the crystalline phases identified by XRD.

Surface area and pore structure characterization: The nitrogen adsorption-desorption (N_2) analysis was performed to evaluate the surface area and pore characteristics of the Zn-Ni-Se nanocomposite. As shown in Fig. 6, the adsorption isotherm exhibits a Type II profile with an H3 hysteresis loop at higher relative pressures ($P/P_0 > 0.8$), which is consistent with the IUPAC classification [29,30]. This profile is associated with multilayer adsorption and textural voids generated by particle aggregation and interparticle spaces. The negligible N_2 uptake at low relative pressures ($P/P_0 < 0.1$) indicates little or no intrinsic microporosity. A sharp increase in adsorption as P/P_0 approaches 1.0 is consistent with capillary condensation within large interparticle voids or macropore-like spaces formed by particle aggregation. The maximum N_2 uptake was approximately $14 \text{ cm}^3 \text{ g}^{-1}$ correspond to a low specific surface area and total pore volume. The BJH pore-size distribution (Fig. 6) further supports this interpretation, with differential pore volumes below $0.0005 \text{ cm}^3 \text{ g}^{-1} \text{ nm}^{-1}$ across the analyzed range.

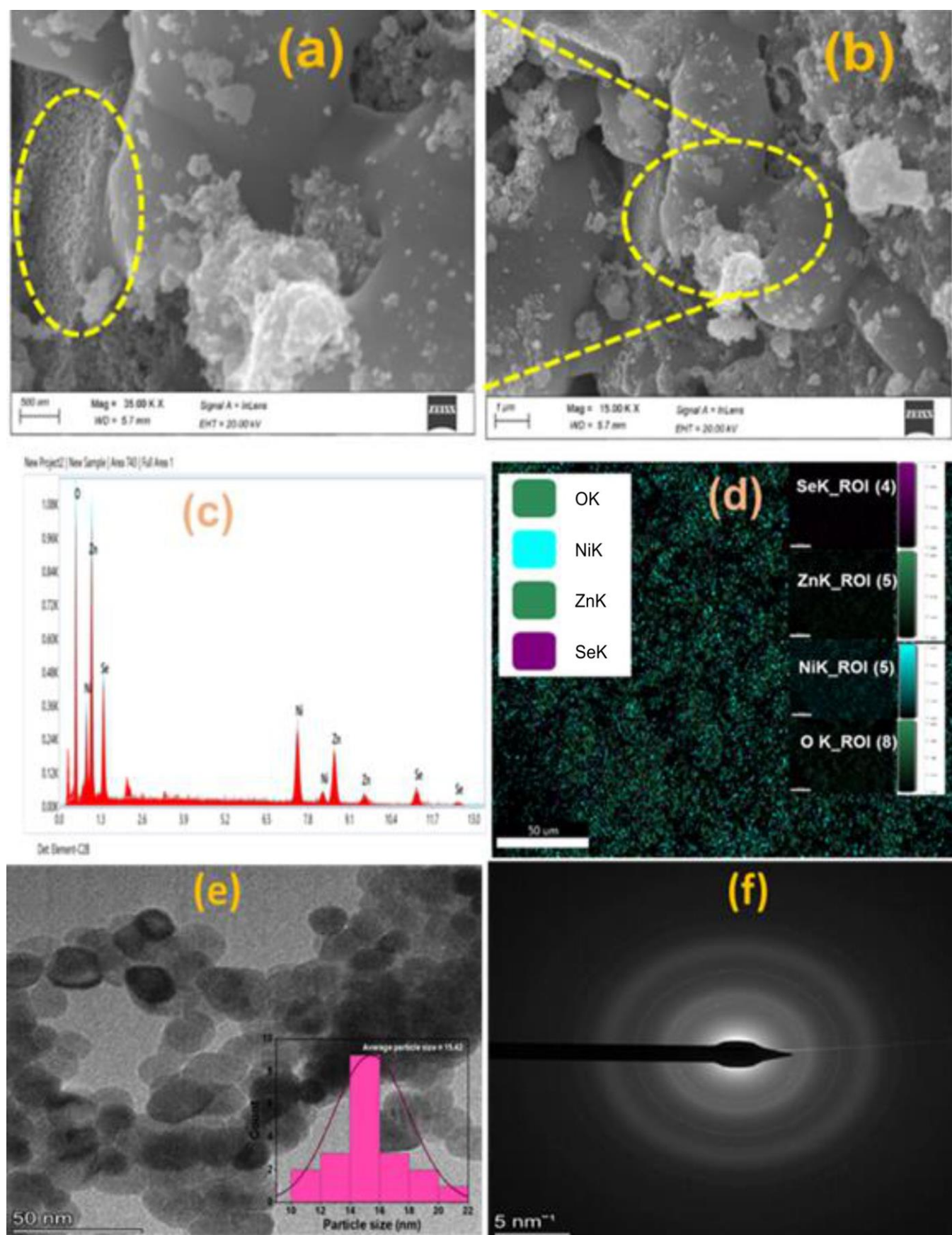


Fig. 5. Morphological and compositional properties of Ni-Zn-Se nanocomposite; (a-b) SEM images, (c) elemental mapping, (d) EDAX spectrum, (e) TEM images with particle size distribution and (f) SAED pattern

