

Eco-friendly synthesis of chitosan-PVA/Ag-CeO₂ composite for crystal violet dye degradation and antibacterial performance

Laellia Denada ^a , Nabila Aprianti ^b , Davin Philo ^c ,
Poedji Loekitowati Hariani ^d * 

- a:** Magister Program of Chemistry, Department of Chemistry, Faculty of Mathematics and Natural Science, Universitas Sriwijaya , Ogan Ilir 580056, Indonesia
- b:** Research Center for Fuel Technology, National Research and Innovation Agency (BRIN) , South Tangerang 15314, Banten, Indonesia
- c:** Research Center for Photonics, National Research and Innovation Agency (BRIN) , South Tangerang, Banten 15314, Indonesia
- d:** Department of Chemistry, Faculty of Mathematics and Natural Science, Universitas Sriwijaya , Ogan Ilir 580056, Indonesia
- * Corresponding author: puji_lukitowati@mipa.unsri.ac.id



Abstract

Environmentally friendly synthesis offers a sustainable approach to material development. In this study, Ag–CeO₂ was successfully synthesized using *Morinda citrifolia* L. leaf extract, which served as both a bioreductant and a stabilizer to prevent agglomeration. A chitosan–polyvinyl alcohol (PVA) matrix was used to host the synthesized Ag–CeO₂, enabling its application in crystal violet dye (CVD) degradation and antibacterial studies. The resulting Chitosan–PVA/Ag–CeO₂ composite was characterized using XRD, SEM-EDX, and UV-DRS. XRD confirmed the composite formation with diffraction patterns reflecting its constituents, whereas UV-DRS characterization identified a 2.12 eV band gap, enabling photocatalytic activity under visible light. Degradation optimization, performed via Response Surface Methodology based on Central Composite Design approach, indicated a quadratic model with optimal conditions at pH 8, 33 mg/L CVD concentration, and 145 min of irradiation, achieving 96.37% degradation efficiency. The degradation kinetics followed a pseudo-first-order model with a rate constant (*k*) of 0.0408 min^{−1}. FTIR analysis demonstrated composite stability with no significant spectral changes after photodegradation. TOC analysis confirmed 84.26% mineralization, and recycling tests showed only a 5.02% decrease in efficiency after five cycles. Furthermore, antibacterial assays against *Staphylococcus aureus* and *Escherichia coli* demonstrated the composite's strong antibacterial potential.

Key findings

- *Morinda citrifolia* L. leaf extract served as a natural reductant in the eco-friendly synthesis of the Chitosan–PVA/Ag–CeO₂ composite.
- An efficiency of 96.37% in crystal violet dye (CVD) degradation was achieved under optimum conditions—pH 8, 33 mg/L concentration, and 145 min irradiation—as predicted by a quadratic model developed through Response Surface Methodology (RSM).
- The composite demonstrated effective inhibition of *Staphylococcus aureus* and *Escherichia coli*.

© 2025, the Authors. This article is published in open access under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

Accompanying information

Article history

Received: 05.10.25

Revised: 06.11.25

Accepted: 19.11.25

Available online: 01.12.25

Keywords

Green synthesis; chitosan-PVA/Ag-CeO₂; degradation; crystal violet dye; antibacterial

Funding

This work was supported by the Ministry of Higher Education, Science, and Technology under the Master's Thesis scheme, 2025

Supplementary information

Transparent peer review:  READ

Sustainable Development Goals



1. Introduction

Water contamination by synthetic dyes is a major environmental concern and a global challenge [1,2]. The utilization of these dyes spans a wide range of fields, including textile

manufacturing, paper, cosmetics, pharmaceuticals, leather, and food-related industries [3,4]. However, dye-containing wastewater is highly resistant to natural degradation, causing severe ecological damage. The presence of dyes in water

decreases light availability, disrupts photosynthesis, and negatively impacts aquatic life. Additionally, numerous dyes incorporate carcinogenic and mutagenic compounds, presenting chronic health risks to humans [3,5].

Among synthetic dyes, crystal violet (CVD) is frequently employed in industrial processes. Classified as a cationic dye, it is also used in microbiology for biological staining and in medicine as an antifungal and antibacterial agent [6,7]. Despite these applications, CVD is a recognized bio-hazard: exposure can cause fainting, eye irritation, diarrhea, headaches, and vomiting, while chronic exposure may lead to kidney failure and carcinogenic effects [8–10].

Effective dye removal technologies are therefore essential. Advanced Oxidation Processes (AOPs) using heterogeneous catalysts are regarded as highly effective compared to methods such as adsorption, coagulation, flocculation, conventional oxidation, or biodegradation [2,11–14]. However, AOPs are limited by sludge production and high operating costs [15]. Their effectiveness lies in generating reactive hydroxyl radicals ($\bullet\text{OH}$), which mineralize dyes into CO_2 , H_2O , and inorganic ions [16].

Cerium oxide (CeO_2) has attracted considerable attention as both a photocatalyst and an antibacterial agent [17]. Its advantages include a reversible $\text{Ce}^{3+}/\text{Ce}^{4+}$ redox cycle, tunable oxygen vacancies, high thermal stability, biocompatibility, and strong redox potential [17,18]. CeO_2 is an n-type semiconductor with a band gap of 2.8–3.1 eV. Its broad band gap together with a small surface area promotes rapid electron-hole recombination and insufficient absorption in the visible range, which hinders photocatalytic activity. Metal doping, particularly with silver (Ag), promotes the formation of heterojunctions that enable electron transfer from the conduction band of CeO_2 to Ag across the interface. The establishment of such heterojunctions effectively mitigates the intrinsic limitations of CeO_2 by enhancing charge separation efficiency, extending visible-light absorption, and facilitating the generation of reactive radical species. Consequently, these effects collectively improve the overall photocatalytic performance of the material.

Moreover, Ag- CeO_2 composites exhibit stronger antibacterial activity than pure CeO_2 [19,20]. Nevertheless, Ag- CeO_2 composites are prone to aggregation due to van der Waals forces. Incorporating chitosan and polyvinyl alcohol (PVA) as a polymeric matrix helps to disperse Ag- CeO_2 particles evenly, prevent clumping, and preserve surface activity [17,21]. Chitosan is biocompatible and swells in acidic solutions but tends to weaken in aqueous environments.

Chitosan is widely recognized as an effective support material for metal oxide-based photocatalysts due to its large surface area, high adsorption capacity, and inherent ability to stabilize catalytic structures [22]. In contrast, PVA is a non-toxic, water-soluble polymer with good biodegradability and mechanical stability [23]. Together, PVA and chitosan form a cross-linked network that enhances the stability and durability of the composite [21,24].

This study aims to synthesize a chitosan-PVA/Ag- CeO_2 composite for crystal violet dye degradation. Ag- CeO_2 was prepared through an environmentally friendly synthesis route using *Morinda citrifolia* L. leaf extract, which provides flavonoids, phenols, and chlorophyll as natural reducing and stabilizing agents [25,26]. The novelty of this study lies in the green synthesis of Ag- CeO_2 using *Morinda citrifolia* L. extract, followed by its incorporation into a Chitosan-PVA matrix to develop a multifunctional material. The resulting composite not only functions as an effective photocatalytic degrading agent but also exhibits significant antibacterial activity. The *Morinda citrifolia* L. leaf extract contains alkaloids, tannins, saponins, and steroids with known antibacterial properties against Gram-positive and Gram-negative bacteria [27]. Optimization of CVD degradation was performed using Response Surface Methodology (RSM), with pH, dye concentration, and irradiation duration as the key variables.

2. Experimental

2.1. Materials

Morinda citrifolia leaves were collected from Banyuasin Regency, Indonesia. The other materials used in this study included ethanol (99.9%), AgNO_3 ($\geq 99.98\%$), $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ ($\geq 98.5\%$), NH_4OH (30–33%), crystal violet dye (CVD, $\geq 90\%$), poly(vinyl alcohol) (PVA, 98–99%), chitosan (degree of deacetylation: 75–85%), NaCl ($\geq 99.5\%$), HCl (37%), NaOH ($\geq 99.0\%$), dimethyl sulfoxide (DMSO, $\geq 99.9\%$), nutrient agar ($\geq 70\%$), and amoxicillin ($\geq 95\%$), all obtained from Sigma-Aldrich.

2.2. Extraction of *Morinda citrifolia* L. Leaf

Fresh leaves were thoroughly washed and dried under sunlight for ~2 days, then ground into powder. 50 g of the powder were extracted with 500 mL of 96% ethanol and left for 24 h at room temperature. The mixture was filtered, and the filtrate was stored at 4 °C until use.

2.3. Synthesis of Ag- CeO_2

Ag- CeO_2 was synthesized via a coprecipitation method. A solution of 1 g AgNO_3 in 100 mL distilled water was mixed with 4.5 g $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ dissolved in 50 mL distilled water. Then, 50 mL of *Morinda citrifolia* L. leaf extract was added and stirred at 250 rpm at room temperature. A 25% NH_4OH solution was added dropwise until the pH reached ~10. The precipitate was collected by centrifugation for 15 min and calcined at 500 °C for 2 h.

