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COMPARATIVE ANTIMICROBIAL AND PHOTOCATALYTIC PERFORMANCE OF MG-DOPED ZNO, NIO, AND COO NANOPARTICLES AGAINST ORGANIC DYES AND PATHOGENS

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ABSTRACT:
Metal oxide nanoparticles have attracted considerable attention because of their potential applications in environmental remediation and antimicrobial technologies. The present study comparatively evaluated the antimicrobial and photocatalytic properties of Mg-ZnO, Mg-NiO and Mg-CoO nanoparticles. The antimicrobial activity was investigated against selected Gram-positive and Gram-negative bacteria and fungal strains using the disc diffusion method. Among the tested nanoparticles, Mg-CoO exhibited the strongest antibacterial activity, producing maximum inhibition zones of 22 mm against Bacillus cereus and 20 mm against Staphylococcus aureus. Mg-CoO showed a minimum inhibitory concentration (MIC) of 420 µg/mL and a minimum bactericidal concentration (MBC) of 460 µg/mL against S. aureus. Mg-ZnO showed comparatively broader antimicrobial activity, with the highest inhibition zone of 18 mm against Escherichia coli. In contrast, Mg-NiO demonstrated relatively weak antimicrobial activity under the tested conditions.
The photocatalytic performance of the nanoparticles was evaluated for the degradation of methylene blue (MB) and Congo red (CR) under UV irradiation at 365 nm. Mg-ZnO demonstrated the highest photocatalytic efficiency, achieving 95.0% degradation of MB and 87.3% degradation of CR after 300 min of irradiation. Mg-NiO exhibited comparable activity toward MB, with 92.5% degradation, whereas Mg-CoO showed only 6.7% MB degradation under identical conditions. Apparent pseudo-first-order kinetic analysis further supported the superior photocatalytic activity of Mg-ZnO, with rate constants of 0.01009 min^{-1} for MB and 0.00691 min^{-1} for CR, compared with 0.00874 min^{-1} for Mg-NiO toward MB. Overall, the findings demonstrate pronounced composition-dependent functional properties among the investigated nanoparticles, with Mg-CoO showing greater antibacterial potential and Mg-ZnO exhibiting superior photocatalytic performance. These findings highlight the potential of Mg-based metal oxide nanoparticles for application-specific antimicrobial and environmental remediation purposes.

KEYWORDS: Mg-ZnO; Mg-NiO; Mg-CoO; metal oxide nanoparticles; antimicrobial activity; photocatalytic degradation; methylene blue; Congo red; UV irradiation; wastewater remediation.

INTRODUCTION

The increasing application of nanomaterials in biomedical and environmental fields has stimulated extensive research into metal oxide nanoparticles because of their distinctive structural, optical, electronic and surface properties. At the nanoscale, metal oxides possess a high surface-to-volume ratio and abundant surface-active sites, which can substantially influence their catalytic, photocatalytic and antimicrobial behavior. These properties have made semiconductor metal oxide nanoparticles attractive for applications including microbial control, wastewater treatment, environmental remediation and degradation of persistent organic pollutants (Pradeev Raj et al., 2018). Among these materials, ZnO, NiO and CoO-based nanostructures have received considerable attention because their physicochemical properties can be modified through changes in particle size, morphology, crystal structure, surface defects and elemental composition.
Zinc oxide (ZnO) is one of the extensively investigated semiconductor metal oxides because of its chemical stability, relatively low cost, suitable optical characteristics and broad applicability in photocatalytic and antimicrobial systems. The photocatalytic activity of ZnO is strongly influenced by its surface characteristics, particle size and defect structure. Modification of ZnO through incorporation of suitable dopant ions has therefore emerged as an effective strategy for controlling its electronic structure and surface properties. In particular, Mg incorporation into the ZnO lattice can modify lattice parameters, optical absorption, defect density and band-gap characteristics, thereby influencing the functional performance of the resulting nanoparticles (Pradeev Raj et al., 2018).
Several experimental studies have demonstrated that Mg incorporation can improve the photocatalytic behavior of ZnO. Pradeev Raj et al. (2018) synthesized Mg-doped ZnO nanoparticles by a co-precipitation approach and reported that Mg incorporation altered the structural and optical properties of ZnO. The authors observed enhanced photocatalytic degradation of Rhodamine B, with 7.5% Mg-doped ZnO exhibiting the highest degradation efficiency under UV–visible irradiation. The enhanced activity was associated with changes in particle characteristics and the presence of defects introduced by Mg incorporation. Similarly, studies examining Mg-doped ZnO prepared through other synthetic

approaches have reported improvements in photocatalytic degradation and antimicrobial performance compared with undoped ZnO, demonstrating the importance of dopant-induced modification of semiconductor properties.

The antimicrobial activity of metal oxide nanoparticles is another important functional property that has attracted considerable scientific interest. Nanoparticles can interact directly with microbial cell surfaces, resulting in changes in membrane permeability, cellular integrity and intracellular metabolic processes. In addition, reactive oxygen species generated at nanoparticle surfaces can contribute to oxidative damage of cellular components. The antimicrobial efficiency of ZnO-based nanoparticles is influenced by several physicochemical factors, including particle size, surface area, crystallinity, morphology and surface defects. Importantly, modification of ZnO with Mg can alter these properties and consequently affect its interaction with microorganisms (Pradeev Raj et al., 2018).

Experimental evidence supports the influence of Mg incorporation on the antibacterial activity of ZnO. Pradeev Raj et al. (2018) reported that Mg-doped ZnO nanoparticles exhibited enhanced antibacterial activity against both Gram-positive and Gram-negative bacteria, with antibacterial performance increasing with Mg concentration within the investigated range. More recently, Mg-doped ZnO nanoparticles synthesized using Lupinus albus leaf extract demonstrated considerable activity against Escherichia coli, Bacillus cereus, Salmonella typhi and Staphylococcus aureus, as well as antifungal activity against Candida albicans. The same study also demonstrated enhanced photocatalytic degradation of methylene blue by Mg-doped ZnO compared with undoped ZnO, highlighting the potential of Mg-modified ZnO as a multifunctional nanomaterial (Abebe et al., 2024).

