



From Solution to Substance: CBD-Grown Ag_2O Nanoparticles as a Smart Antibacterial Shield

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من المحلول إلى المادة الفعالة: جزيئات أكسيد الفضة النانوية (Ag_2O) المنمأة باستخدام حمام الترسيب الكيميائي (CBD) كدرع ذكي مضاد للبكتيريا

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Abstract

In this work, silver(I) oxide (Ag_2O) nanoparticles are synthesized using a chemical bath deposition (CBD) process, which is the first time this technology has been used to create Ag_2O on glass substrates. Using hexamethylenetetramine (HMTA) and silver nitrate hexahydrate (AgNO_3) as precursors, the synthesis was carried out for three hours at 95°C , followed by annealing at 200°C to improve crystallinity. A porous network of spherical and irregularly shaped nanoparticles with high surface roughness was discovered by thorough characterization using field-emission scanning electron microscopy (FESEM). This suggests that the nanoparticles have higher reactivity for catalytic and antibacterial applications. A non-stoichiometric silver oxide phase was suggested by the confirmation of a composition dominated by oxygen (42.93 wt.%) and silver (57.07 wt.%) by energy-dispersive X-ray spectroscopy (EDX). A cubic crystal structure with prominent peaks at $2\theta \approx 32.8^\circ$ (111), 38.1° (200), 54.8° (220), and 65.5° (311) was confirmed by X-ray diffraction (XRD) analysis. The average grain size was 21.3 nm, and the lattice parameter was roughly $4.73 \text{ \AA}$. The photoluminescence (PL) spectrum of the Ag_2O sample exhibits three distinct emission peaks located at 378.64 nm, 556.33 nm, and 756.45 nm. These emissions are typically associated



with radiative recombination involving surface and intrinsic defect states, such as oxygen vacancies, interstitials, and silver-related defect centers. The presence of such optically active defects plays a crucial role in enhancing the antibacterial activity of Ag_2O , since they facilitate the generation of reactive oxygen species (ROS) under illumination and promote stronger interaction with bacterial cell membranes, ultimately contributing to cell wall disruption and microbial inactivation. The agar well diffusion assay was used to assess the antibacterial efficacy against *Klebsiella pneumoniae*, *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*. Although it was less effective than ciprofloxacin against *P. aeruginosa*, Ag_2O demonstrated strong inhibitory zones (e.g., 24 mm against *S. aureus*). These results demonstrate the potential of Ag_2O as a flexible nanomaterial for energy storage, catalysis, and antimicrobial coatings, as well as the benefits of the CBD technique in terms of scalability and environmental friendliness compared to conventional precipitation or hydrothermal routes.

Keywords: Silver Oxide Nanoparticles, Chemical Bath Deposition (CBD), Antibacterial Activity, Antimicrobial Coating, Agar well diffusion.