2.4. Synthesis of chitosan-PVA/Ag- CeO_2 composite

The composite was prepared following a modified procedure [21,28]. To obtain the PVA solution, 0.5 g of PVA was mixed with 100 mL of distilled water and heated to 70 °C with stirring at 250 rpm. Separately, 100 mL of 1% (w/v) chitosan solution was prepared, then mixed with the PVA solution (weight ratio = 1:0.5) under stirring at 250 rpm to

obtain a homogeneous chitosan–PVA solution. Next, 2 g of Ag–CeO₂ was added to the chitosan–PVA solution. The mixture was sonicated for 30 min and subsequently stirred at room temperature for 3 h. The resulting precipitate was separated by filtration, washed with distilled water, and dried in an oven at 80 °C for 4 h. The obtained composite was then stored in a desiccator until further use.

2.5. Determination of pH_{pzc}

A total of 50 mL of 0.1 M NaCl solution was placed in Erlenmeyer flasks, and the pH was adjusted to values between 2 and 12 using 0.1 M HCl or 0.1 M NaOH. Then, 0.1 g of the chitosan-PVA/Ag–CeO₂ composite was added to each solution and shaken at 220 rpm at 25 °C for 2 h. The suspensions were left to equilibrate for 24 h. The pH_{pzc} was determined from the plot of initial pH versus ΔpH [16,29].

2.6. Instrumentation

The composite was characterized using X-ray Diffraction (XRD, SmartLab Rigaku), Scanning Electron Microscopy coupled with Energy-Dispersive X-ray spectroscopy (SEM-EDX, JEOL JSM-IT200), UV-Vis Diffuse Reflectance Spectroscopy (UV-DRS, Hitachi U-2900), and Fourier Transform Infrared Spectroscopy (FTIR, PerkinElmer UATR). The surface area was determined using the NET method (Quantachrome TouchWin v1.22). Dye degradation was monitored using a UV-Vis Spectrophotometer (Thermo Orion AquaMate 8000).

2.7. Experimental design of photocatalytic

Photocatalytic degradation of CVD using the chitosan-PVA/Ag–CeO₂ composite was investigated through Response Surface Methodology (RSM) with a Central Composite Design (CCD). Each experiment was performed in 50 mL of CVD solution containing 0.01 g of the composite under visible light irradiation. A total of 20 runs were conducted, with solution pH, CVD concentration, and irradiation time as the experimental variables, as summarized in Table 1. Statistical analysis was carried out using Design Expert 13 software.

2.8. Recycling of chitosan-PVA/Ag–CeO₂ composite

In this study, recycling was performed by washing the used chitosan-PVA/Ag–CeO₂ composite with distilled water and ethanol, followed by drying at 105 °C for 1 hour [30–32]. The recycling experiment was conducted for five consecutive cycles, and the degradation efficiency was determined for each cycle.

Table 1 Experimental Parameters of RSM-CCD.

Variables	1	0	–1
pH	4	6	8
CVD concentration (mg/L)	20	40	60
Irradiation time (min)	30	90	150

2.9. Antibacterial

The disc diffusion assay, following modifications of previously described protocols [32,33], was employed to evaluate the antibacterial performance of the chitosan-PVA/Ag–CeO₂ composite. *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) were selected as test organisms. Discs of filter paper (≈5 mm) were saturated with composite solutions in DMSO at concentrations between 1000 and 5000 mg/L. The discs were then placed on agar plates previously inoculated with bacterial suspensions (≈10⁶ CFU/mL) grown in Mueller–Hinton broth. Following 24 h incubation at 37 °C, antibacterial efficacy was evaluated from the diameter of inhibition zones (mm) surrounding each disc, with DMSO acted as the negative control, whereas amoxicillin was used as the positive control.

3. Results and Discussion

3.1. Characterization

The XRD patterns of Ag–CeO₂ and the chitosan-PVA/Ag–CeO₂ composite are shown in Figure 1. In Figure 1(a), the diffraction peaks correspond to the combination of Ag and CeO₂ phases. Ag exhibits characteristic reflections at $2\theta = 38.11^\circ$, 44.30° , 64.11° , and 78.1° , corresponding to the (111), (200), (220), and (311) planes (JCPDS No. 04-0783). The sharp peak near 38° is particularly indicative of Ag [34]. CeO₂ displays peaks at $2\theta = 28.68^\circ$, 33.21° , 47.73° , 56.41° , 59.10° , and 69.43° , which match the (111), (200), (220), (311), (222), and (400) planes (JCPDS No. 34-0394).

In Figure 1(b), the same patterns are observed, but with decreased intensity due to the amorphous nature of chitosan and PVA. The same phenomenon occurs in the CeO₂–SiO₂ composite, where the peak width and intensity are lower in the CeO₄–SiO₂ peak compared to CeO₂ [35]. Chitosan typically shows peaks at $\sim 10^\circ$ and 20° , while PVA exhibits a peak around 19.5° [21,36]. However, these are not clearly visible, likely masked by the dominant CeO₂ peaks. Using the Debye–Scherrer equation at the highest intensity CeO₂ (111) peak, the crystallite size of Ag–CeO₂ was estimated as 18.88 nm, while that of the chitosan-PVA/Ag–CeO₂ composite was 24.07 nm. The increase in crystallite size observed in the chitosan-PVA/Ag–CeO₂ composite can be attributed to the stabilizing effect of the polymer matrix, which facilitates particle growth and recrystallization. Crystallite size calculations using the Williamson–Hall (W–H) equation yielded larger values of 21.45 nm and 28.30 nm. This discrepancy is likely because the Williamson–Hall method accounts for both crystallite size and microstrain within the crystal lattice [37].

SEM images (Figure 2) reveal that Ag–CeO₂ possesses an uneven surface morphology characterized by aggregated particles. The agglomeration is likely caused by Van der Waals interactions between particles and the drying process during synthesis.

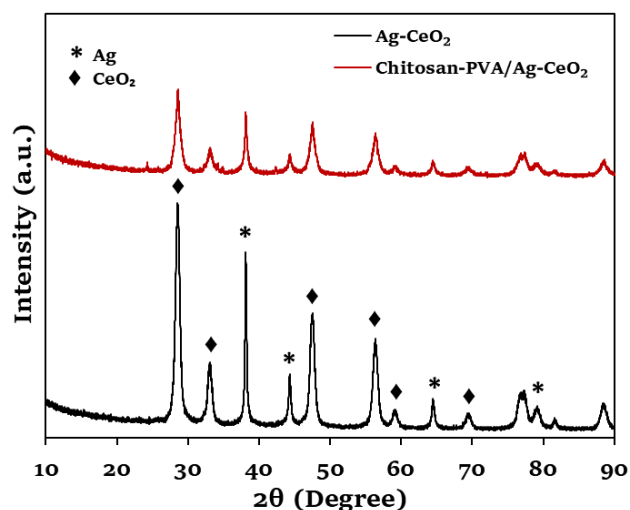


Figure 1 XRD pattern of Ag-CeO₂ and chitosan-PVA/Ag-CeO₂ composite.

In contrast, the chitosan-PVA/Ag-CeO₂ composite exhibits well-dispersed granules, indicating that Ag-CeO₂ particles are uniformly distributed within the polymer matrix.

EDX mapping (Figure 3) confirms the composite composition of O (22.03%), Ag (16.23%), C (13.84%), Ce (46.96%), and N (0.94%), demonstrating that Ag-CeO₂

was effectively embedded into the chitosan-PVA structure. Although distribution is not entirely uniform, Ag-CeO₂ particles are clearly embedded within the surface.

Figure 4 presents the UV-Vis spectra and calculated band gap values. The band gap of Ag-CeO₂ was determined to be 2.30 eV, slightly smaller than the 2.5 eV reported for Ag-CeO₂ synthesized using *Morinda tinctoria* extract [18]. The chitosan-PVA/Ag-CeO₂ composite exhibited a further reduced band gap of 2.12 eV. This red shift is attributed to improved dispersion of Ag-CeO₂ within the polymer and the formation of oxygen vacancies, which enhance visible-light absorption. Comparable findings have been reported for Ag@CeO₂/rGO (2.75 eV) and CeO₂ (3.05 eV) [20].

The surface area of Ag-CeO₂ is lower than that of the chitosan-PVA/Ag-CeO₂ composite (Table 2). A similar trend has been reported when TiO₂ is dispersed within a polydopamine-chitosan matrix, where the surface area increased from 9.689 m²/g for pure TiO₂ to 114.465 m²/g for the polydopamine-chitosan-TiO₂ composite [38]. This enhancement in surface area can be attributed to surface modification by polymer layers such as chitosan and PVA, which promote the formation of a porous structure while simultaneously preventing the agglomeration of Ag-CeO₂ particles.