The simultaneous antimicrobial and photocatalytic properties of metal oxide nanoparticles are particularly interesting because both activities can be influenced by surface-mediated redox processes. During photocatalysis, irradiation of a semiconductor with photons possessing sufficient energy can generate electron–hole pairs. These charge carriers may subsequently participate in reactions involving adsorbed oxygen and water, producing reactive species capable of oxidizing organic compounds. The efficiency of this process depends on charge generation, charge separation, surface adsorption, defect states and the availability of reactive surface sites. Consequently, structural modification of a semiconductor can substantially alter its photocatalytic performance.

Photocatalytic degradation has become an important approach for the treatment of dye-contaminated wastewater. Synthetic dyes are extensively used in textile, printing, leather and related industries, and their release into aquatic environments can adversely affect water quality and aquatic ecosystems. Methylene blue and Congo red are frequently employed as model pollutants in photocatalytic investigations because they possess stable chromophoric structures and can be readily monitored by UV–visible spectroscopy. The decrease in dye concentration during irradiation provides a convenient approach for evaluating the photocatalytic efficiency of semiconductor catalysts.

ZnO-based nanomaterials have demonstrated considerable potential for dye degradation, while incorporation of Mg can further modify their photocatalytic properties. Pradeev Raj et al. (2018) reported that Mg-doped ZnO showed substantially greater Rhodamine B degradation than undoped ZnO under UV–visible irradiation. Their observations indicated that Mg incorporation could introduce structural defects and modify the optical properties of ZnO, thereby contributing to improved photocatalytic performance. In another study, Mg-doped ZnO nanoparticles showed enhanced photocatalytic activity together with improved antibacterial properties, suggesting that Mg modification can generate multifunctional materials suitable for both environmental and biological applications.

Nickel oxide (NiO) is another technologically important metal oxide that has attracted increasing interest as a photocatalytic and antimicrobial material. NiO possesses favorable chemical stability and surface properties, although its photocatalytic efficiency can be affected by rapid charge-carrier recombination and its intrinsic electronic structure. Consequently, modification of NiO and incorporation of additional elements have been investigated to improve its photocatalytic performance. Recent studies have demonstrated that NiO nanoparticles can exhibit both dye-degradation and antimicrobial properties. For example, green-synthesized NiO nanoparticles have demonstrated substantial methylene-blue degradation together with antibacterial activity against Gram-positive and Gram-negative microorganisms, indicating their potential as multifunctional materials for environmental and biological applications (Gebremichael et al., 2026).

Recent work further demonstrates the versatility of NiO nanoparticles for photocatalytic remediation. Siddique et al. (2025) reported efficient degradation of crystal violet by greenly synthesized NiO nanoparticles and simultaneously demonstrated antibacterial activity against several bacterial strains. The authors also investigated reactive species involved in the photocatalytic process, emphasizing the importance of surface-generated reactive species in dye degradation. Similarly, recent investigations of NiO-based nanomaterials have demonstrated their capacity for photocatalytic dye degradation and antibacterial activity, supporting the suitability of NiO as a multifunctional platform for environmental remediation and biological applications.

Cobalt oxide (CoO)-based nanomaterials represent another class of transition-metal oxide materials with potentially useful electronic, surface and redox properties. However, compared with ZnO and NiO, comparatively fewer studies have systematically evaluated Mg-containing CoO systems for simultaneous antimicrobial and photocatalytic applications. The incorporation of Mg into a transition-metal oxide matrix may influence lattice structure, defect chemistry, surface characteristics and electronic behavior. Such changes can potentially alter the interaction of nanoparticles with microbial cells as well as their ability to participate in light-driven oxidation reactions. Therefore, comparative investigation of Mg-containing ZnO, NiO and CoO systems can provide useful information regarding the relationship between metal-oxide composition and functional activity.

An important aspect of photocatalytic performance is that the efficiency of a catalyst may differ substantially depending on the chemical structure and charge characteristics of the target dye. Differences between cationic dyes such as methylene blue and anionic dyes such as Congo red can influence adsorption onto catalyst surfaces and consequently affect the

subsequent photocatalytic process. Therefore, evaluating more than one structurally distinct dye provides a more comprehensive assessment of photocatalytic potential than investigating a single model pollutant.

Despite considerable research on individual metal oxide nanoparticles, direct comparative studies involving Mg-ZnO, Mg-NiO and Mg-CoO under comparable experimental conditions remain limited. In particular, comparative assessment combining antimicrobial activity with the photocatalytic degradation of both methylene blue and Congo red may provide useful information regarding the functional specialization of different Mg-based metal oxide systems. Such an approach is important because a material exhibiting high antimicrobial activity does not necessarily possess equivalent photocatalytic efficiency, and vice versa.

Therefore, the present study was designed to comparatively evaluate three Mg-based metal oxide nanoparticles, namely Mg-ZnO, Mg-NiO and Mg-CoO, with respect to their antimicrobial and photocatalytic properties. The antimicrobial activity of the nanoparticles was assessed against selected Gram-negative and Gram-positive bacterial strains and fungal pathogens using the agar disc diffusion method. The minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) were further determined for the most active nanoparticle. In parallel, the photocatalytic performance of the three nanoparticles was investigated using methylene blue and Congo red as model organic dyes under UV irradiation. The comparative approach adopted in this study was intended to establish differences in functional performance among Mg-ZnO, Mg-NiO and Mg-CoO and to identify nanoparticles with greater potential for antimicrobial applications and photocatalytic remediation of dye-contaminated water.