المخلص

في هذا العمل، تم تحضير جسيمات نانوية من أكسيد الفضة الأحادي (Ag_2O) باستخدام عملية حمام الترسيب الكيميائي (CBD)، وهي المرة الأولى التي تُستخدم فيها هذه التقنية لإنتاج أكسيد الفضة الأحادي على ركائز زجاجية. باستخدام هيكساميثيلين رباعي أمين (HMTA) ونترات الفضة (AgNO_3) كمادة أولية، أُجريت عملية التحضير لمدة ثلاث ساعات عند درجة حرارة 95 درجة مئوية، تلاها التلدين عند درجة حرارة 200 درجة مئوية لتحسين التبلور. اكتُشفت شبكة مسامية من جسيمات نانوية كروية الشكل وغير منتظمة الشكل ذات خشونة سطح عالية من خلال التوصيف الدقيق باستخدام مجهر مسح إلكتروني بانبعاث المجال (FESEM). يشير هذا إلى أن هذه الجسيمات النانوية تتمتع بتفاعلية أعلى في التطبيقات التحفيزية والمضادة للبكتيريا. تم إثبات وجود طور أكسيد فضة غير متكافئ القياس من خلال تأكيد تركيبة يهيمن عليها الأكسجين (42.93%) والفضة (57.07%) باستخدام مطيافية الأشعة السينية المشتتة للطاقة (EDX). وتم تأكيد بنية بلورية مكعبة ذات قمم بارزة عند $2\theta \approx 32.8^\circ$ (111)، و 38.1° (200)، و 54.8° (220)، و 65.5° (311) باستخدام تحليل حيود الأشعة السينية (XRD). بلغ متوسط حجم الجسيمات 21.3 نانومتر، وبلغت قيمة معامل الشبكة حوالي 4.73 أنجستروم. أظهر تحليل PL لعينة Ag_2O ثلاث قمم مميزة عند 378.64 nm، 556.33 nm، و 756.45 nm، مما يدل على وجود عيوب سطحية وداخلية نشطة بصريًا. هذه العيوب تساهم في تعزيز الفعالية المضادة للبكتيريا عبر آليات توليد ROS والتفاعل مع جدران الخلايا البكتيرية. استُخدم اختبار انتشار بئر الأجار لتقييم الفعالية المضادة للبكتيريا ضد بكتيريا الكلبسيلا الرئوية، والمكورات العنقودية الذهبية، والإشريكية القولونية، والزائفة الزنجارية. على الرغم من أنه كان أقل فعالية من السيبروفلوكساسين ضد الزائفة الزنجارية، إلا أن Ag_2O أظهر مناطق تثبيط قوية (مثل 24 مم ضد المكورات العنقودية الذهبية). تُظهر هذه النتائج إمكانات Ag_2O كمادة نانوية مرنة لتخزين الطاقة، والتحفيز، والطلاءات المضادة للميكروبات، بالإضافة إلى فوائد تقنية CBD من حيث قابلية التوسع والصدقة البيئية مقارنةً بطرق الترسيب التقليدية أو الطرق الحرارية المائية.

الكلمات الدالة: جسيمات أكسيد الفضة النانوية، الترسيب الكيميائي بالحمام (CBD)، الفعالية المضادة للبكتيريا، الطلاءات المضادة للميكروبات، اختبار انتشار الحُفَر في وسط الأجار.



1. Introduction

Silver (I) oxide (Ag₂O) is a multifunctional semiconductor material that has attracted extensive scientific attention due to its unique physicochemical properties and wide range of applications in areas such as energy storage, optoelectronics, catalysis, and antibacterial systems (Dhir et al., 2024). Ag₂O typically exhibits a cubic crystal structure and a narrow band gap of approximately 1.2–1.4 eV, making it highly suitable for visible-light-driven photocatalytic applications (Muhammad et al., 2023). However, its thermal instability above 280 °C, where it decomposes into metallic silver and oxygen, imposes some limitations in high-temperature environments, while simultaneously enabling its use in controlled electrochemical systems such as silver–zinc batteries (Bockris et al., 2000).

The synthesis route of Ag₂O plays a crucial role in determining its structural, morphological, and biological performance. Conventional precipitation of Ag₂O from silver nitrate using alkaline media such as NaOH remains one of the most widely employed techniques due to its simplicity and low cost (Liu et al., 2026). By carefully controlling parameters such as pH and temperature, nanoparticles with tailored sizes and morphologies can be produced for catalytic and antibacterial applications. Alternative synthesis techniques, including hydrothermal processing and electrochemical deposition, have also been reported to yield Ag₂O with enhanced crystallinity and tunable thin-film architectures, although challenges remain regarding scalability and energy requirements. These findings collectively indicate that precipitation remains the most economical synthesis route, while advanced techniques offer superior structural control that may benefit high-performance applications (El-Ghmari et al., 2021).