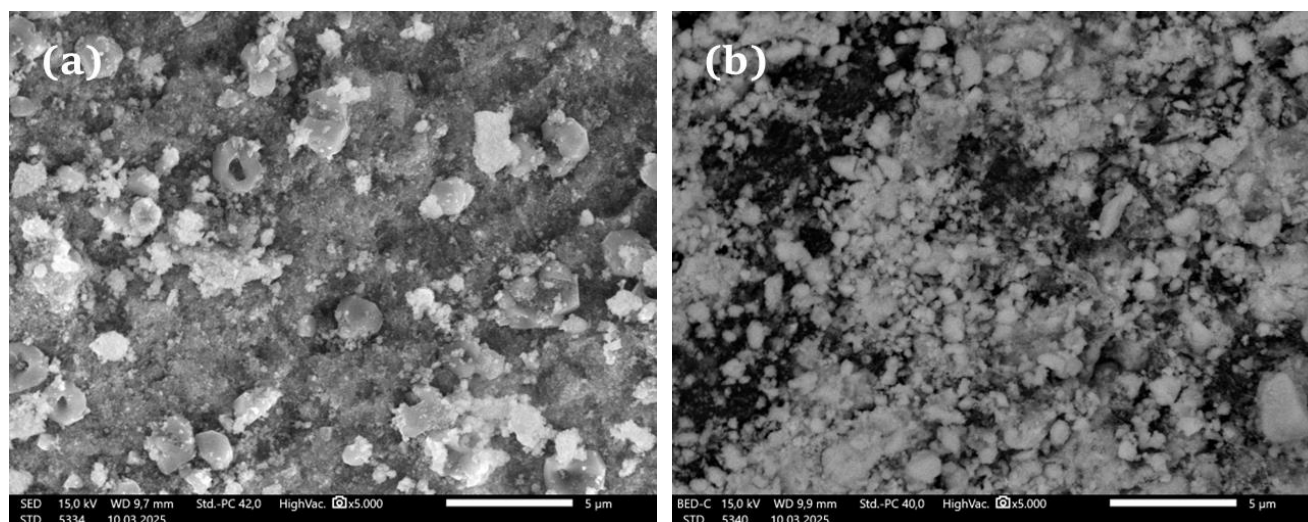


Figure 2 SEM image of (a) Ag-CeO₂ and (b) Chitosan-PVA/Ag-CeO₂ composite.

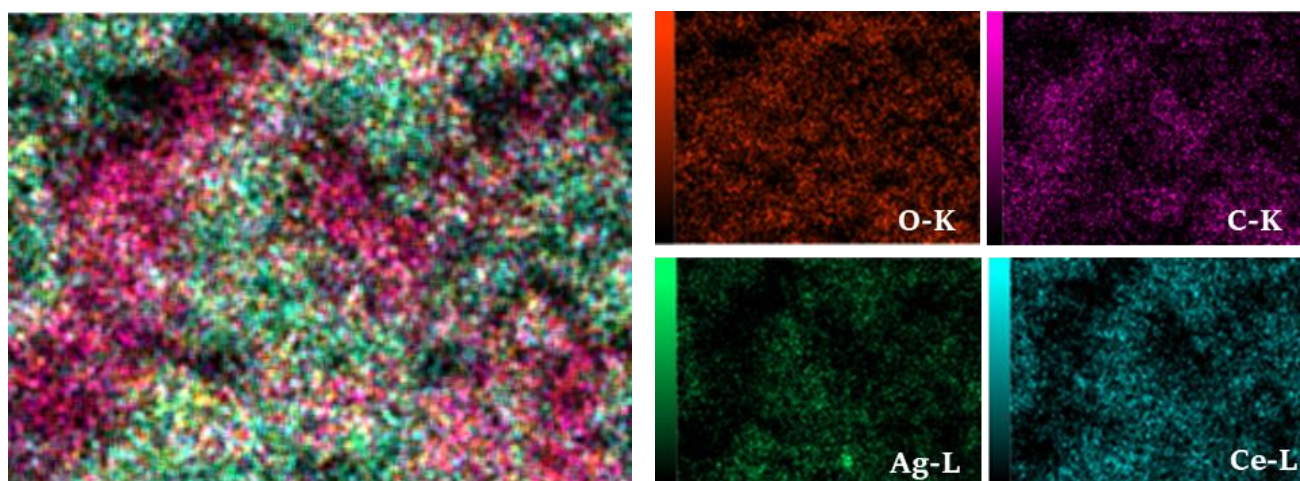


Figure 3 EDX mapping for chitosan-PVA/Ag-CeO₂ composite.

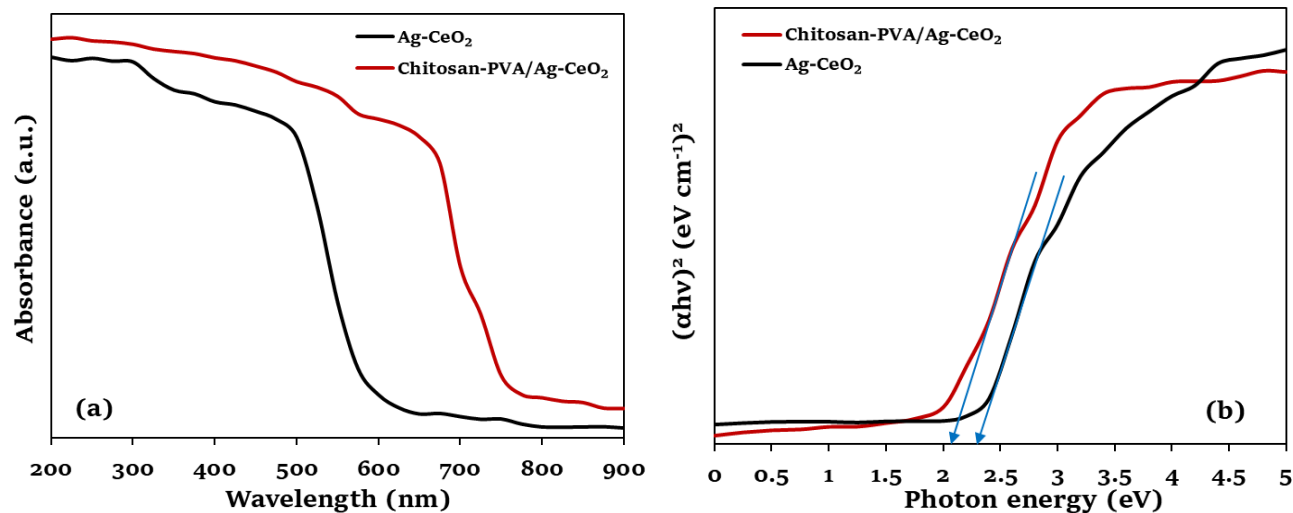


Figure 4 (a) UV-visible spectra and (b) Tauc plot of Ag-CeO₂ and chitosan-PVA/Ag-CeO₂ composite.

Table 2 Surface area parameters.

Materials	S _{BET} (m ² /g)	Pore vol. (cm ³ /g)	Pore size (nm)
Ag/CeO ₂	71.458	0.362	4.985
Chitosan-PVA/Ag-CeO ₂	98.410	0.625	6.324

The point of zero charge (pHpzc) of the chitosan-PVA/Ag-CeO₂ composite was determined as 6.4 (Figure 5). This parameter is crucial as it dictates the surface charge of the photocatalyst, thereby affecting pollutant adsorption and radical generation [16,39].

3.2. CCD model Analysis

RSM is a multivariate statistical approach used to design experiments, develop empirical models, and analyze the effects of multiple operational parameters on process outcomes [40]. This study employed a CCD-based RSM experimental design with three variables: solution pH (A), CVD concentration (B), and irradiation time (C). The CCD model is widely used due to its flexibility in exploring variable interactions with a relatively small number of experiments [41]. Table 3 presents the actual and predicted degradation efficiencies. The difference between them (0.01–2.11) was minimal, indicating excellent model fit.

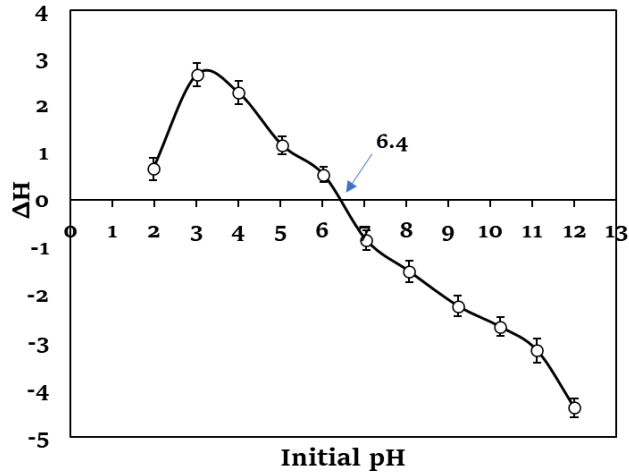


Figure 5 pHpzc of chitosan-PVA/Ag-CeO₂ composite.

This was further supported by the close alignment of data points along the diagonal line ($y = x$) in Figure 6, demonstrating the model’s strong predictive ability and very small residual errors.

ANOVA results (Table 4) confirmed that the quadratic model was the most appropriate for describing CVD degradation using the chitosan-PVA/Ag-CeO₂ composite, as indicated by p value < 0.05 and a non-significant lack of fit ($p = 0.5648$) [42]. Among the main factors, pH (A) was the most influential ($F = 782.87$; $p < 0.0001$), showing that solution acidity strongly affected degradation efficiency. Irradiation time (B) also had a significant effect ($F = 71.58$; $p < 0.0001$), whereas CVD concentration (C) was not significant ($p = 0.8055$), suggesting that within the studied range, the concentration changes did not substantially alter the response.

Table 3 CCD design with actual and predicted values.