2. MATERIALS AND METHODS

2.1 Nanoparticle samples

Three Mg-based metal oxide nanoparticle samples were investigated in the present study: Mg-ZnO nanoparticles (Sample 1), Mg-NiO nanoparticles (Sample 2), and Mg-CoO nanoparticles (Sample 3). The nanoparticles are synthesized via calcination using corn husk as a bio-template.The synthesized nanoparticles were subjected to comparative evaluation of their antimicrobial and photocatalytic properties. The nanoparticles were stored under appropriate conditions until further analysis and biological and photocatalytic assays.

2.2 Test microorganisms

The antimicrobial potential of the three nanoparticle samples was evaluated against selected bacterial and fungal microorganisms. The bacterial panel comprised both Gram-negative and Gram-positive organisms, including Escherichia coli ATCC 8739, Pseudomonas aeruginosa ATCC 9027, Enterobacter aerogenes ATCC 13048, Staphylococcus aureus ATCC 6538 and Bacillus cereus ATCC 6633. The fungal organisms included Candida albicans ATCC 10231 and Aspergillus niger ATCC 16404.

2.3 Preparation of nanoparticle suspension

The nanoparticle samples were prepared in dimethyl sulfoxide (DMSO) to obtain a working concentration of 100 µg/mL. The nanoparticle suspensions were appropriately mixed before use to ensure uniform dispersion of the test material. DMSO was used as the negative control to determine whether the solvent itself produced any inhibitory effect on the test microorganisms.

2.4 Evaluation of antimicrobial activity

The antimicrobial activity of Mg-ZnO, Mg-NiO and Mg-CoO nanoparticles was determined using the agar disc diffusion method. Mueller–Hinton Agar (MHA) was used for bacterial assays, whereas Sabouraud Dextrose Agar (SDA) was used for fungal assays. The respective media were prepared and sterilized according to standard microbiological procedures and subsequently poured into sterile Petri plates.

Standardized microbial cultures were uniformly inoculated onto the surface of the respective agar medium using sterile cotton swabs. Sterile 6-mm-diameter filter-paper discs were impregnated with 10 µL of the respective nanoparticle suspension and carefully placed on the inoculated agar surface. DMSO-impregnated discs served as the negative control. Ciprofloxacin was used as the positive control for bacterial strains, whereas fluconazole was used as the positive control for fungal strains. The inoculated bacterial plates were incubated at 37 °C for 24 h, while fungal plates were incubated for 48 h. Following incubation, the diameter of the zone of inhibition (ZOI) surrounding each disc was measured in millimeters. The antimicrobial activity of each nanoparticle was compared with the corresponding standard drug and negative control.

2.5 Determination of minimum inhibitory concentration

The minimum inhibitory concentration (MIC) was determined for the nanoparticle exhibiting comparatively higher antibacterial activity. Based on the disc diffusion results, Mg-CoO (Sample 3) was selected for further MIC evaluation. A stock suspension of Sample 3 was prepared in DMSO and serially diluted in sterile Mueller–Hinton Broth to obtain concentrations ranging from 50 to 500 µg/mL.

Each concentration was inoculated with a standardized suspension of Staphylococcus aureus ATCC 6538 and incubated at 37 °C for 24 h. A growth control containing broth and bacterial inoculum and a DMSO control were included. Following incubation, the tubes were examined for visible turbidity. The MIC was defined as the lowest concentration of Sample 3 at which no visible microbial growth was observed. Ciprofloxacin was evaluated as the reference antibacterial agent.

2.6 Determination of minimum bactericidal concentration

The minimum bactericidal concentration (MBC) of Mg-CoO was determined using the tubes showing no visible growth during the MIC assay. Aliquots from the clear tubes corresponding to concentrations of 420, 440, 460, 480 and 500 µg/mL were aseptically streaked onto sterile Mueller–Hinton Agar plates. The plates were incubated at 37 °C for 24 h and subsequently examined for colony formation. The lowest concentration at which no bacterial growth was observed on the agar surface was considered the MBC.

2.7 Preparation of dye solutions

The photocatalytic activity of Mg-ZnO, Mg-NiO and Mg-CoO nanoparticles was evaluated using two model organic dyes, methylene blue (MB) and Congo red (CR). Dye solutions were prepared using distilled water. The experimental design included different working concentrations of the dyes, as recorded in the experimental study.

2.8 Photocatalytic Degradation Experiment

For the photocatalytic degradation experiments, 0.1 g of each nanoparticle sample (Mg-ZnO, Mg-NiO and Mg-CoO) was separately added to 100 mL of dye solution in a conical flask. The nanoparticle–dye suspensions were initially stirred in the dark for 30 min to establish adsorption–desorption equilibrium between the catalyst surface and dye molecules.

Following the dark equilibration period, the suspensions were exposed to UV irradiation at a wavelength of 365 nm. At predetermined irradiation intervals, aliquots of the reaction mixture were withdrawn and centrifuged to remove the nanoparticle catalyst. The resulting clear supernatant was collected and analyzed using a UV–Visible spectrophotometer. For methylene blue (MB), the absorbance was monitored at 664 nm, whereas Congo red (CR) degradation was monitored at 497 nm. The decrease in absorbance with increasing irradiation time was used to evaluate the photocatalytic degradation efficiency.

2.9 Calculation of Photocatalytic Degradation Efficiency

The photocatalytic degradation efficiency of the dyes was calculated from the decrease in dye concentration during irradiation using the following equation:

$$\text{Degradation (\%)} = [(C_o - C_t) / C_o] \times 100$$

Where:

C_o = initial concentration of the dye after dark adsorption–desorption equilibrium

C_t = concentration of the dye at irradiation time t

Since dye concentration is proportional to absorbance under the experimental conditions, degradation efficiency was also calculated from the UV–Visible absorbance values using:

$$\text{Degradation (\%)} = [(A_o - A_t) / A_o] \times 100$$

Where:

A_o = initial absorbance of the dye after dark adsorption–desorption equilibrium

A_t = absorbance of the dye solution at irradiation time t

2.10 Statistical analysis

All experimental measurements should be expressed as mean ± standard deviation based on the number of independent experimental replicates performed. Statistical comparisons among nanoparticle treatments should be conducted using an appropriate statistical test after checking the assumptions of the selected analysis. Differences should be considered statistically significant at $p < 0.05$.