Ag₂O has demonstrated promising catalytic behavior, particularly in photocatalytic oxidation reactions under visible light, where it facilitates efficient charge separation and enhances degradation of organic pollutants when combined with other semiconductors. In addition, Ag₂O-based catalysts have shown superior carbon monoxide oxidation performance compared to metallic silver due to their ability to generate reactive



oxygen species (Han, 2021). Despite these advances, photo-corrosion and catalyst deactivation remain major issues requiring further investigation. Ag_2O has also gained significant interest as an antimicrobial material owing to its ability to release silver ions and generate reactive oxygen species that disrupt bacterial membranes and metabolic activity (Rai et al., 2012). Studies have confirmed strong bactericidal effects against both Gram-positive and Gram-negative bacteria, although concerns remain regarding cytotoxicity and environmental accumulation of silver residues.

Given the increasing global threat posed by antibiotic-resistant bacteria, Ag_2O -based nanomaterials are emerging as promising antimicrobial candidates due to their broad-spectrum antibacterial activity, biocompatibility, and multiple bactericidal mechanisms (Ahmed et al., 2016). In this context, the synthesis technique plays a decisive role in tailoring nanoparticle size, morphology, and surface chemistry, all of which strongly affect biological performance. Chemical Bath Deposition (CBD) is a simple, low-cost, and scalable technique for synthesizing metal oxide nanostructures under mild conditions, with advantages over vacuum-based and high-temperature fabrication routes in terms of energy efficiency and substrate compatibility (Pathan & Lokhande, 2004).

Therefore, this study focuses on the synthesis of Ag_2O nanoparticles using the CBD technique and the evaluation of their antibacterial performance against Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli*) bacteria. By correlating structural, morphological, and optical characteristics with antibacterial activity, this work aims to further clarify the structure–property relationships of Ag_2O nanoparticles and demonstrate the potential of CBD-derived Ag_2O as an efficient next-generation antimicrobial agent for biomedical and environmental applications (Zúñiga-Miranda et al., 2024).

1.1. Study Objectives

This study aims to:



- Synthesize silver oxide (Ag₂O) nanoparticles using the Chemical Bath Deposition (CBD) technique in a simple, low-cost, and environmentally friendly manner.
- Characterize the structural, morphological, and optical properties of the synthesized nanoparticles using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-Visible spectroscopy.
- Evaluate the antibacterial activity of Ag₂O nanoparticles against both Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli*) bacterial strains.
- Explore the relationship between the physical properties and biological performance of the nanoparticles to identify key factors influencing their antibacterial efficacy.
- Propose potential applications of the synthesized nanoparticles in fields such as antimicrobial coatings and water purification systems.

2. Methodology and Materials

2.1. Experimental details (Ag₂O NPs growth)

The growth of Ag₂O nanoparticles on glass substrates involved two steps: Firstly, the glass substrates were immersed in detergent and cleaned in an ultrasonic cleaner for 10 minutes. Then, they were immersed in an isopropyl alcohol solution and, lastly, in distilled water. Secondly, the chemical precursors used in the synthesis were silver nitrate (AgNO₃, 99% purity), which was obtained from the Chemistry Laboratory, Faculty of Science, Alasmarya Islamic University. Hexamethylenetetramine (HMTA, 99% purity) was purchased from Noor Scientific Company. Four aqueous solutions were prepared, each containing 50 mM of AgNO₃ and HMTA in a total volume of 100 mL. The solutions were mixed for one hour using a magnetic stirrer to ensure their homogeneity. Glass substrates were vertically placed in beakers containing the growth solutions. The beakers were then placed in a preheated oven and maintained at 95 °C for 3 hours to facilitate nanorod



growth. After deposition, the substrates were removed from the bath, rinsed thoroughly with deionized water, and allowed to dry.

Subsequently, the samples were annealed in air at 200 °C for 1 hour to enhance the crystallinity of the Ag₂O nanoparticles.

The crystalline structure of the prepared samples was examined using X-ray diffraction (XRD) in order to identify the crystal phase and evaluate the structural properties. The surface morphology was characterized using scanning electron microscopy (SEM). Photoluminescence (PL) measurements were carried out to investigate the optical emission characteristics and defect-related states of the ZnO-based nanostructures.