Run	A	B (mg/L)	C (min)	Degradation (%)	
				Actual	Predicted
1	6	40	90	81.87	80.48
2	4	40	90	61.33	62.43
3	6	40	90	78.37	80.48
4	8	40	90	92.86	91.19
5	6	40	90	81.66	80.48
6	8	60	30	97.26	98.51
7	6	60	90	84.20	82.81
8	8	60	150	92.37	92.27
9	4	60	30	69.23	68.59
10	6	40	90	81.56	80.48
11	6	40	90	78.37	80.48
12	6	40	150	89.20	89.21
13	6	40	30	79.80	80.22
14	4	20	150	79.36	78.01
15	6	20	90	81.27	83.08
16	4	20	30	53.77	53.78
17	4	60	150	75.21	76.12
18	6	40	90	81.87	80.48
19	8	20	30	98.15	97.15
20	8	20	150	100.07	102.61

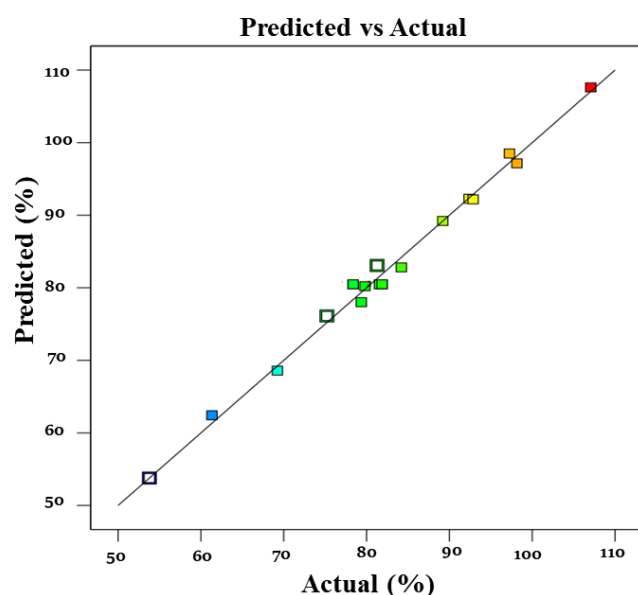


Figure 6 The predicted versus actual value.

Table 4 ANOVA analysis for CVD degradation.

Source	Sum of square	df	Mean square	F-value	p-value
Model	2846.57	9	316.29	111.84	< 0.0001
A	2214.05	1	2214.05	782.87	< 0.0001
B	0.1808	1	0.1808	0.0639	0.8055
C	202.44	1	202.44	71.58	< 0.0001
AB	90.41	1	90.41	31.97	0.0002
AC	94.74	1	94.74	33.50	0.0002
BC	139.48	1	139.48	49.32	< 0.0001
A ²	27.69	1	27.69	9.79	0.0107
B ²	16.69	1	16.69	5.90	0.0355
C ²	49.23	1	49.23	17.41	0.0019
Residual	28.28	10	2.83		
Lack of Fit	13.06	5	2.61	0.8578	0.5648
Pure Error	15.22	5	3.04		
Cor Total	2874.85	19			

All interaction terms (AB, AC, and BC) were significant, highlighting the synergistic effects of combined factors on degradation efficiency.

Model evaluation parameters are summarized in Table 5. The model exhibited good precision, as shown by a relatively small standard deviation (1.68) compared with the mean response (82.24). The high R^2 value (0.9902) and adjusted R^2 (0.9813) confirmed an excellent fit, with 99.02% of response variation explained by the model.

The difference between adjusted R^2 and predicted R^2 was less than 0.2, indicating strong internal consistency [43,44]. Moreover, the high Adeq precision value (452.699) reflected a robust signal-to-noise ratio, ensuring the model's reliability in capturing true factor effects rather than random variation.

The resulting quadratic model describing the relationship between degradation efficiency (%) and the variables A, B, and C can be expressed as:

$$\begin{aligned} \text{Degradation (\%)} = & 80.48 + 14.88A - 0.1345(B) \\ & + 4.50(C) - 3.36(AB) - 3.44(AC) - 4.18(BC) - \\ & 3.17(A^2) + 2.46(B^2) + 4.23(C^2). \end{aligned} \quad (1)$$

3.3. Interactions between variables

The 3D response surface and contour plots for CVD degradation using the chitosan-PVA/Ag-CeO₂ composite are shown in Figure 7. In these plots, blue regions represent areas of low degradation efficiency, while red regions indicate areas of high efficiency. The general trend observed is that degradation efficiency increases with higher pH values, lower CVD concentrations, and longer irradiation times.

The optimum degradation efficiency was achieved at pH 8. Since CVD is a cationic dye, the surface charge of the photocatalyst plays an important role. The composite had a pH_{pzc} of 6.4; thus, at pH values above this point, the surface became negatively charged, promoting electrostatic attraction with CVD molecules and improving adsorption. In addition, higher pH levels increased the availability of OH⁻ ions, which enhanced •OH radical formation and, consequently, photocatalytic degradation.

The optimum initial concentration was determined to be 33 mg/L. At lower dye concentrations, fewer CVD molecules were present in solution, allowing reactive species (•OH, •O₂⁻) generated by the photocatalyst to interact more efficiently and uniformly. As a result, degradation effectiveness was higher at lower concentrations. An increase in pollutant concentration initially enhanced the degradation efficiency; however, at higher concentrations, the efficiency declined. This decrease can be attributed to the excessive number of pollutant molecules adsorbed on the catalyst surface, which compete for active sites and hinder light penetration. Consequently, the generation of reactive radicals was reduced, leading to the inhibition of the photocatalytic process [31,39].

Irradiation time also improved degradation efficiency up to an optimum point, beyond which additional exposure did not yield improvements. This plateau effect is attributed to the limited number of remaining pollutant molecules and the saturation of active catalytic sites [33,45].

Desirability analysis was applied to convert each response into a scale of 0–1 and combine them into a single optimization function, enabling the determination of conditions that simultaneously satisfy all the response targets.

Table 5 Statistical parameters for CVD degradation.

Parameters	Value
Standard Deviation	1.68
Mean	82.24
C.V. %	2.04
R^2	0.9902
Adjusted R^2	0.9813
Predicted R^2	0.9356
Adeq Precision	452.699

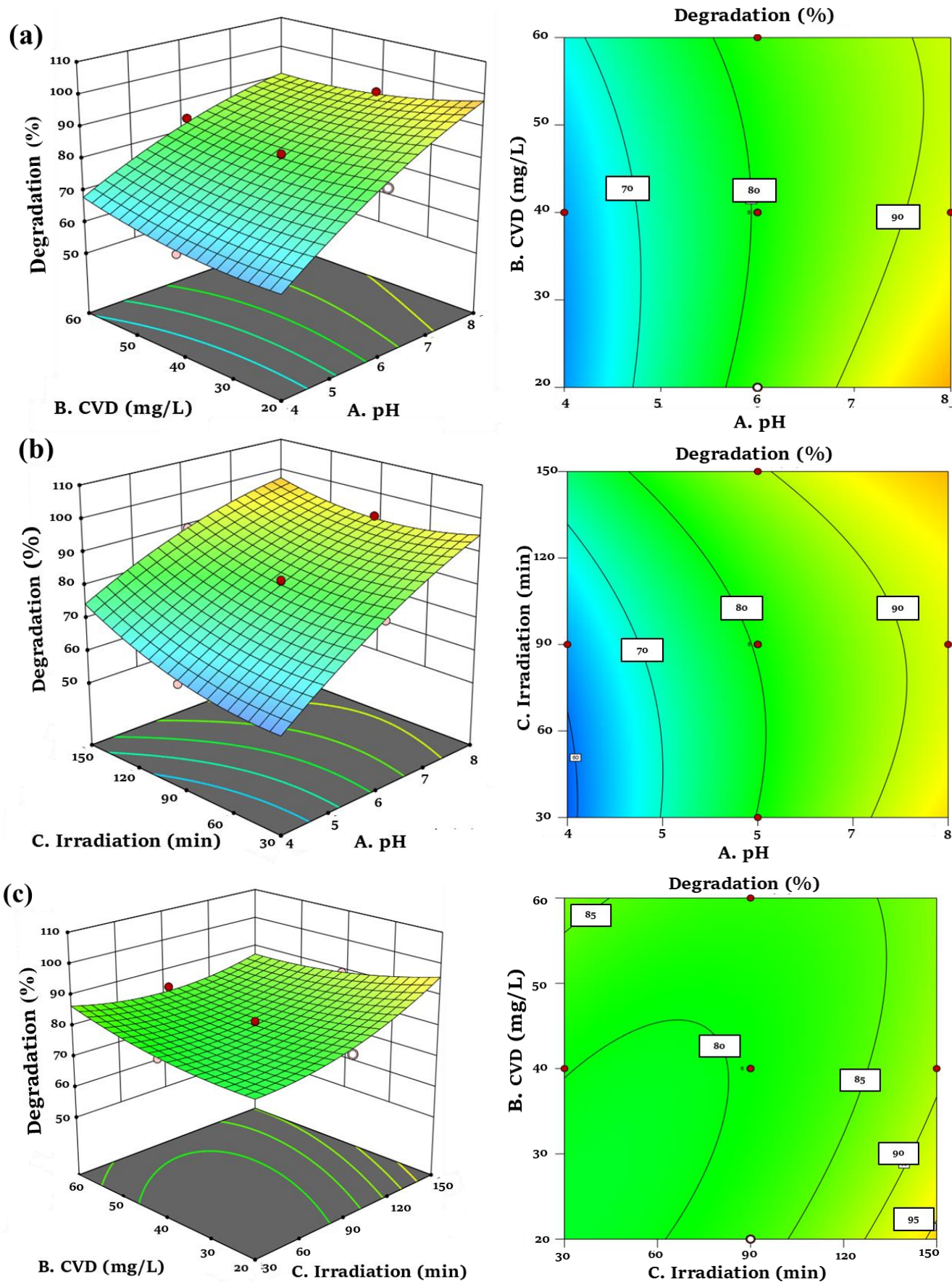


Figure 7 3D surface plots and contour of effect (a) pH (b) CVD concentration and (c) Irradiation time.