3. Results and Discussion

3.1 Comparative Antimicrobial Activity of Mg-ZnO, Mg-NiO and Mg-CoO Nanoparticles

The antimicrobial activities of Mg-ZnO (Sample 1), Mg-NiO (Sample 2) and Mg-CoO (Sample 3) nanoparticles were evaluated against five bacterial strains, comprising three Gram-negative bacteria and two Gram-positive bacteria, as well as two fungal strains. The activity was determined by the disc diffusion method at a nanoparticle concentration of 100 µg/mL. DMSO was used as the negative control, while ciprofloxacin and fluconazole were used as positive controls for bacterial and fungal strains, respectively.

Table 1. Antimicrobial activity of Mg-ZnO, Mg-NiO and Mg-CoO nanoparticles

Microorganism	Type	DMSO (mm)	Standard drug (mm)	Mg-ZnO (mm)	Mg-NiO (mm)	Mg-CoO (mm)
Escherichia coli ATCC 8739	Gram-negative	0	22	18	6	18
Pseudomonas aeruginosa ATCC 9027	Gram-negative	0	29	10	0	6
Enterobacter aerogenes ATCC 13048	Gram-negative	0	20	0	0	0
Staphylococcus aureus ATCC 6538	Gram-positive	0	22	6	0	20
Bacillus cereus ATCC 6633	Gram-positive	0	25	4	3	22
Candida albicans ATCC 10231	Fungi	0	26	13	0	0
Aspergillus niger ATCC 16404	Fungi	0	28	10	0	6

Values are reported as zone of inhibition (ZOI) in mm.

The results demonstrated considerable differences in antimicrobial activity among the three nanoparticle formulations. The standard antimicrobial agents exhibited the largest inhibition zones against all tested microorganisms, confirming their expected antimicrobial effectiveness. In contrast, the nanoparticle samples displayed organism-dependent and composition-dependent activity. DMSO produced no inhibition against any of the tested microorganisms, indicating that the observed inhibition was attributable to the nanoparticle treatments rather than the solvent. Among the three nanoparticles, Mg-CoO (Sample 3) exhibited the most pronounced overall antibacterial activity. It produced inhibition

zones of 18 mm against E. coli, 6 mm against P. aeruginosa, 20 mm against S. aureus and 22 mm against B. cereus. The highest activity of Mg-CoO was therefore observed against B. cereus, followed by S. aureus. No inhibition was detected against E. aerogenes or C. albicans. These results indicate that the antimicrobial effect of Mg-CoO was strongly dependent on the microbial species.

The comparatively greater activity of Mg-CoO against the Gram-positive organisms S. aureus and B. cereus is particularly noteworthy. The inhibition zones of 20 and 22 mm, respectively, were substantially greater than those produced by Mg-ZnO and Mg-NiO against the same organisms. Mg-ZnO produced inhibition zones of only 6 and 4 mm against S. aureus and B. cereus, respectively, whereas Mg-NiO produced no inhibition against S. aureus and only 3 mm against B. cereus. Thus, the data indicate a marked advantage of Mg-CoO for inhibition of the tested Gram-positive bacteria.

Mg-ZnO exhibited a different antimicrobial profile. Its highest activity was observed against E. coli, with an inhibition zone of 18 mm, followed by C. albicans and A. niger, with inhibition zones of 13 and 10 mm, respectively. Moderate activity was observed against P. aeruginosa (10 mm), whereas only weak activity was observed against S. aureus (6 mm) and B. cereus (4 mm). No inhibition was observed against E. aerogenes.

Mg-NiO exhibited the weakest antimicrobial profile among the three nanoparticles. It showed only limited activity against E. coli (6 mm) and B. cereus (3 mm), while no inhibition was observed against P. aeruginosa, E. aerogenes, S. aureus, C. albicans or A. niger. These findings indicate that, under the experimental conditions used, Mg-NiO had considerably lower antimicrobial effectiveness than Mg-ZnO and Mg-CoO. Overall, the antimicrobial ranking was organism dependent; however, Mg-CoO demonstrated the strongest broad antibacterial performance among the tested nanoparticles, particularly against Gram-positive bacteria. The differential antimicrobial response may be associated with differences in nanoparticle composition, surface characteristics, particle–cell interactions and the ability of the respective materials to promote oxidative or other cellular damage. However, because ROS generation, ion release and membrane damage were not directly measured in the present study, these mechanisms should be regarded as possible explanations rather than experimentally confirmed mechanisms.

3.2 Comparative Analysis of Antimicrobial Activity

For a clearer comparison, the maximum inhibition zone produced by each nanoparticle was considered.

Table 2. Maximum antimicrobial activity of the tested nanoparticles

Nanoparticle	Maximum ZOI (mm)	Microorganism showing maximum activity
Mg-ZnO	18	E. coli
Mg-NiO	6	E. coli
Mg-CoO	22	B. cereus

Mg-CoO exhibited the highest maximum inhibition zone (22 mm), followed by Mg-ZnO (18 mm) and Mg-NiO (6 mm). The 22-mm inhibition zone produced by Mg-CoO against B. cereus was also close to the activity of ciprofloxacin against the same organism (25 mm). Nevertheless, the nanoparticle should not be described as equivalent to the standard antibiotic because the inhibition-zone assay alone does not establish equivalence in antimicrobial potency.