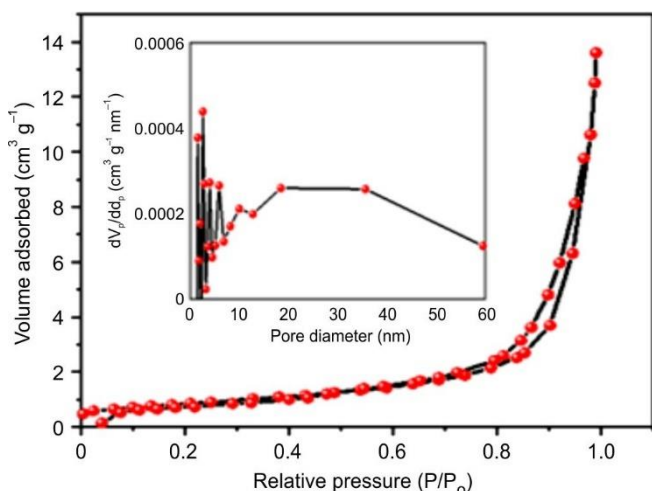


Fig. 6. N₂ adsorption-desorption isotherm of the Zn-Ni-Se nanocomposite

and no distinct maximum within the mesopore region (2-50 nm). The Zn-Ni-Se nanocomposite can therefore be regarded as predominantly non-microporous, with its measured textural properties largely associated with external surfaces and inter-particle or inter-aggregate voids.

XPS analysis: The XPS results of the Zn-Ni-Se nanocomposite are shown in Fig. 7a-d and were used to examine its elemental composition and chemical states. The survey and high-resolution spectra confirm the presence of Zn, Ni, Se and O in the synthesized material. The Zn 2*p* spectrum (Fig. 7a) contains two distinct peaks at 1022.91 and 1045.10 eV, assigned to Zn 2*p*_{3/2} and Zn 2*p*_{1/2}, respectively. The spin orbit separation of approximately 22.2 eV is consistent with Zn²⁺ species and confirm the oxidized state of zinc in the composite. Furthermore, no prominent satellite features are observed in this region.

The O 1*s* spectrum (Fig. 7b) is dominated by a peak at 531.88 eV, which can be assigned to oxygen associated with metal-oxygen bonding in the oxide component. The relatively high binding energy may also involve surface hydroxyl species or oxygen-deficient sites, which depend on the local chemical environment [31]. Such surface species can influence the adsorption and interfacial charge-transfer processes during photocatalysis. The Ni 2*p* spectrum (Fig. 7c) exhibits peaks at 855.9 and 872.9 eV, corresponding to Ni 2*p*_{3/2} and Ni 2*p*_{1/2}, respectively. These binding energies are characteristic of Ni²⁺ and are consistent with nickel-oxygen environments reported for NiO and related nickel-containing oxides [32-34]. The Ni