For CVD degradation using the chitosan-PVA/Ag-CeO₂ composite, the analysis yielded a desirability value of 1 under optimum conditions of pH 8, CVD concentration of 33 mg/L, and irradiation time of 145 min, achieving a degradation efficiency of 96.37% (Figure 8). A desirability value of 1 indicates that the predicted response perfectly meets the target criteria.

3.4. Kinetic study

The kinetics of CVD degradation using the chitosan-PVA/Ag-CeO₂ composite were analyzed based on a pseudo-first-order model, which assumes that the dye is present in excess and that the degradation rate depends solely on the dye concentration [41]. The kinetic equation is expressed as follows:

$$kt = -\ln \frac{C}{C_0} \quad (2)$$

where C_0 and C represent the initial and residual CVD concentrations at time t , respectively, while k (min⁻¹) denotes the degradation rate constant.

The high coefficient of determination ($R^2 = 0.9942$) indicates an excellent fit with the pseudo-first-order kinetic model (Figure 9). The obtained rate constant ($k = 0.0408$ min⁻¹) suggests that the degradation proceeds at a relatively rapid rate and is influenced by the initial CVD concentration. This result is consistent with previous studies reporting that CVD degradation using ZnO and TiO₂ catalysts also follows pseudo-first-order kinetics [10].

3.5. Stability of chitosan-PVA/Ag-CeO₂ composite

The stability of the chitosan-PVA/Ag-CeO₂ composite was evaluated through FTIR analysis conducted before and after photodegradation and recycling tests. As shown in Figure 10, the main FTIR peaks remained essentially unchanged after the degradation process, confirming good structural stability. Minor shifts or intensity variations could be attributed to residual CVD molecules or intermediate degradation products adsorbed on the composite surface.

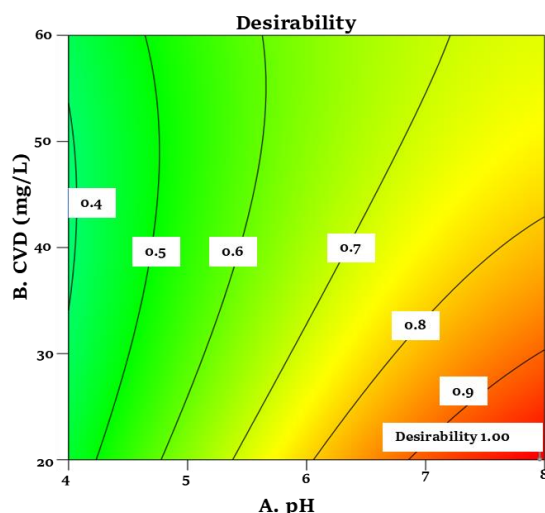


Figure 8 Desirability for the optimization of CVD degradation by chitosan-PVA/Ag-CeO₂ composite.

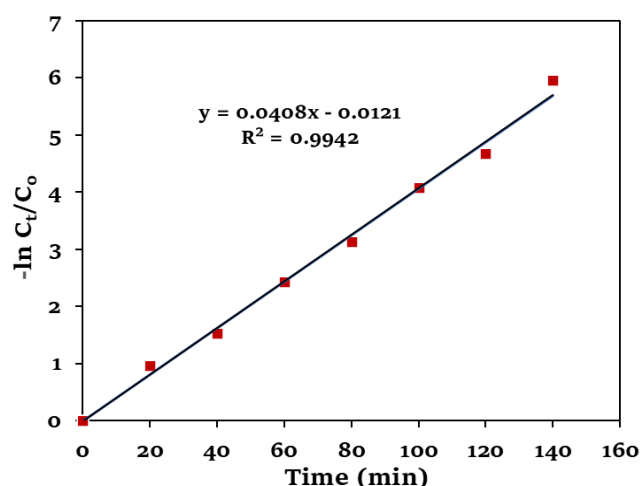


Figure 9 Pseudo-first-order for photocatalytic degradation of CVD.

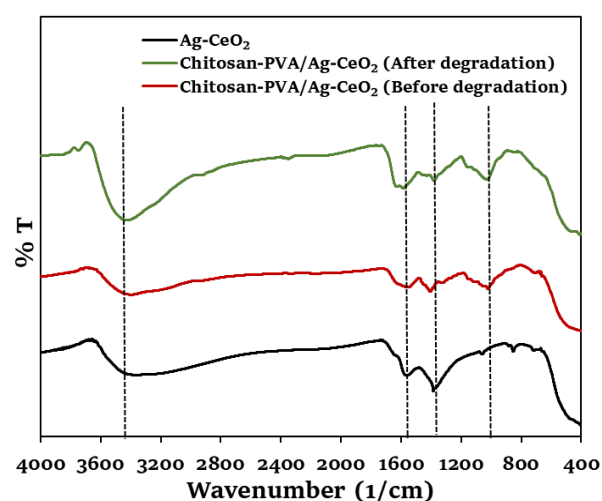


Figure 10 FTIR spectra of chitosan-PVA/Ag-CeO₂ composite.

The broad absorption band at 3200–3400 cm⁻¹ corresponds to N–H and O–H stretching vibrations derived from chitosan, PVA, and overlapping water molecules. The band at ~1590 cm⁻¹ is associated with N–H bending or C–N stretching, while the peak near 1300 cm⁻¹ reflects C=O stretching [46]. The Ce–O vibration was observed in the 400–800 cm⁻¹ range, appearing at ~700 cm⁻¹ in this study, which confirms the presence of CeO₂ (17). Pure Ag⁰ does not produce FTIR bands due to the absence of covalent bond vibrations.

Catalyst regeneration is crucial for assessing long-term stability, reusability, and minimizing environmental impacts [42,47]. After five cycles of reuse under optimal degradation conditions, the chitosan-PVA/Ag-CeO₂ composite maintained a degradation efficiency of 91.35%, corresponding to only a 5.02% reduction (Figure 11). This slight decrease may result from catalyst mass loss during washing and drying, as well as partial surface blockage by unreleased dye residues [16,48].

For comparison, previous research on CVD degradation using Sr–ZnO/activated carbon nanoneedles reported a greater decline in efficiency of 10.99% after five cycles [4].

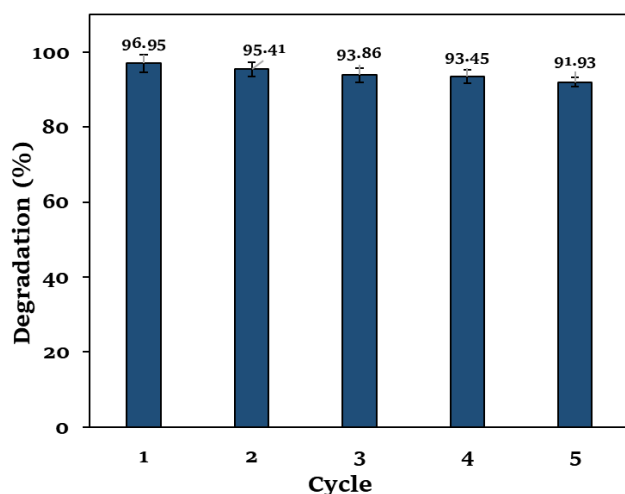


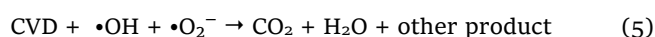
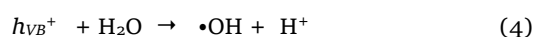
Figure 11 Recycling of chitosan-PVA/Ag-CeO₂ composite.

Therefore, the relatively stable performance of the chitosan-PVA/Ag-CeO₂ composite highlights its promising potential as a reusable and efficient photocatalyst for wastewater treatment applications.

3.6. Photocatalytic mechanism

A scavenger test was conducted to identify the dominant reactive species involved in the photodegradation mechanism. Ethylenediaminetetraacetic acid (EDTA) was used as a hole (h⁺) scavenger, silver nitrate (AgNO₃) for electrons (e⁻), benzoquinone (BQ) for superoxide radicals (O₂^{•-}), and isopropyl alcohol (IPA) as a hydroxyl radical (•OH) scavenger [41]. The experimental results demonstrated that the addition of IPA produced the lowest degradation efficiency (28.43%), indicating that hydroxyl radicals are the primary reactive species responsible for CVD degradation. The presence of BQ reduced the efficiency to 44.64%, confirming a secondary contribution from superoxide radicals, while the effects of h⁺ and e⁻ trapping were relatively minor (Figure 12).

These findings are consistent with previous reports, such as the study on rGO/ZnCo₂O₄ nanocomposites, where hydroxyl radicals were identified as the dominant reactive species in CVD degradation [49]. Therefore, the degradation mechanism of CVD by the chitosan-PVA/Ag-CeO₂ composite is controlled mainly by •OH and O₂^{•-} radicals, which can be described as follows [3,18]:



The end product of the photocatalytic reaction is a molecule that is less harmful or easier to remove than the original pollutant [50].

Table 6 presents a comparison of degradation efficiencies obtained using various CeO₂-based catalysts. It can be observed that the chitosan-PVA/Ag-CeO₂ composite exhibits its superior performance in CVD degradation compared to the other reported catalysts.