3.3 Minimum Inhibitory Concentration of Mg-CoO

Based on its comparatively superior antibacterial activity in the disc diffusion assay, Mg-CoO (Sample 3) was selected for further MIC evaluation against S. aureus ATCC 6538. Serial concentrations ranging from 50 to 500 µg/mL were evaluated using the broth dilution method. The MIC was defined as the lowest concentration at which no visible bacterial growth was observed.

Table 3. MIC of Mg-CoO against Staphylococcus aureus

Treatment	Microorganism	MIC (µg/mL)
Mg-CoO	S. aureus ATCC 6538	420
Ciprofloxacin	S. aureus ATCC 6538	80

Mg-CoO exhibited an MIC of 420 µg/mL against S. aureus, whereas ciprofloxacin showed an MIC of 80 µg/mL. Thus, although Mg-CoO demonstrated considerable inhibition in the disc diffusion assay, its MIC was higher than that of ciprofloxacin. The result confirms that Mg-CoO possesses antibacterial activity but is less potent than the reference antibiotic under the conditions tested.

The difference between the disc diffusion and MIC results also highlights the importance of using complementary antimicrobial assays. Disc diffusion is influenced by both antimicrobial activity and diffusion of the test material through agar, whereas MIC provides a concentration-based measure of growth inhibition.

3.4 Minimum Bactericidal Concentration of Mg-CoO

The bactericidal activity of Mg-CoO was subsequently evaluated against S. aureus. Clear broth tubes from the MIC experiment were subcultured onto Mueller–Hinton Agar to determine whether viable bacteria remained. Growth was observed at 420 and 440 µg/mL, whereas no growth was observed at 460, 480 and 500 µg/mL.

Table 4. Determination of MBC of Mg-CoO against Staphylococcus aureus

Mg-CoO concentration (µg/mL)	Growth on agar
420	Growth observed
440	Growth observed
460	No growth
480	No growth

500	No growth

Accordingly, the MBC of Mg-CoO against S. aureus was determined to be 460 µg/mL. The MBC was only 40 µg/mL higher than the MIC, indicating that concentrations slightly above the inhibitory threshold were sufficient to prevent subsequent bacterial growth under the experimental conditions. The MIC/MBC relationship can be expressed as an MBC/MIC ratio of approximately 1.10 (460/420), although interpretation of this ratio should be made cautiously because nanoparticle antimicrobial behavior may differ from conventional antibiotics.

3.5 Photocatalytic Degradation of Methylene Blue

The photocatalytic activities of Mg-ZnO, Mg-NiO and Mg-CoO were evaluated using methylene blue (MB) as a model organic dye under UV irradiation at 365 nm. The decrease in absorbance was monitored at 664 nm. Before irradiation, the nanoparticle–dye suspensions were maintained under dark conditions for 30 min to establish adsorption–desorption equilibrium.

3.5.1 Methylene Blue Degradation by Mg-ZnO

Mg-ZnO demonstrated strong photocatalytic activity toward methylene blue. The initial absorbance was 1.20, which progressively decreased to 0.06 after 300 min of UV irradiation. The corresponding degradation increased from 0% at 0 min to 95.0% at 300 min.

Table 5. Photocatalytic degradation of methylene blue by Mg-ZnO

Time (min)	Absorbance	Degradation (%)
0	1.20	0.0
30	0.96	20.0
60	0.81	32.5
90	0.58	51.7
120	0.42	65.0
180	0.29	75.8
240	0.11	90.8
300	0.06	95.0

The degradation increased progressively with irradiation time. At 120 min, 65.0% degradation was achieved, which increased to 90.8% at 240 min and ultimately reached 95.0% after 300 min. This progressive decrease in absorbance indicates effective removal of MB from the aqueous phase during UV irradiation in the presence of Mg-ZnO.

The strong performance of Mg-ZnO may be related to the semiconductor properties and surface characteristics of the ZnO-based material. Under UV irradiation, photoexcitation can generate electron–hole pairs, which may participate in the formation of reactive oxygen species capable of oxidizing adsorbed dye molecules. However, the present study did not directly measure charge-carrier dynamics or reactive oxygen species; therefore, this mechanism remains a proposed explanation.

3.5.2 Methylene Blue Degradation by Mg-NiO

Mg-NiO also demonstrated substantial photocatalytic activity toward methylene blue. The absorbance decreased from 1.20 at the beginning of irradiation to 0.09 after 300 min, corresponding to 92.5% degradation.

Table 6. Photocatalytic degradation of methylene blue by Mg-NiO

Time (min)	Absorbance	Degradation (%)
0	1.20	0.0
30	1.00	16.7
60	0.86	28.3
90	0.63	47.5
120	0.48	60.0
180	0.36	70.0
240	0.15	87.5
300	0.09	92.5

Mg-NiO displayed a similar overall degradation profile to Mg-ZnO, although its final degradation efficiency was slightly lower. At 240 min, Mg-NiO achieved 87.5% degradation compared with 90.8% for Mg-ZnO. After 300 min, the degradation efficiencies were 92.5% and 95.0%, respectively. Thus, Mg-ZnO exhibited a modestly superior photocatalytic performance toward MB under the experimental conditions.

The relatively high MB degradation obtained with Mg-NiO indicates that this material also possesses considerable photocatalytic potential. The difference between Mg-ZnO and Mg-NiO may arise from differences in their optical properties, surface characteristics, adsorption behavior and charge-carrier processes. Because these parameters were not quantitatively correlated with the photocatalytic data in the present dataset, further characterization would be necessary to establish the precise reason for the difference.

3.5.3 Methylene Blue Degradation by Mg-CoO

In contrast to Mg-ZnO and Mg-NiO, Mg-CoO exhibited only negligible photocatalytic degradation of methylene blue. The absorbance decreased from 1.20 to 1.12 after 300 min, corresponding to only 6.7% degradation.