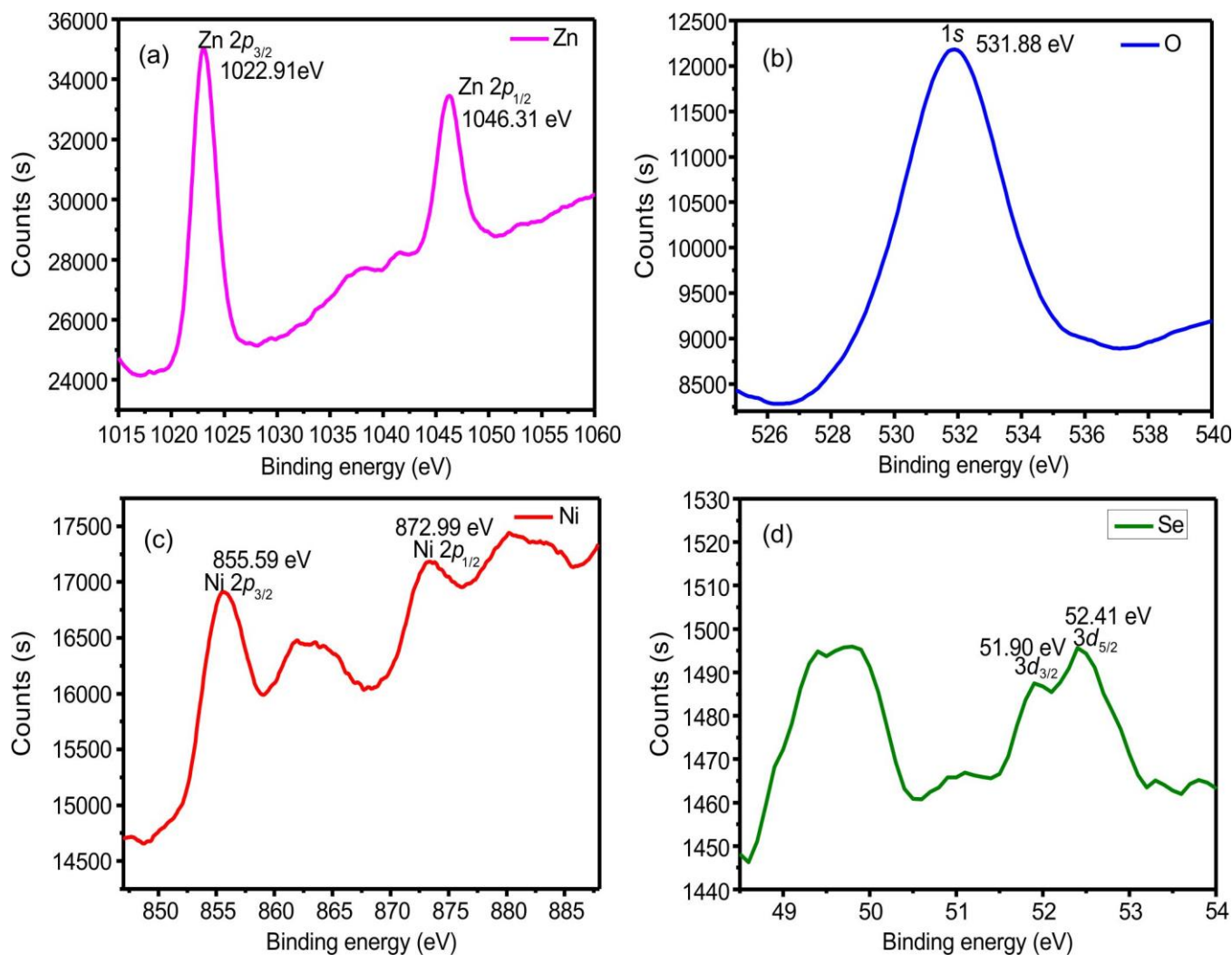


Fig. 7. High-resolution XPS spectra of (a) Zn 2*p*, (b) O 1*s*, (c) Ni 2*p* and (d) Se 3*d* regions of the synthesized Zn-Ni-Se nanocomposite

2p profile supports the presence of nickel in an oxidized chemical state within the composite.

The Se 3d spectrum (Fig. 7d) exhibits two components at 51.92 and 52.41 eV, assigned to the Se 3d_{5/2} and Se 3d_{3/2} levels, respectively. These binding energies are consistent with oxidized selenium species and may be associated with selenite- or selenate-like surface environments. The XPS analysis confirms the presence of Zn²⁺, Ni²⁺, oxygen and oxidized Se species in the Zn–Ni–Se nanocomposite. Surface hydroxyl groups and oxygen-deficient sites, where present, may influence pollutant adsorption and interfacial charge-transfer processes, which contribute to the photocatalytic activity of the material.

Photocatalytic degradation performance and kinetic analysis

The photocatalytic activity of the green-synthesized Zn–Ni–Se nanocomposite was assessed by degrading dye contaminants under UV-light irradiation. Fig. 8a–d illustrates the photocatalytic degradation behaviour of reactive red 120 (RR120) and methylene blue (MB) dyes under UV-light irradiation using the synthesized photocatalyst. The gradual decrease in the characteristic absorption peaks of both dyes with increasing irradiation time confirms their effective degradation.

As indicated in Fig. 8a, the UV-Vis absorption spectra of RR120 indicate a continuous reduction in approximately 554 nm that steadily decreases with increasing irradiation period from 0 to 150 min. A progressive decrease in the characteristic absorption band of RR120 reflects the breakdown of the azo chromophore and aromatic moieties within the dye molecule. The substantial decrease in absorbance after prolonged irradiation confirms the efficient photocatalytic decomposition of RR120. The degradation process can be attributed to the attack of photogenerated reactive oxygen species on the azo (–N=N–) bonds, leading to the decolorization and progressive structural breakdown of the dye molecules. Similarly, the UV-Vis absorption spectra of MB shown in Fig. 8b reveal a significant decrease in the intensity of the characteristic absorption peak centered around 664 nm with increasing irradiation time. The continuous reduction in absorbance demonstrates the effective degradation of MB molecules through the destruction of their conjugated chromophoric system. After 150 min of irradiation, the absorption peak nearly disappears, which indicate extensive degradation of the dye and confirms the effective photocatalytic degradation capability of the Zn–Ni–Se nanocomposite.