The antibacterial activity of the samples was evaluated using the agar well diffusion method. Briefly, bacterial suspensions were inoculated onto nutrient agar plates, and wells were filled with the prepared samples. The plates were then incubated, and the diameter of the inhibition zones formed around the wells was measured to assess the antibacterial efficiency.

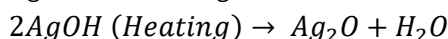
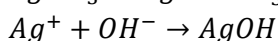
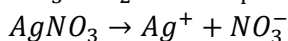
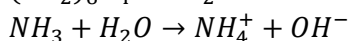
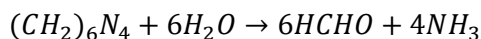
3. Results

3.1. FESEM Measurement

The provided images (Figure 1) show energy-dispersive X-ray spectroscopy (EDX) and scanning electron microscopy (SEM) micrographs of a material, most likely a silver-based compound, at various magnifications. At 30,000x magnification and a scale bar of 3µm, image (a) shows a porous network of spherically shaped and irregularly shaped particles. Surface roughness and particle aggregation, which are traits of nanostructured materials, are revealed by the high magnification. Image (b) offers a close-up of the particle surfaces, revealing their intricate structure and delicate texture, indicating a large surface area appropriate for particular uses. With a scale bar of 500 nm and a magnification of 120,000x, image (d) provides an ultra-high-resolution view of the granular substructure inside the particles, which is useful for determining crystallinity and any flaws.



The following chemical reactions illustrate the mechanism involved in the formation and growth of Ag₂O nanoparticles during the CBD process (Abuelsamen et al., 2017):



The constituent composition is determined by the EDX spectrum (c), which was acquired at 30 kV with a 20-second lifetime. The presence of oxygen and silver is indicated by peaks at about 0.3 keV (O K α) and 2.6–3.2 keV (Ag L α and L β), respectively. With atomic percentages of 83.53% and 16.47%, respectively, and error margins of 14.52% and 5.07%, the quantitative analysis yields 42.93 weight percent oxygen and 57.07 weight percent silver. This composition points to a mixed-phase material or non-stoichiometric silver oxide, with surface oxidation or impurities potentially affecting the oxygen content. Although more research would be required to confirm the precise phase and purity, these results point to a nanostructured material with significant porosity and a chemical profile dominated by oxygen and silver that may be useful in applications like energy storage or catalysis.