Table 7. Photocatalytic degradation of methylene blue by Mg-CoO

Time (min)	Absorbance	Degradation (%)

0	1.20	0.0
30	1.18	1.7
60	1.17	2.5
90	1.16	3.3
120	1.15	4.2
180	1.14	5.0
240	1.13	5.8
300	1.12	6.7

The very low degradation efficiency indicates that Mg-CoO was ineffective for MB degradation under the specific experimental conditions used. This result is particularly interesting because Mg-CoO was the strongest antibacterial nanoparticle in the present study. Thus, the results demonstrate that high antimicrobial activity does not necessarily correspond to high photocatalytic dye-degradation efficiency.

3.6 Comparative Photocatalytic Performance toward Methylene Blue

Table 8. Comparative photocatalytic performance of the three nanoparticles toward methylene blue after 300 min

Nanoparticle	Initial absorbance	Final absorbance	Degradation after 300 min (%)
Mg-ZnO	1.20	0.06	95.0
Mg-NiO	1.20	0.09	92.5
Mg-CoO	1.20	1.12	6.7

The overall photocatalytic efficiency followed the order:

Mg-ZnO > Mg-NiO >>> Mg-CoO

Mg-ZnO showed the highest degradation efficiency (95.0%), closely followed by Mg-NiO (92.5%), whereas Mg-CoO showed only 6.7% degradation. Thus, the ZnO- and NiO-containing nanoparticles were substantially more effective photocatalysts for MB than Mg-CoO under the conditions examined.

The difference is particularly pronounced between Mg-NiO and Mg-CoO. Although both materials contain transition-metal oxides, their photocatalytic behavior was markedly different. This observation emphasizes that photocatalytic performance is strongly dependent on the electronic and surface properties of the specific semiconductor material rather than simply the presence of a transition-metal oxide.

3.7 Photocatalytic Degradation of Congo Red

The photocatalytic degradation of Congo red (CR) was investigated under UV irradiation, with the degradation process monitored at 497 nm. Among the three nanoparticles, Mg-ZnO demonstrated clear photocatalytic activity toward Congo red.

3.7.1 Congo Red Degradation by Mg-ZnO

The absorbance of Congo red decreased progressively from 1.10 at 0 min to 0.14 after 300 min of irradiation. The corresponding degradation efficiency increased from 0% to 87.3%.

Table 9. Photocatalytic degradation of Congo red by Mg-ZnO

Time (min)	Absorbance	Degradation (%)
0	1.10	0.0
30	0.95	13.6
60	0.82	25.5
90	0.65	40.9
120	0.51	53.6
180	0.39	64.5
240	0.22	80.0
300	0.14	87.3

The degradation profile indicates a continuous increase in CR removal with irradiation time. At 120 min, 53.6% degradation was achieved, increasing to 80.0% after 240 min and 87.3% after 300 min. Although the final degradation of Congo red was lower than that obtained for methylene blue using the same Mg-ZnO catalyst, the result nevertheless demonstrates substantial photocatalytic activity toward both dyes.

The difference in degradation efficiency between MB and CR may be associated with differences in dye structure, charge, molecular size, adsorption behavior and interaction with the catalyst surface. However, these factors were not independently investigated in the present study and should therefore be presented as possible explanations rather than confirmed mechanisms.

3.7.2 Congo Red Degradation by Mg-NiO and Mg-CoO

According to the experimental report, Mg-NiO and Mg-CoO did not exhibit significant photocatalytic degradation of Congo red during the experimental period. The report states that the absorbance values remained nearly constant and that no visible color change or substantial decrease in dye intensity was observed.

3.8 Overall Comparative Performance of the Nanoparticles

The results demonstrate that the three nanoparticles did not exhibit identical functional behavior. Mg-ZnO showed the strongest photocatalytic performance, achieving 95.0% degradation of methylene blue and 87.3% degradation of Congo red after 300 min. Mg-NiO showed comparable photocatalytic activity toward methylene blue, reaching 92.5% degradation, but substantially lower antimicrobial activity. In contrast, Mg-CoO demonstrated the strongest antibacterial activity, particularly against B. cereus and S. aureus, but exhibited only 6.7% methylene-blue degradation. This contrasting

behavior is scientifically significant because it demonstrates that the material showing the highest antimicrobial activity was not necessarily the most efficient photocatalyst. The difference may arise from composition-dependent differences in surface chemistry, electronic structure, defect characteristics, adsorption behavior and interactions with microbial cells or dye molecules.

From an application perspective, the results suggest that Mg-ZnO is a promising candidate for UV-assisted photocatalytic treatment of dye-containing wastewater, whereas Mg-CoO may be more attractive for antimicrobial applications. Mg-NiO displayed strong methylene-blue photocatalytic activity but comparatively limited antimicrobial activity under the tested conditions.

3.10 Proposed Relationship between Nanoparticle Composition and Functional Activity

The observed results suggest that nanoparticle composition plays an important role in determining functional performance. Mg-ZnO showed high photocatalytic activity toward both methylene blue and Congo red, suggesting favorable interaction between the ZnO-based semiconductor surface and the dye molecules under UV irradiation. The apparent pseudo-first-order rate constants further supported the superior photocatalytic performance of Mg-ZnO.

Mg-NiO also demonstrated high methylene-blue degradation, although its rate constant was slightly lower than that of Mg-ZnO. This indicates that Mg-NiO can function effectively as a photocatalyst for MB under the present experimental conditions. However, its weak antimicrobial activity suggests that the physicochemical characteristics responsible for dye degradation do not necessarily translate into strong microbial inhibition.

Mg-CoO displayed the opposite functional pattern. Its strong antibacterial activity, particularly against Gram-positive bacteria, was accompanied by very low photocatalytic activity toward methylene blue. This observation highlights the importance of considering the intended application when selecting a nanoparticle composition. Overall, the present findings support a composition-dependent functional specialization of Mg-based metal oxide nanoparticles: Mg-ZnO showed superior photocatalytic behavior, whereas Mg-CoO showed comparatively superior antibacterial activity. Further studies involving particle-size analysis, surface-area measurements, band-gap determination, ROS analysis, zeta-potential measurements and identification of degradation intermediates would be useful to establish the mechanisms responsible for these differences.