The degradation efficiency was further quantified using the relation C_0/C_t where C_t and C_0 represent the absorbance at

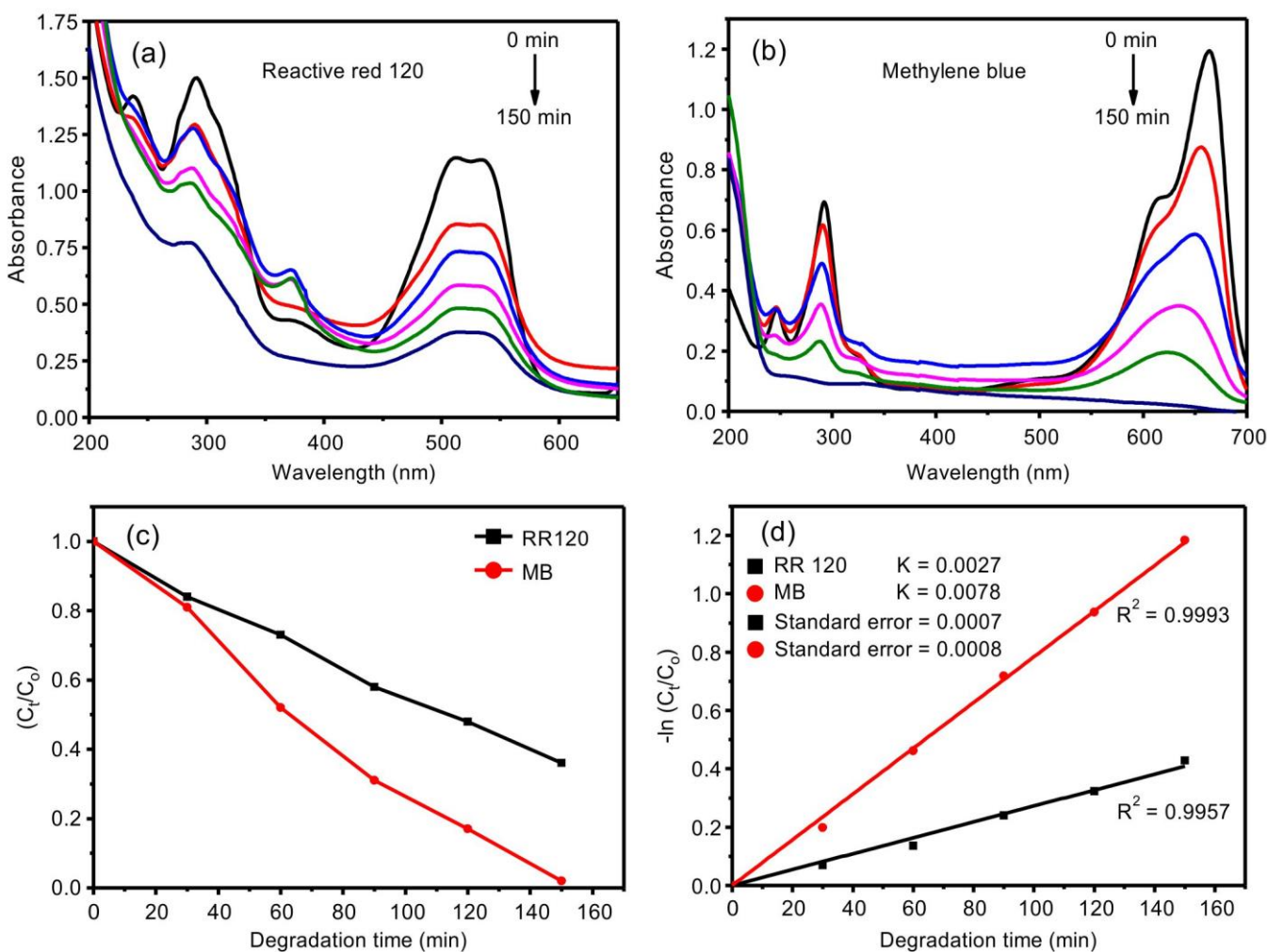


Fig. 8. UV-light-driven degradation of RR120 and MB dyes: (a,b) UV-vis spectra, (c) C_t/C_0 profiles and (d) kinetic analysis

time t and d initial absorbance, respectively. The value of $\ln(C_0/C_t)$ increased steadily with irradiation time is consistent with the progressive degradation of the dye molecules (Fig. 8c). The photocatalytic process achieved nearly complete dye removal after 150 min of UV-light exposure, with the synthesized material exhibiting strong photocatalytic activity.