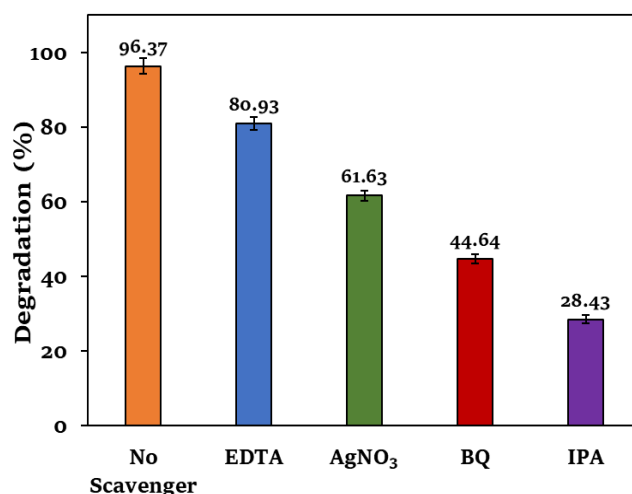


Figure 12 Active species scavengers in the degradation of CVD by chitosan-PVA/Ag-CeO₂ composite.

Table 6 Comparison of degradation using CeO₂ catalysts.

Materials	Pollutants	Degradation (%)	Ref.
Ag/CeO ₂	Methylene blue	92.21	(19)
Ag-CeO ₂ @SnO ₂	Tetracycline	96	(46)
Ag-CeO ₂ @SnO ₂	Metronidazole	94	(46)
Ag/Zn-CeO ₂	Methyl orange	85	(51)
CeO ₂	Methylene blue	72.12	(52)
g-C ₃ N ₄ /CeO ₂	Methylene blue	95.70	(52)
CeO ₂ /h-BN	Methylene blue	93	(53)
Chitosan-PVA/Ag-CeO ₂	Crystal violet	96.37	This study

Evidence of CVD mineralization was confirmed through TOC analysis, which measures the remaining organic carbon content. Before degradation, the TOC value was 13.810 mg/L, which decreased to 2.174 mg/L after treatment under optimal conditions (pH 8, initial CVD concentration of 33 mg/L, and irradiation time of 145 min), corresponding to an 84.26% reduction. This result strongly supports the effective photocatalytic mineralization of CVD by the composite.

3.7. Antibacterial activity

To assess antibacterial performance, the chitosan-PVA/Ag-CeO₂ composite was examined against representative Gram-positive (*S. aureus*) and Gram-negative (*E. coli*) bacteria, which are commonly encountered in environmental settings. Amoxicillin was used as a positive control, while DMSO served as a negative control. The inhibition zones obtained are summarized in Table 7 and illustrated in Figure 13.

The results demonstrate that the inhibition of bacterial growth increased with higher concentrations of the composite. Although the inhibitory effect was lower compared to the commercial antibiotic (amoxicillin), the composite still exhibited a clear antibacterial effect. Silver ion (Ag⁺) release is considered the primary mechanism responsible for the antibacterial activity.

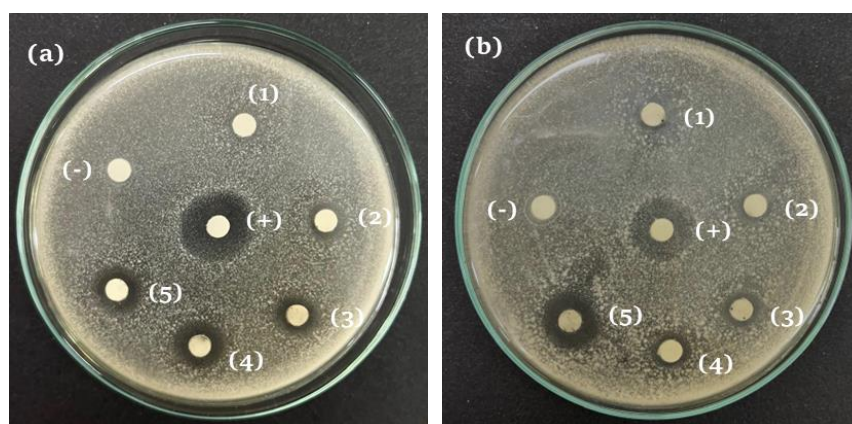


Figure 13 Bacterial zone of inhibitions of (a) *S. aureus* and (b) *E. coli*.

Table 7 Bacterial zone of inhibition of chitosan-PVA/Ag-CeO₂ composite.

Concentration (μg/mL)	Zone of inhibitions (mm)	
	<i>S. aureus</i>	<i>E. coli</i>
(1) 1000	10.0 ± 0.01	10.1 ± 0.02
(2) 2000	11.1 ± 0.03	10.2 ± 0.04
(3) 3000	13.0 ± 0.02	12.4 ± 0.06
(4) 4000	13.6 ± 0.05	13.1 ± 0.03
(5) 5000	13.8 ± 0.02	14.8 ± 0.04
(+) Amoxicillin	18.9 ± 0.04	18.6 ± 0.05
(-) DMSO	6.0 ± 0.01	6.0 ± 0.02

It can disrupt bacterial cell structures by binding to proteins and DNA, as well as induce oxidative stress that ultimately leads to cell death [54,55]. Furthermore, the incorporation of CeO₂ enhances antibacterial performance by generating Reactive Oxygen Species (ROS), such as superoxide radicals ($\text{O}_2^{\bullet-}$) and hydroxyl radicals ($\text{OH}^{\bullet}$), which synergistically intensify bacterial cell damage [27].

4. Limitations

In this study, the chitosan-PVA/Ag-CeO₂ composite was synthesized and applied for both CVD degradation and antibacterial activity. The Ag-CeO₂ component was prepared via a green synthesis approach using *Morinda citrifolia* L. leaf extract. However, some limitations should be noted. First, no variations in the composition ratio between Ag and CeO₂ were explored, even though such variations are crucial because CeO₂ plays a dominant role in catalytic activity. Second, the optimization of variables using the RSM-CCD method could be further expanded by considering additional factors, such as catalyst dosage, degradation temperature, and radiation intensity, to obtain more comprehensive and representative optimization results.

5. Conclusions

This study demonstrated the successful green synthesis of Ag-CeO₂ using *Morinda citrifolia* L. leaf extract as a bioreductant, followed by incorporating chitosan and PVA to form a chitosan-PVA/Ag-CeO₂ composite. The composite

displayed a narrow band gap of approximately 2.12 eV, which promoted photocatalytic activity under visible-light irradiation. Application of the RSM-CCD approach yielded an optimal degradation efficiency of 96.37% for Crystal Violet dye (CVD) at pH 8, an initial dye concentration of 33 mg/L, and an irradiation time of 145 min. The material also showed excellent stability, with FTIR spectra revealing no significant wavenumber shifts after degradation and only a 5.02% decrease in efficiency after five cycles. The photocatalytic process was primarily driven by hydroxyl ($\text{OH}^{\bullet}$) and superoxide ($\text{O}_2^{\bullet-}$) radicals. Beyond its photocatalytic performance, the composite displayed antibacterial activity against *S. aureus* and *E. coli*, highlighting its dual functionality as both a photocatalyst and antibacterial agent. These findings suggest that the chitosan-PVA/Ag-CeO₂ composite holds strong potential for practical applications in wastewater treatment, particularly for the removal of organic dyes.

Supplementary materials

No supplementary materials are available

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Acknowledgment

This research was funded by the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology, in accordance with the State University Operational Assistance Program Implementation Contract, Research Program Number: 109/C3/DT.05.00/PL/2025, under the Master's Thesis scheme.

Author contributions

Conceptualization: L.D., P.L.H.
 Data curation: N.A., D.P.
 Formal Analysis: L.D., D.P.
 Funding acquisition: L.D., N.A., P.L.H.
 Investigation: L.D., N.A., D.P., P.L.H.
 Methodology: L.D., P.L.H.
 Project administration: L.D., P.L.H.
 Resources: N.A., D.P.
 Software: L.D., P.H.H.
 Supervision: L.D., P.L.H.
 Validation: N.A., D.P.

Visualization: L.D., N.A., P.L.H.
 Writing – original draft: L.D.
 Writing – review & editing: P.L.H.

Conflict of interest

The author declare no conflict of interest.

Additional information

Author IDs:

Nabila Aprianti, Scopus ID [57218685890](#);
 Davin Philo, Scopus ID [57202716435](#);
 Poedji Loekitowati Hariani, Scopus ID [55907597200](#).

Websites:

Universitas Sriwijaya: <https://www.unsri.ac.id/>;
 BRIN: <https://www.brin.go.id/>.