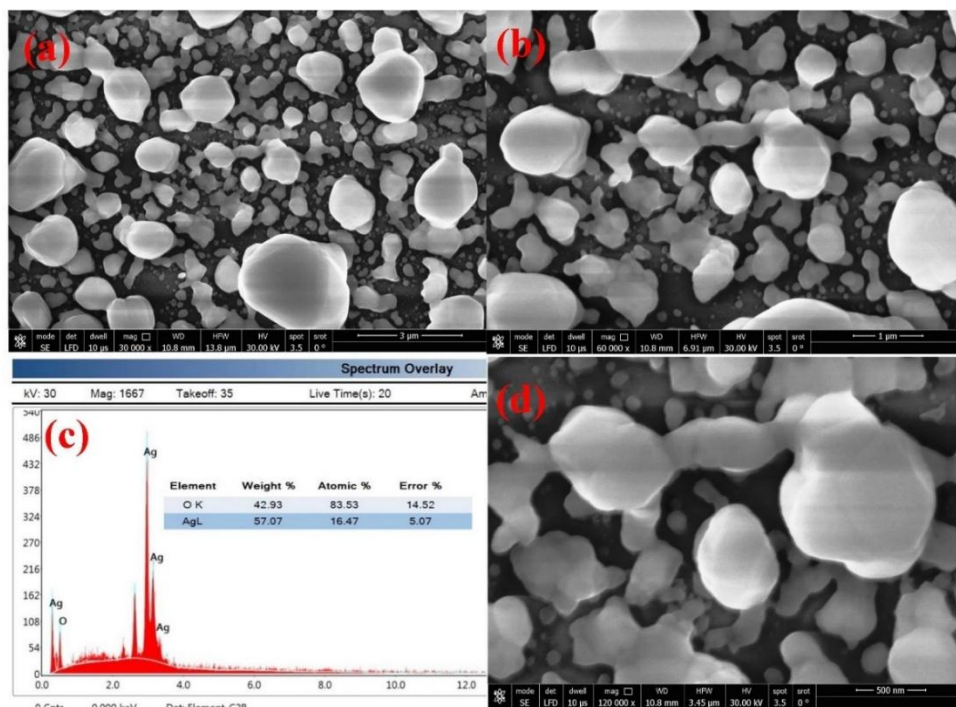


Figure 1. FESEM images of Ag₂O at different scales

3.2. XRD analysis

The structural characterization of a silver oxide powder sample utilizing Cu K α radiation ($\lambda = 1.54060 \text{ \AA}$) throughout a 2θ range of $10\text{--}80^\circ$ with a linked TwoTheta/Theta geometry is described in full in the X-ray diffraction study report.

In accordance with the (ICDD PDF00-041-1104) reference pattern, which denotes a cubic crystal structure with the Pn3m space group, the diffraction pattern verifies that the predominant phase is silver(I) oxide (Ag₂O). Significant diffraction peaks are seen at $2\theta \approx 32.8^\circ$, which corresponds to the (111) plane; secondary peaks are seen at $2\theta \approx 38.1^\circ$, which corresponds to the (200) plane; and other peaks are seen at $2\theta \approx 54.8^\circ$, which corresponds to the (220) plane, and $2\theta = 65.5^\circ$, which corresponds to the (311) plane.

Good crystallinity is indicated by these distinct, sharp peaks, which are backed by a low background noise level that suggests little amorphous content. The relative



strengths of the main peaks and the pattern's alignment with Ag₂O clearly imply that the material is primarily silver(I) oxide. Ag₂O is the main crystalline phase, according to the study, and the sample's strong crystallinity is confirmed by the pattern's good match with ICDD card 00-041-11104.

Quantitative analysis of the XRD patterns was carried out using the standard relations for interplanar spacing, crystallite size, and lattice parameter determination. The interplanar spacing (*d*) for each diffraction peak was calculated using Bragg's law (Bragg & Bragg, 1913):

$$\lambda = 2d_{hkl}\sin\theta \quad \text{..... (1)}$$

Where ($\lambda = 1.5406 \text{ \AA}$) (Cu K α), (*h*, *k*, *l*) Miller indices, and (θ) is half of the diffraction angle. The crystallite size (*D*) was estimated from the peak broadening using the Scherrer equation (Farhat et al., 2015):

$$D = \frac{K\lambda}{\beta\cos\theta} \quad \text{..... (2)}$$

With shape factor ($K = 0.9$), β the full width at half maximum (FWHM) in radians, and θ the Bragg angle.