The kinetic behaviour of the degradation reaction was examined using the pseudo-first-order kinetic model (eqn. 5):

$$\ln\left(\frac{C_0}{C_t}\right) = Kt \quad (5)$$

where K is the apparent rate constant and t is the irradiation time. The linear relationship (Fig. 8d) with a high correlation coefficient ($R^2 \approx 0.999$) confirms that the degradation process follows pseudo-first-order kinetics. The excellent linearity suggests that the adsorption of dye molecules and the generation of reactive species on the catalyst surface occur efficiently throughout the reaction period. The calculated apparent rate constant (k) reflects the high photocatalytic activity of the synthesized material, while both RR120 and MB dyes undergo rapid degradation under UV-light irradiation.

The enhanced photocatalytic activity of the Zn–Ni–Se nanocomposite can be attributed to the synergistic interaction among ZnO, NiO and Se-containing species. ZnO provides the semiconductor framework, while NiO facilitates electron trapping and charge separation. Se incorporation modifies the electronic structure, narrows the effective band gap and enhances UV-light absorption. During synthesis, phytochemicals present in *M. oleifera* leaf extract, such as polyphenols, flavonoids and proteins, act as reducing and stabilizing agents, which influence the particle growth and dispersion. Although these organic species are largely removed during calcination at 500 °C, their templating effect contributes to the final morphology [35]. Despite the low surface area and non-porous structure confirmed by BET analysis, the material exhibits efficient photocatalysis due to heterojunction formation, suppressed electron–hole recombination and defect sites such as oxygen vacancies.

Under UV irradiation, photogenerated electrons and holes participate in redox reactions, producing superoxide ($\bullet O_2^-$) and hydroxyl ($\bullet OH$) radicals. These reactive oxygen species attack the chromophoric structures of RR120 and MB molecule, which promote de-ethylation, ring opening and subsequent fragmentation [36]. The enhanced charge separation and ROS generation facilitate dye degradation and contribute to the favourable reaction kinetics observed for the Zn–Ni–Se nanocomposite. These features make the material a potential photocatalyst for wastewater treatment.

Reusability: The reusability and operational stability of the Zn–Ni–Se nanocomposite were evaluated through five consecutive photocatalytic cycles for MB degradation under identical experimental conditions. As shown in Fig. 9, the catalyst achieved 98% decolourization in the first cycle, followed by 97%, 95%, 92.5% and 89.5% in the second, third, fourth and fifth cycles, respectively. Thus, the catalyst retained nearly 90% of its initial degradation efficiency after five cycles, with a complete decrease of 8.5%. The gradual decrease may be associated with minor catalyst loss during reco-

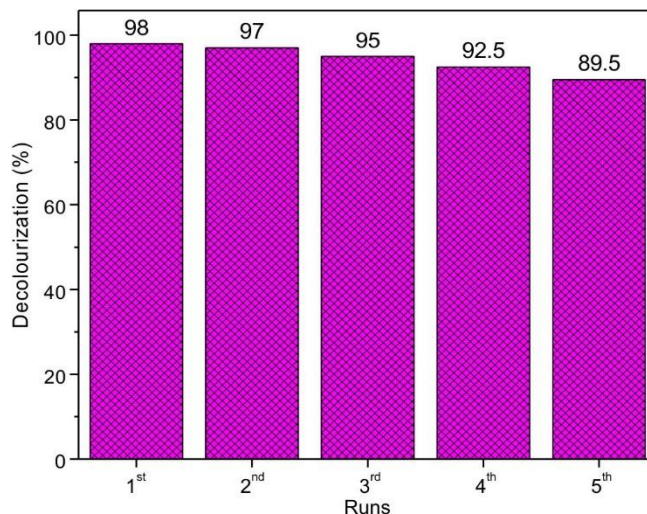


Fig. 9. Reusability of the Zn–Ni–Se nanocomposite for photocatalytic degradation of MB dye over successive cycles

very, washing and centrifugation, as well as the adsorption of degradation intermediates on the catalyst surface, which can reduce the availability of active sites. Surface changes during repeated irradiation may also contribute to the observed decrease in activity. Nevertheless, the photocatalytic efficiency decreased only slightly over five successive cycles, while the Zn–Ni–Se nanocomposite retained its activity and showed good operational stability.

Photocatalytic degradation pathway of MB dye: The degradation pathway of MB over the Zn–Ni–Se nanocomposite was proposed from the identified intermediates and is shown in Fig. 10. UV irradiation promotes charge-carrier generation and the formation of ROS, mainly $\bullet OH$ and $\bullet O_2^-$, which initiate oxidative degradation of MB. The proposed pathway involves successive N-demethylation followed by cleavage of the phenothiazine framework. ROS attack at the N-methyl groups can yield Azure B, Azure A, Azure C and thionine through stepwise demethylation [37]. Subsequent oxidation disrupts the heterocyclic structure and generates smaller organic intermediates. ROS attack on the conjugated phenothiazine framework can further cleave C–S and C–N bonds, causing chromophore disruption, ring opening and progressive fragmentation. Although the decrease in MB absorbance confirms extensive chromophore destruction, complete mineralization to CO_2 and H_2O cannot be established without TOC or COD measurements.