3. DISCUSSION

The present study demonstrated that the biological and photocatalytic properties of Mg-ZnO, Mg-NiO and Mg-CoO nanoparticles were strongly dependent on nanoparticle composition. An important finding was the contrasting functional behavior of the three materials: Mg-CoO exhibited the highest antibacterial activity, whereas Mg-ZnO exhibited the highest photocatalytic activity toward both methylene blue and Congo red. This observation indicates that antimicrobial and photocatalytic properties cannot necessarily be predicted from one another and are strongly influenced by the physicochemical characteristics of the individual metal oxide system.

The antimicrobial results demonstrated distinct differences among the three nanoparticle formulations. Mg-CoO produced the highest inhibition zones, particularly against the Gram-positive bacteria Bacillus cereus (22 mm) and Staphylococcus aureus (20 mm). In comparison, Mg-ZnO produced inhibition zones of 4 and 6 mm against these organisms, while Mg-NiO showed 3 and 0 mm, respectively. Mg-CoO also inhibited Escherichia coli with an 18-mm zone, demonstrating activity against both Gram-positive and Gram-negative bacteria.

The relatively strong activity of Mg-CoO against S. aureus and B. cereus is consistent with previous reports showing that cobalt oxide nanoparticles can possess appreciable antibacterial activity. Al-Fakeh and Alsaedi (2021) reported antimicrobial activity of CoO nanoparticles against S. aureus, E. faecalis, E. coli and P. aeruginosa, demonstrating that CoO nanomaterials can interact with microorganisms belonging to different taxonomic groups. More recently, plant-mediated CoO nanoparticles have also demonstrated concentration-dependent antibacterial activity, with particularly strong inhibition reported against Bacillus subtilis and E. coli.

The antimicrobial activity of metal oxide nanoparticles has been attributed in the literature to several possible mechanisms, including direct interaction with the microbial cell envelope, generation of reactive oxygen species, alteration of membrane permeability and oxidative damage to cellular components. However, the present study did not directly measure ROS generation, membrane damage or metal-ion release. Therefore, these mechanisms should be regarded as plausible explanations rather than experimentally established mechanisms for the Mg-CoO nanoparticles investigated here.

The lower susceptibility of P. aeruginosa and the complete absence of activity against E. aerogenes also demonstrate that nanoparticle activity was microorganism dependent. Such differences may arise from differences in cell-envelope architecture, membrane permeability, extracellular polymeric substances and cellular defense mechanisms. Importantly, the present findings should not be interpreted as evidence that Mg-CoO has universally greater antimicrobial activity; rather, it showed superior activity within the particular microbial panel and experimental conditions used in this study.

Mg-ZnO exhibited its strongest activity against E. coli, producing an 18-mm inhibition zone, while moderate inhibition was observed against P. aeruginosa, C. albicans and A. niger. Previous experimental studies have similarly demonstrated antimicrobial activity of Mg-modified ZnO, supporting the ability of Mg-containing ZnO systems to interact with both bacterial and fungal cells. The biological activity of Mg-doped ZnO has been associated with changes in surface properties and oxidative processes that can affect microbial viability.

Mg-NiO displayed comparatively weak antimicrobial activity in the present investigation. It produced only 6 mm against E. coli and 3 mm against B. cereus, with no detectable inhibition against the remaining organisms. This finding does not indicate that NiO nanoparticles intrinsically lack antimicrobial activity. In fact, recent studies have reported substantial antibacterial activity for NiO nanoparticles against both Gram-positive and Gram-negative organisms. For example, Gebremichael et al. (2026) reported inhibition zones of approximately 19 mm against S. aureus and 17 mm against Salmonella typhi using bio-derived NiO nanoparticles. The difference between those observations and the present results

may reflect differences in particle size, morphology, synthesis route, surface functionalization, nanoparticle concentration, microbial strain and assay conditions.

The selection of Mg-CoO for MIC and MBC determination was justified by its comparatively greater antibacterial activity in the disc diffusion assay. Mg-CoO exhibited an MIC of 420 µg/mL against S. aureus, whereas ciprofloxacin exhibited an MIC of 80 µg/mL. The MBC of Mg-CoO was 460 µg/mL, with bacterial growth observed at 420 and 440 µg/mL and no growth at 460–500 µg/mL.

The difference between the MIC of Mg-CoO and ciprofloxacin indicates that the nanoparticle was less potent than the conventional antibiotic under the conditions investigated. Nevertheless, the relatively small difference between the MIC and MBC of Mg-CoO suggests that the concentration required to produce complete bactericidal activity was only moderately higher than that required to inhibit visible growth. The MBC/MIC ratio obtained in the present study was approximately 1.10 (460/420).

The MIC and MBC findings should therefore be interpreted as evidence of antibacterial potential rather than as evidence that Mg-CoO can replace conventional antibiotics. Further studies involving time-kill kinetics, membrane integrity assays, ROS measurements and cytotoxicity evaluation would be necessary before considering biomedical applications.

The photocatalytic experiments revealed a markedly different ranking from the antimicrobial assay. Mg-ZnO demonstrated the highest methylene-blue degradation, reaching 95.0% after 300 min, followed closely by Mg-NiO with 92.5%. In contrast, Mg-CoO showed only 6.7% degradation.

The superior performance of Mg-ZnO is consistent with previous experimental studies demonstrating that Mg modification can enhance the photocatalytic properties of ZnO. Pradeev Raj et al. (2018) reported enhanced photocatalytic activity of Mg-doped ZnO and attributed the improvement to changes in the structural and optical characteristics of the ZnO system. Such modification can influence defect states, surface properties and charge-carrier behavior, which are important determinants of photocatalytic efficiency.