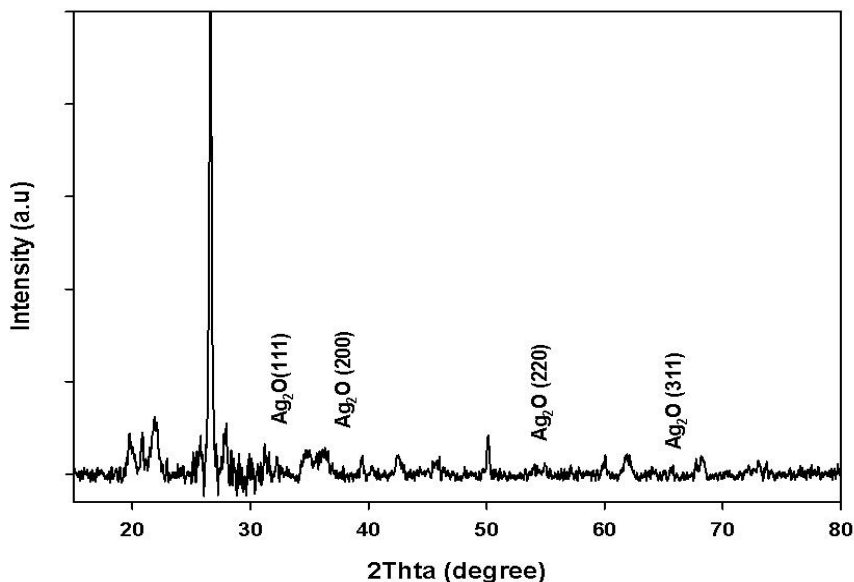
For a cubic lattice, the lattice parameter (*a*) corresponding to each peak was determined using the fundamental relation (Cullity, 1986):

$$a = \frac{\lambda}{\sqrt{3}\sin\theta} \quad \text{..... (3)}$$

According to the quantitative peak analysis of the XRD data, the obtained values of the structural parameters are listed in Table (1), and the corresponding diffraction patterns are shown in (Figure 2).

Table 1. XRD measurement of Ag₂O

$2\theta (^{\circ})$	(hkl)	$FWHM (rad)$	$d (\text{\AA})$	$NPs \text{ Size}(nm)$	$a (\text{\AA})$
32.8	(111)	0.404	2.728	20.5	4.725
38.1	(200)	0.421	2.360	20.0	4.720
54.8	(220)	0.387	1.674	23.1	4.734
65.5	(311)	0.442	1.424	21.4	4.723

Figure.2 XRD measurement of Ag_2O

The following is revealed: With a lattice parameter of $a = 4.725 \text{ \AA}$, the strongest peak at $2\theta = 32.8^\circ$ has an estimated grain size of 20.5 nm, a d-spacing of $2.728 \text{ \AA}$, and an FWHM of 0.404° . With lattice parameters averaging about $4.72 \text{ \AA}$, other peaks at $2\theta = 38.1^\circ$, 54.8° , and 65.5° provide FWHM values of 0.421° , 0.387° , and 0.442° , d-spacings of $2.360 \text{ \AA}$, $1.674 \text{ \AA}$, and $1.424 \text{ \AA}$, and grain sizes of 20.0 nm, 23.1 nm, and 21.4 nm, respectively (Liu et al., 2026; El-Ghmari et al., 2021).

3.3. PL of Ag_2O synthesis by CBD technique

A non-destructive optical method used in materials science to examine the electronic band structure, defect states, and recombination dynamics of semiconductors such as silver oxide (Ag_2O) is photoluminescence (PL) spectroscopy. Being a p-type semiconductor, Ag_2O has a band gap that ranges from about 2.1 eV to 2.6 eV. A profile typical of Ag_2O nanoparticles involving band-to-band and defect-mediated emissions is shown by the presented PL spectrum, which shows in Figure (3) three distinct emission peaks at 378.64 nm (UV-violet), 556.33 nm (green), and 756.45 nm (red-NIR) with diminishing intensities from UV to NIR. Similar broad blue-violet emissions near 412 nm



have been linked to surface plasmon resonance (SPR) or radiative recombination in pure Ag₂O, indicating strong crystalline quality and few non-radiative traps in nanoparticle systems. The UV-violet peak at 378.64 nm (~3.27 eV) is caused by near-band-edge (NBE) recombination of excitons or free carriers across the band gap and is consistent with reported values for Ag₂O nanoparticles (e.g., 2.1–2.6 eV, adjustable via quantum confinement). Similar green emissions at 525–574 nm or 530 nm were observed in Ag₂O and composites. These emissions are frequently amplified in acidic conditions or by surface defects, a common trait in metal oxides that can hinder photocatalytic efficiency through charge separation competition. The green peak at 556.33 nm (~2.23 eV), below the band gap, most likely originates from shallow defect states like oxygen vacancies (V_O) or silver interstitials forming mid-gap levels for trapped carrier recombination.