The photocatalytic degradation of MB and RR120 involves photogenerated electrons and holes together with ROS formed under UV irradiation. Excitation of the Zn–Ni–Se nanocomposite promotes electrons from the VB to the CB. The conduction-band electrons can reduce dissolved O_2 to $\bullet O_2^-$, whereas VB holes can oxidize H_2O or OH^- to generate $\bullet OH$. These reactive species attack the dye structures and initiate oxidative transformations. MB degradation mainly involves N-demethylation and phenothiazine-framework cleavage, whereas RR120 degradation is expected to begin with attack at the azo ($-N=N-$) linkage. Azo-bond cleavage can generate aromatic amine containing intermediates, followed by further oxidation and fragmentation during continued irradiation [38,39].

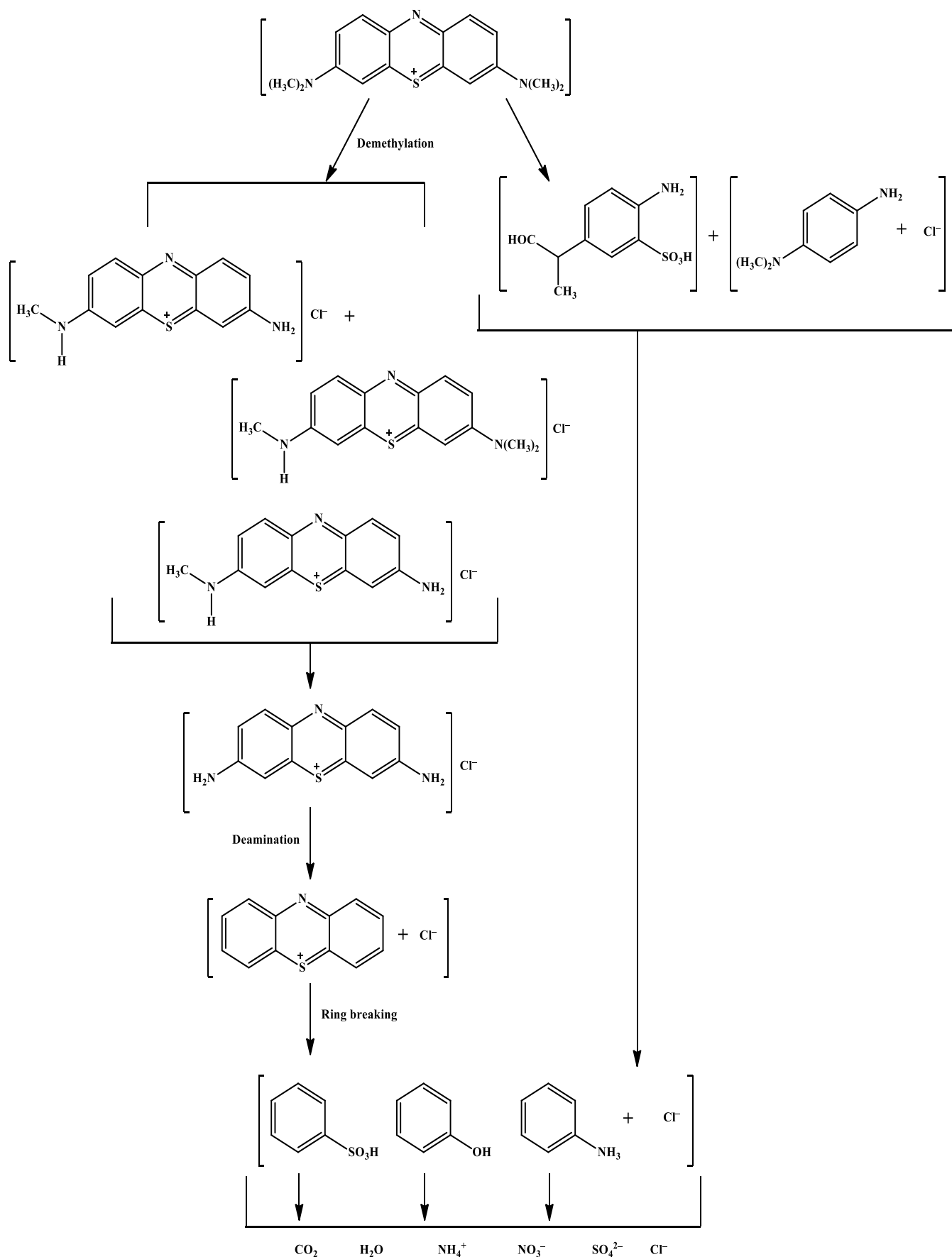
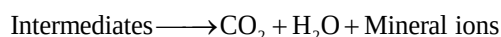
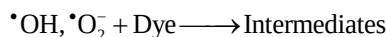
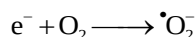
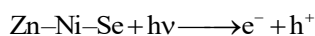