References

- Liu Z, Wang N, Ma L, Liu Y, Liu W, Li J, et al. Elaboration and photocatalytic properties of $\text{CoFe}_2\text{O}_4/\text{TiO}_2$ composite nanowires with the side-by-side structure. *Mater Res Bull.* 2021;141:111354. doi:[10.1016/j.materresbull.2021.111354](#)
- Sanadi PD, Chougale RK, Malavekar DB, Kim JH, Masimukku S, Chang-Chien GP, et al. Controllable synthesis of semiconducting anatase TiO_2 nanostructures for visible light driven photocatalytic degradation of Crystal violet and Methylene blue dye. *Spectrochim Acta A Mol Biomol Spectrosc.* 2025;341:126404. doi:[10.1016/j.saa.2025.126404](#)
- Sultan M, Tabassam L, Waseem M, Arif S, Rizwan M. Synergistic catalytic degradation of Crystal violet dye using silicon and titanium oxide/graphene nanocomposites. *J Indian Chem Soc.* 2025;102(8):10188. doi:[10.1016/j.jics.2025.101888](#)
- Dhanabal R, Priya PG. Optimization and photocatalytic degradation of Crystal violet dye using Sr-ZnO/activated carbon nanoneedles. *Mater Sci Semicond Process.* 2025;192:109481. doi:[10.1016/j.mssp.2025.109481](#)
- Ganiyu SO, Sable S, Gamal El-Din M. Advanced oxidation processes for the degradation of dissolved organics in produced water: A review of process performance, degradation kinetics and pathway. *Chem Eng J.* 2022;429:132492. doi:[10.1016/j.cej.2021.132492](#)
- Ganea IV, Nan A, Baciuc C, Turcu R. Effective removal of Crystal violet dye using neoteric magnetic nanostructures based on functionalized poly(Benzofuran-co-arylacetic acid): Investigation of the adsorption behaviour and reusability. *Nanomaterials.* 2021;11(3):1–15. doi:[10.3390/nano11030679](#)
- Ozkan E, Allan E, Parkin IP. White-Light-Activated Antibacterial Surfaces Generated by Synergy between Zinc Oxide Nanoparticles and Crystal violet. *ACS Omega.* 2018;3(3):3190–9. doi:[10.1021/acsomega.7b01473](#)
- Patil SR, Sutar SS, Jadhav JP. Sorption of Crystal violet from aqueous solution using live roots of *Eichhornia crassipes*: Kinetic, isotherm, phyto and cyto-genotoxicity studies. *Environ Technol Innov.* 2020;18:100648. doi:[10.1016/j.eti.2020.100648](#)
- Omer AM, Elgarhy GS, El-Subriti GM, Khalifa RE, Eltaweil AS. Fabrication of novel iminodiacetic acid-functionalized carboxymethyl cellulose microbeads for efficient removal of cationic crystal violet dye from aqueous solutions. *Int J Biol Macromol.* 2020;148:1072–83. doi:[10.1016/j.ijbiomac.2020.01.182](#)
- Sifat M, Shin E, Schevon A, Ramos H, Pophali A, Jung HJ, et al. Photocatalytic degradation of Crystal violet (CV) dye over metal oxide (MOx) catalysts. *Catalysts.* 2024;14(6):377. doi:[10.3390/catal14060377](#)
- Benalia A, Derbal K, Baatache O, Lehchili C, Khalfaoui A, Pizzi A. Removal of dyes from water using aluminum-based water treatment sludge as a low-cost coagulant: Use of Response Surface Methodology. *Water.* 2024;16(10):1400. doi:[10.3390/w16101400](#)
- Jiani L, Zhicheng X, Hao X, Dan Q, Zhengwei L, Wei Y, et al. Pulsed electrochemical oxidation of Acid red G and Crystal violet by PbO_2 anode. *J Environ Chem Eng.* 2020;8(3):103773. doi:[10.1016/j.jece.2020.103773](#)
- Tian Y, Wu K, Lin S, Shi M, Liu Y, Su X, et al. Biodegradation and decolorization of Crystal violet dye by cocultivation with fungi and bacteria. *ACS Omega.* 2024;9:7668–7678. doi:[10.1021/acsomega.3c06978](#)
- Algarni TS, Al-Mohaimeed AM, Al-Odayni AB, Abduh NAY. Activated carbon/ ZnFe_2O_4 nanocomposite adsorbent for efficient removal of Crystal violet cationic dye from aqueous solutions. *Nanomater.* 2022;12(18):3224. doi:[10.3390/nano12183224](#)
- Zhou Y, Lu J, Zhou Y, Liu Y. Recent advances for dyes removal using novel adsorbents: A review. *Environ Pollut.* 2019;252:352–65. doi:[10.1016/j.envpol.2019.05.072](#)
- Riyanti F, Hariani PL, Hasanudin H, Rachmat A, Purwaningrum W. Optimization photodegradation of Methylene blue dye using bentonite/PDA/ Fe_3O_4 @CuO Composite by Response Surface Methodology. *Bull Chem React Eng Catal.* 2024;19(2):252–64. doi:[10.9767/bcrec.20132](#)
- Ali SK, Hakami O, Parveen H, Bakather OY, Dhama M, Ahmad I, et al. Eco-friendly plant extract-assisted fabrication of CeO_2 @CH@Ag nanocomposite: A heterogeneous catalyst for organic pollutant remediation. *Mater Chem Phys.* 2024;327:129898. doi:[10.1016/j.matchemphys.2024.129898](#)
- Ahmad A, Javed MS, Khan S, Almutairi TM, Mohammed AAA, Luque R. Green synthesized Ag decorated CeO_2 nanoparticles: Efficient photocatalysts and potential antibacterial agents. *Chemosphere.* 2023;310:136841. doi:[10.1016/j.chemosphere.2022.136841](#)
- Ayodhya D, Veerabhadram G. Green synthesis of garlic extract stabilized Ag@ CeO_2 composites for photocatalytic and sonocatalytic degradation of mixed dyes and antimicrobial studies. *J Mol Struct.* 2020;127611. doi:[10.1016/j.molstruc.2019.127611](#)
- Vanasundari K, Ponnarasi P, Mahalakshmi G. A green approach to synthesis of Ag-doped CeO_2 nanorods embedded reduced graphene oxide nanocomposite for excellent photocatalytic and antimicrobial activity. *Inorg Chem Commun.* 2024;165:112523. doi:[10.1016/j.inoche.2024.112523](#)
- Ragab HM, Diab NS, Obeidat ST, Alghamdi AM, Khaled AM, Farea MO, et al. Improving the optical, thermal, mechanical, electrical properties and antibacterial activity of PVA-chitosan by biosynthesized Ag nanoparticles: Eco-friendly nanocomposites for food packaging applications. *Int J Biol Macromol.* 2024;264:130668. doi:[10.1016/j.ijbiomac.2024.130668](#)
- Mohd Adnan MA, Majnis MF, Mat Norman MA, Mohd MD, Johan MR, Muhd Julkapli N. Visible-light-activated TiO_2/ZnO -chitosan catalyst for photodegradation of methylene blue dye: An experimental and predictive modelling using artificial neural networks. *J Water Proc Eng.* 2025;77:108423. doi:[10.1016/j.jwpe.2025.108423](#)
- Hoang TD, Nguyen TC, Doan TT, Ngo TD, Nguyen TY, Ngo BT, et al. Preparation and photocatalytic and antibacterial properties of polyvinyl alcohol/chitosan/ TiO_2 @Ag electrospun nanofibers. *Thin Solid Films.* 2024;797:140344. doi:[10.1016/j.tsf.2024.140344](#)
- Kamanna K, Amaregouda Y, N MK. Chitosan/polyvinyl alcohol-based nanocomposite films incorporated with L-Glu surface functionalized ZnO NPs: Physicochemical, photocatalytic, antimicrobial and antioxidant properties evaluation. *Environ Nanotechnol Monit Manag.* 2023;20:100861. doi:[10.1016/j.enmm.2023.100861](#)
- Rosi H, Janci M, Preethi M. Phyto-mediated green synthesis of CeO_2 -ZnO nanoparticles using glycosmis mauritiana leaf extract: Antibacterial activity and photodegradative applications. *Mater Today.* 2019;48(2):561–7. doi:[10.1016/j.matpr.2021.09.091](#)