The present kinetic analysis further supports the superior performance of Mg-ZnO. The apparent pseudo-first-order rate constants calculated from the supplied absorbance data were 0.01009 min^{-1} for Mg-ZnO, 0.00874 min^{-1} for Mg-NiO and 0.00021 min^{-1} for Mg-CoO. Thus, the kinetic ranking was consistent with the degradation-efficiency ranking:

Mg-ZnO > Mg-NiO >>> Mg-CoO

The strong photocatalytic activity of Mg-ZnO may be related to efficient absorption of UV radiation and subsequent generation of electron–hole pairs. These charge carriers can participate in surface redox reactions leading to formation of reactive species capable of attacking dye molecules. However, because the present study did not directly quantify charge separation, ROS generation or degradation intermediates, this interpretation should remain mechanistic speculation rather than a demonstrated pathway.

The high activity observed for Mg-NiO is also supported by recent experimental literature. Gebremichael et al. (2026) reported approximately 96% methylene-blue degradation using bio-derived NiO nanoparticles under optimized solar-irradiation conditions. Other recent investigations have likewise demonstrated that NiO nanoparticles can simultaneously exhibit photocatalytic and antibacterial properties. The 92.5% MB degradation observed for Mg-NiO in the present study therefore falls within the range demonstrating that NiO-based nanomaterials can be effective photocatalysts, although direct comparison must account for differences in irradiation source, catalyst loading, dye concentration and reaction time.

The very low MB degradation obtained with Mg-CoO was notable. Only 6.7% degradation was achieved after 300 min, despite Mg-CoO showing the strongest antibacterial activity. This contrasting behavior suggests that the physicochemical features responsible for microbial inhibition are not necessarily the same as those controlling photocatalytic dye degradation. In particular, antimicrobial activity may depend strongly on surface–cell interactions and oxidative stress, whereas photocatalysis additionally requires favorable light absorption, charge generation and charge separation.

Mg-ZnO also exhibited substantial photocatalytic activity against Congo red, achieving 87.3% degradation after 300 min. The corresponding apparent pseudo-first-order rate constant was 0.00691 min^{-1}. The degradation was lower than the 95.0% obtained for methylene blue under the same irradiation period, indicating that the efficiency of Mg-ZnO was influenced by the identity of the dye.

The difference between methylene blue and Congo red degradation may be associated with differences in molecular structure, charge characteristics, molecular size and adsorption affinity toward the nanoparticle surface. Adsorption is particularly important because photocatalytic reactions generally occur at or near the catalyst surface. Consequently, differences in dye–surface interactions can influence the concentration of pollutant molecules available for photochemical transformation.

The strong Congo red degradation observed with Mg-ZnO further supports the potential of this nanoparticle as a photocatalyst rather than its activity being restricted to a single model dye. However, numerical degradation data for Mg-NiO and Mg-CoO against Congo red were not available in the experimental report; therefore, a quantitative comparison among all three nanoparticles for Congo red should not be made until the original spectrophotometric measurements are available.

3.6 Environmental and biological significance

The photocatalytic results are relevant to wastewater remediation because methylene blue and Congo red are representative synthetic dyes that can be used as model organic pollutants. The ability of Mg-ZnO to degrade both dyes under UV irradiation demonstrates its potential as a semiconductor-based photocatalyst. The 95.0% degradation of methylene blue and 87.3% degradation of Congo red after 300 min indicate substantial removal under the conditions used in the present study.

At the same time, the antimicrobial findings suggest a complementary biological application of Mg-CoO. Its 22-mm inhibition zone against B. cereus and 20-mm zone against S. aureus demonstrate substantial activity in the tested panel.

Recent experimental studies have likewise identified CoO nanoparticles as materials with promising antibacterial properties, although activity depends strongly on nanoparticle concentration and synthesis characteristics.
Thus, the present study provides evidence that Mg-based metal oxide nanoparticles can display distinct application profiles depending on their transition-metal component. However, practical application would require additional investigation of nanoparticle stability, reusability, leaching, toxicity toward non-target organisms, degradation intermediates and long-term environmental behavior.

4. CONCLUSION

The present study comparatively evaluated the antimicrobial and photocatalytic properties of Mg-ZnO, Mg-NiO and Mg-CoO nanoparticles. The findings demonstrated pronounced composition-dependent differences in their functional performance. Among the three nanoparticles, Mg-CoO exhibited the strongest antimicrobial activity, particularly against the Gram-positive bacteria B. cereus and S. aureus, with inhibition zones of 22 and 20 mm, respectively. Mg-CoO showed an MIC of 420 µg/mL and an MBC of 460 µg/mL against S. aureus. Although its antibacterial activity was lower than that of ciprofloxacin on a concentration basis, the results demonstrate appreciable antibacterial potential. In contrast, Mg-ZnO demonstrated the best photocatalytic performance. It achieved 95.0% degradation of methylene blue and 87.3% degradation of Congo red after 300 min of UV irradiation. The calculated apparent pseudo-first-order rate constants further supported its superior photocatalytic activity. Mg-NiO also showed substantial methylene-blue degradation (92.5%), whereas Mg-CoO showed only 6.7% degradation under the same conditions. Overall, the results demonstrate that the three nanoparticles possess different functional strengths: Mg-ZnO is the most promising photocatalytic material, whereas Mg-CoO shows greater potential as an antimicrobial material. This composition-dependent specialization highlights the importance of selecting metal oxide nanoparticles according to the intended application rather than assuming that high antimicrobial activity will correspond to high photocatalytic efficiency. Further studies involving detailed surface and optical characterization, reactive oxygen species analysis, photocatalyst reusability, dye-degradation intermediates, mechanistic investigations and toxicity assessment are recommended to establish the practical applicability and mechanistic basis of these Mg-based nanoparticles.

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