Fig. 10. Proposed photocatalytic degradation pathway of methylene blue (MB) over Zn–Ni–Se nanocomposite under UV-light irradiation

The key reaction steps involved in the photocatalytic process are outlined below:



The proposed mechanism describes the degradation of both cationic MB and anionic RR120 by the Zn–Ni–Se nanocomposite through ROS-mediated oxidation, with substantial decolorization and disruption of their chromophoric structures.

Scavenger activity: A scavenger study was performed to identify the reactive species involved in the photocatalytic degradation of MB by the green-synthesized Zn–Ni–Se nanocomposite prepared using *M. oleifera* leaf extract. As shown in Fig. 11, MB degradation reached approximately 98% in the absence of scavengers. The addition of individual scavengers caused a marked reduction in degradation efficiency, which confirmed the involvement of multiple reactive species in the photocatalytic process. KI, used as a scavenger for photo-generated holes (h^+), produced the largest decrease in degradation efficiency, which fell to 38.1%. This pronounced inhibition points to h^+ as the dominant reactive species in MB degradation. *tert*-Butanol (TBA), a hydroxyl radical ($\cdot\text{OH}$) scavenger, reduced the degradation efficiency to 52.4%, supporting an important role for $\cdot\text{OH}$ in the oxidation of MB molecule. Addition of *p*-benzoquinone (BQ), a scavenger of superoxide radicals ($\cdot\text{O}_2^-$), decreased the efficiency to 57.2%, indicate the participation of $\cdot\text{O}_2^-$ in the degradation pathway. The marked decrease in degradation efficiency to 59.5% following AgNO_3 addition points to a substantial contribution of photogenerated electrons to ROS formation. Based on the extent of inhibition, the relative contribution of the investigated species can be expressed as $h^+ > \cdot\text{OH} > \cdot\text{O}_2^- > e^-$.

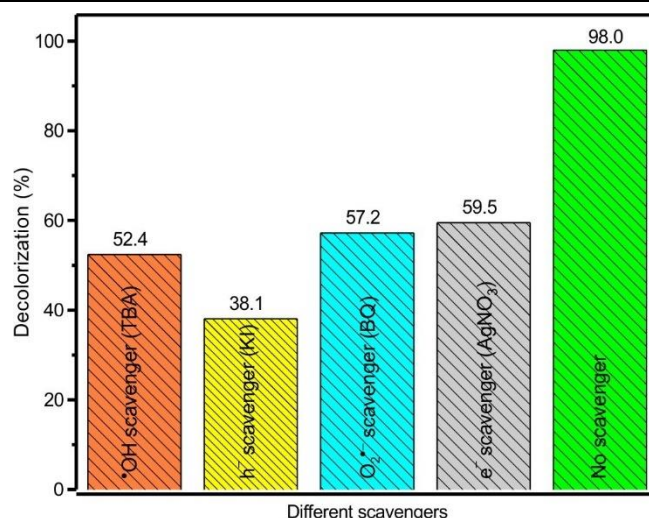


Fig. 11. Effect of different scavengers on the photocatalytic degradation efficiency

The combined Zn, Ni and Se components may facilitate charge separation and modify the light-response characteristics of the nanocomposite, reducing the probability of rapid electron–hole recombination. The phytochemical constituents from *M. oleifera* may also influence particle nucleation and surface stabilization during synthesis, while the subsequent calcination step promotes formation of the inorganic composite structure [40]. These features may facilitate interfacial charge transfer and generation of reactive species despite the relatively low intrinsic surface area of the material.

Minimum inhibitory concentration (MIC): As shown in Table-1, the optical density values generally decreased with increasing nanomaterial concentration, particularly at 100 and 200 $\mu\text{g/mL}$. The bacterial growth was comparatively less affected at 5 $\mu\text{g/mL}$, as evidenced by the higher absorbance values. Increasing the treatment concentration led to a gradual decline in absorbance for most strains, with the lower absorbance values corresponding to stronger growth inhibition.