26. Vinitha P, Arularasu MV, Vignesh R. A review on green synthesis and applications of CeO₂ nanomaterials – An eco-friendly approach. Chem Inorg Mater. 2025;5:100084. doi:[10.1016/j.cinorg.2024.100084](https://doi.org/10.1016/j.cinorg.2024.100084)
27. Sukumaran J, Venkatesan R, Priya M, Kim SC. Eco-friendly synthesis of CeO₂ nanoparticles using *Morinda citrifolia* L. leaf extracts: Evaluation of structural, antibacterial, and anti-inflammatory activity. Inorg Chem Commun. 2024;170:113411. doi:[10.1016/j.inoche.2024.113411](https://doi.org/10.1016/j.inoche.2024.113411)
28. Kayani FB, Rafique S, Akram R, Hussain M, Raja K, Khan JS. Fabrication of novel chitosan@Ag/CeO₂ hybrid nanocomposites for the study of antibacterial activity. Physica E Low Dimens Syst Nanostruct. 2023 May 1;149. doi:[10.1016/j.inoche.2024.113411](https://doi.org/10.1016/j.inoche.2024.113411)
29. Chkirida S, Zari N, Achour R, Hassoune H, Lachehab A, Qaiss A el kacem, et al. Highly synergic adsorption/photocatalytic efficiency of alginate/bentonite impregnated TiO₂ beads for wastewater treatment. J Photochem Photobiol A Chem. 2021;412:113215. doi:[10.1016/j.jphotochem.2021.113215](https://doi.org/10.1016/j.jphotochem.2021.113215)
30. Sajid A, Zahid J, Sajid A, Shaikat N, Nadeem F, Manzoor Q, et al. Utilization of two biomasses from *Bauhinia variegata* and *Lawsonia inermis* for biogenic synthesis of MgO Nanoparticles: A comparative study on structural attributes and pharmaceutical Applications. Waste Biomass Valor. 2025;03285-1. doi:[10.1007/s12649-025-03285-1](https://doi.org/10.1007/s12649-025-03285-1)
31. Hariani PL, Salni, Yusmartini ES, Aprianti N, Ahadito BR. Green synthesis of CdFe₂O₄ by *Terminalia catappa* leave extract for photodegradation Methyl red dye by response surface methodology. Chim Techno Acta. 2024;11(4):1-10. doi:[10.15826/chimtech.2024.11.4.02](https://doi.org/10.15826/chimtech.2024.11.4.02)
32. Ahmad I, Ahmad I, Muneer M, Alsimaree AA, Alsantali RI, Ahmed SA. Enhanced visible-light-driven photocatalytic degradation of organic pollutants using NiFe-layered double hydroxide/BiOBr Z-scheme heterojunction: RSM-based optimization for superior efficiency. J Mol Struct. 2025;1335:141922. doi:[10.1016/j.molstruc.2025.141922](https://doi.org/10.1016/j.molstruc.2025.141922)
33. Hariani PL, Salni S, Said M, Farahdiba R. Core-shell Fe₃O₄/SiO₂/TiO₂ magnetic modified Ag for the photocatalytic degradation of Congo red dye and antibacterial activity. Bull Chem React Eng Catal. 2023;18(2):315-30. doi:[10.9767/bcrec.19275](https://doi.org/10.9767/bcrec.19275)
34. Iqbal Y, Ahmed S, Aziz MH, Alam M, Asif M, Huang Q. Greener approach for the synthesis of Ag decorated ZnO–CeO₂ nanostructure using *Moringa oleifera* LE and its investigation as photocatalyst for degradation of ciprofloxacin and Methylene orange. Mater Chem Phys. 2024;318:129299. doi:[10.1016/j.matchemphys.2024.129299](https://doi.org/10.1016/j.matchemphys.2024.129299)
35. Kovenan C, Lo AY, Chang CC, Tsai ML. Development of high-performance supercapacitor electrodes based on CeO₂/SiO₂/CMK-3 composites. Processes. 2025;13(6):1766. doi:[10.3390/pr13061766](https://doi.org/10.3390/pr13061766)
36. Rengasamy G, Chinnalagu DK, Chinniah K, Mahalingam S. Biodegradable multifunctional fabrication of silver-doped zinc oxide nanoparticle on chitosan/polyvinyl alcohol flexible film for effective antibacterial potential and attenuation of human liver carcinoma cells. Int J Biol Macromol. 2025;321: 146309. doi:[10.1016/j.ijbiomac.2025.146309](https://doi.org/10.1016/j.ijbiomac.2025.146309)
37. Sajid A, Javed R, Manzoor Q, Sajid A, Saleem A, Imtiaz F, et al. Development of Ag–CeO₂ bimetallic nanocomposite for visible-light-induced photocatalytic degradation of Eriochrome black T. Chem Afr. 2024;7(4):2103–10. doi:[10.1007/s42250-023-00864-4](https://doi.org/10.1007/s42250-023-00864-4)
38. Sun Q, Hu X, He Q, Sun M, Dai L, Khan S, et al. Polydopamine-Chitosan Modified TiO₂ Nanoparticles for temperature-response removal of diclofenac sodium under visible light irradiation. J Taiwan Inst Chem Eng. 2022;131:104151. doi:[10.1016/j.jtice.2021.11.018](https://doi.org/10.1016/j.jtice.2021.11.018)
39. Mohammadi L, Khodadadi R, Fazaeli R. New insights into visible light active SnS semiconductor for the elimination of methylene blue: RSM and DFT approaches. Mater Chem Phys. 2024;313:128770. doi:[10.1016/j.matchemphys.2023.128770](https://doi.org/10.1016/j.matchemphys.2023.128770)
40. Afzal S, Julkapli NM, Mun LK. Response surface approach for visible light assisted photocatalytic degradation of ortho-nitrophenol by magnetically separable TiO₂/CS nanocomposite. Mater Sci Semicond Process. 2019;99:34–43. doi:[10.1016/j.mssp.2019.04.022](https://doi.org/10.1016/j.mssp.2019.04.022)
41. Khosravi-Far M, Mohebat R, Ghaedi M, Tabatabaee M. Efficient photocatalytic degradation of malachite green dye from wastewater using facilely synthesized ternary ZIF-8/Ag/Ag₂S nanocomposite: Optimization by RSM (CCD). Process Saf Environ Prot. 2024;190:46–62. doi:[10.1016/j.psep.2024.08.036](https://doi.org/10.1016/j.psep.2024.08.036)
42. Afaq M, Sajid A, Manzoor Q, Imtiaz F, Sajid A, Javed R, et al. Sonochemical synthesis of CoO–ZnO nanocomposite and optimizing the degradation of toxic anionic dye using RSM-BBD. Mater Sci Eng B. 2025;312:117847. doi:[10.1016/j.mseb.2024.117847](https://doi.org/10.1016/j.mseb.2024.117847)
43. Semwal N, Mahar D, Arya MC. Response surface methodology-driven optimization of dye-sensitized Fe-doped CeO₂ photocatalysts for efficient phenol degradation. J Mol Struct. 2025; 2025;1341:142639. doi:[10.1016/j.molstruc.2025.142639](https://doi.org/10.1016/j.molstruc.2025.142639)
44. Hmamouchi S, El Yacoubi A, El Hezzat M, Sallek B, El Idrissi BC. Optimization of photocatalytic parameters for MB degradation by g-C₃N₄ nanoparticles using Response Surface Methodology (RSM). Diam Relat Mater. 2023;136:109986. doi:[10.1016/j.diamond.2023.109986](https://doi.org/10.1016/j.diamond.2023.109986)
45. Sofia G, Kovenan C, Kanmani S, Lo AY. Green synthesized rGO/TiO₂/g-C₃N₄ nanocomposites via *Plectranthus amboinicus* extract for efficient photocatalytic degradation of Methylene blue: RSM optimization, antimicrobial and phytotoxicity assessment. J Environ Chem Eng. 2025;13(1):115267. doi:[10.1016/j.jece.2024.115267](https://doi.org/10.1016/j.jece.2024.115267)
46. Rani M, Choudhary S, Shukla G, Shanker U. Highly efficient photo-adsorptive degradation of tetracycline and metronidazole antibiotics by green synthesized Ag doped CeO₂@SnO₂ nanocomposites. Environ Nanotechnol Monit Manag. 2024;21:100935. doi:[10.1016/j.enmm.2024.100935](https://doi.org/10.1016/j.enmm.2024.100935)
47. Lee YS, Lee KM, Ong BH. Magnetic recoverable cobalt ferrite nanophotocatalyst for Crystal violet dye degradation. Ceram Int. 2025;51(23):39630–38. doi:[10.1016/j.ceramint.2025.06.198](https://doi.org/10.1016/j.ceramint.2025.06.198)
48. Moosavi S, Li RYM, Lai CW, Yusof Y, Gan S, Akbarzadeh O, et al. Methylene blue dye photocatalytic degradation over synthesised Fe₃O₄/AC/TiO₂ nano-catalyst: Degradation and reusability studies. Nanomater. 2020;10(12):1–15. doi:[10.3390/nano10122360](https://doi.org/10.3390/nano10122360)
49. Manikandan V, Gayathri R, Zeenath MA. Facile synthesis of rGO/ZnCo₂O₄ nanocomposite for enhanced photocatalytic dye degradation of Crystal violet dye solution. Nano-Struct Nano-Objects. 2024;40:101330. doi:[10.1016/j.nanoso.2024.101330](https://doi.org/10.1016/j.nanoso.2024.101330)
50. Yelapale AM, Patil VL, Bhosale SR, Bhosale RR, Dhavale RP, Vhangutte PP, et al. Efficient photocatalytic degradation of Crystal violet dye using time-dependent ZnO nano spindle. Mater Sci Eng B. 2024;310:117687. doi:[10.1016/j.mseb.2024.117687](https://doi.org/10.1016/j.mseb.2024.117687)
51. Iqbal Y, Ahmed S, Aziz MH, Alam M, Asif M, Huang Q. Greener approach for the synthesis of Ag decorated ZnO–CeO₂ nanostructure using *Moringa oleifera* LE and its investigation as photocatalyst for degradation of Ciprofloxacin and Methylene orange. Mater Chem Phys. 2024;318:129299. doi:[10.1016/j.matchemphys.2024.129299](https://doi.org/10.1016/j.matchemphys.2024.129299)
52. Ho QD, Lai VD, Nguyen QA, Vu DN, Dang TKL, La DD. Green synthesis of g-C₃N₄/CeO₂ nanocomposites for enhanced photocatalytic degradation of organic dye under simulated sunlight. Diam Relat Mater. 2025;157:112484. doi:[10.1016/j.diamond.2025.112484](https://doi.org/10.1016/j.diamond.2025.112484)
53. Vijay G, Dhavud SS, Chen SM, Riyas ZM, Sethupathi M, Ramalingam KR, et al. Two-dimensional hexagonal boron nitride (h-BN) decorated on CeO₂ heterojunction nanocomposite for improved photocatalysis degradation and antibacterial application. Diam Relat Mater. 2025;157:112494. doi:[10.1016/j.diamond.2025.112494](https://doi.org/10.1016/j.diamond.2025.112494)
54. Amrute V, Monika N, Supin KK, Vasundhara M, Chanda A. Observation of excellent photocatalytic and antibacterial

activity of Ag doped ZnO nanoparticles. RSC Adv. 2024;14(45):32786–801. doi:[10.1039/d4ra05197a](https://doi.org/10.1039/d4ra05197a)

55. Feizollah R, Meshkini A. Photochemically enhanced antibacterial activity of polydopamine-coated CeO₂@Ag nanocomposites: Surface and colloidal engineering for wound pathogen treatment. Colloids Surf A Physicochem Eng Asp. 2025;725:137641. doi:[10.1016/j.colsurfa.2025.137641](https://doi.org/10.1016/j.colsurfa.2025.137641)