TABLE-1
ANTIBACTERIAL ACTIVITY DATA OF THE SYNTHESIZED NANOMATERIALS
AT DIFFERENT CONCENTRATIONS (5, 10, 25, 50, 100 AND 200 $\mu\text{g/mL}$)

Sample	Bacteria	5 $\mu\text{g/mL}$	10 $\mu\text{g/mL}$	25 $\mu\text{g/mL}$	50 $\mu\text{g/mL}$	100 $\mu\text{g/mL}$	200 $\mu\text{g/mL}$
Ni NPs	<i>S. aureus</i>	0.617	0.453	0.436	0.656	0.358	0.212
	<i>E. coli</i>	0.450	0.406	0.396	0.374	0.284	0.167
	<i>S. pneumoniae</i>	0.381	0.449	0.460	0.464	0.313	0.202
	<i>P. aeruginosa</i>	0.349	0.302	0.280	0.364	0.293	0.200
Zn NPs	<i>S. aureus</i>	0.507	0.473	0.435	0.462	0.311	0.209
	<i>E. coli</i>	0.472	0.329	0.341	0.282	0.237	0.091
	<i>S. pneumoniae</i>	0.441	0.410	0.426	0.361	0.178	0.112
	<i>P. aeruginosa</i>	0.252	0.345	0.271	0.358	0.339	0.108
Zn/Se NPs	<i>S. aureus</i>	0.528	0.419	0.425	0.397	0.372	0.144
	<i>E. coli</i>	0.406	0.332	0.421	0.266	0.205	0.130
	<i>S. pneumoniae</i>	0.480	0.391	0.376	0.323	0.371	0.178
	<i>P. aeruginosa</i>	0.340	0.296	0.309	0.316	0.195	0.055
Ni/Zn/Se NPs	<i>S. aureus</i>	0.401	0.373	0.355	0.363	0.233	0.108
	<i>E. coli</i>	0.405	0.330	0.315	0.265	0.213	0.057
	<i>S. pneumoniae</i>	0.480	0.405	0.339	0.234	0.214	0.069
	<i>P. aeruginosa</i>	0.329	0.279	0.288	0.376	0.248	0.052

Among the tested concentrations, 200 µg/mL produced the highest reduction in bacterial growth. The Ni/Zn nanocomposite exhibited particularly pronounced antibacterial activity at this concentration, with optical density values of 0.108, 0.057, 0.069 and 0.052 against *S. aureus*, *E. coli*, *S. pneumoniae* and *P. aeruginosa*, respectively (Table-1). The differences in antibacterial activity among the tested bacterial strains may be associated with variations in their cell envelope structures and physiological characteristics. The interaction of nanoparticles with bacterial cells can result in membrane disruption, increased permeability, oxidative stress, enzyme inactivation and damage to intracellular components [41]. The enhanced antibacterial effect at higher concentrations may be attributed to the better availability of nanoparticles for interaction with bacterial cell surfaces and the increased generation of reactive oxygen species. The superior performance of the Ni/Zn nanocomposite compared with the other tested materials may be associated with synergistic effects between Ni and Zn. Incorporation of Ni may modify the surface characteristics and electronic properties of Zn, thereby enhancing its interaction with bacterial cells and potentially increasing reactive oxygen species generation.

The lower optical density values recorded for Zn–Ni–Se, particularly at 200 µg/mL, support its higher inhibitory effect on bacterial growth. *P. aeruginosa* and *E. coli* exhibited pronounced reductions in optical density at the higher nanomaterial concentrations. The extent of inhibition varied among the bacterial strains and nanomaterial compositions, which may be related to differences in cell-wall structure, membrane composition, surface charge and cellular defense mechanisms.

Table-1 reveals a concentration-dependent antibacterial response, with the higher inhibition generally observed at 200 µg/mL. Zn–Ni–Se showed inhibitory effects against all four tested bacterial strains. Further statistical analysis and mechanistic studies involving ROS detection, membrane-integrity assays and microscopic examination would help establish the magnitude and possible basis of this antibacterial activity.

Conclusion

A green Zn–Ni–Se nanocomposite was synthesized using *M. oleifera* leaf extract through a simple co-precipitation route. Structural, optical and morphological characterization confirmed the formation of a crystalline nanocomposite. Under UV irradiation, the material achieved approximately 98% degradation of methylene blue (MB) and 65% degradation of reactive red 120 (RR120) within 150 min. The degradation kinetics followed a pseudo-first-order model with a high correlation coefficient ($R^2 = 0.999$). The photocatalytic performance can be associated with improved charge separation and reduced electron–hole recombination within the Zn–Ni–Se system. Scavenger experiments identified photogenerated holes (h^+) as the dominant reactive species, followed by $\cdot OH$, $\cdot O_2^-$ and e^- . The retention of approximately 90% of the initial degradation efficiency after five successive cycles indicates that the material can maintain substantial photocatalytic activity upon reuse. The antibacterial response increased with nanocomposite concentration for *S. aureus*, *E. coli*, *S. pneumoniae* and *P. aeruginosa*.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

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