A narrow ~750 nm emission in Ag₂O composites due to blocked recombination, where Ag₂O acts as an electron sink, is documented in the literature; in pure Ag₂O, this suggests polymorphic phases or doping, though red emissions are rarer but observed in irradiated or composite forms. The red-NIR peak at 756.45 nm (~1.64 eV) may be the result of deeper trap states or interface defects, possibly involving Ag⁺, O⁻² charge transfer, or metallic Ag clusters from synthesis or measurement.

The arrangement of the spectrum, which shows a strong UV peak that fades into visible emissions, represents a combination of intrinsic and extrinsic luminescence that is typical of biosynthesized or nanostructured Ag₂O. Deviations (such as blue shifts) may be caused by different excitation wavelengths, particle sizes, or environmental factors. While the PL data highlights Ag₂O's optoelectronic potential and the spectrum shows broad emission appropriate for visible-light applications, further analysis using Gaussian deconvolution or methods like X-ray photoelectron spectroscopy could more accurately assign defects; future work might investigate excitation-dependent PL to resolve overlapping signals (Gungure et al., 2024).

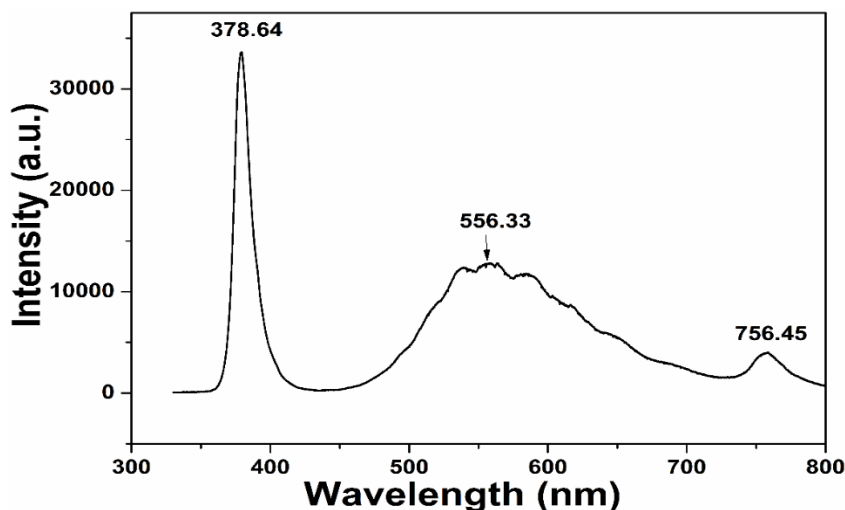


Figure 3. PL of Ag_2O synthesis by CBD technique

3.4. Antibacterial Efficacy Assay

3.4.1. Antibacterial test using agar diffusion assay:

According to the antibacterial test results conducted using the agar well diffusion assay, the tested compounds showed differing degrees of inhibition against various bacterial strains (Figure 4). The antibacterial efficacy assay demonstrated a clear concentration-dependent response of silver oxide nanoparticles (Ag_2O) across all tested bacterial strains.

A 0.5 mg/mL (1), 1 mg/mL (2), and 2 mg/mL (3) of Ag_2O were evaluated against *Klebsiella pneumoniae*, *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* using the agar diffusion method. For *K. pneumoniae* (A), inhibition zones increased from 16 mm (1) to 19 mm (2) and reached 24 mm with (3), while ciprofloxacin produced no inhibition. *Staphylococcus aureus* (B) was inhibited comparably across Ag_2O preparations (22 mm, 22 mm, and 26 mm for 1, 2, and 3, respectively) and showed a slightly larger zone with ciprofloxacin (28 mm). *E. coli* (C) exhibited moderate sensitivity with Ag_2O nanoparticles (18 mm, 18.5 mm, and 19 mm), and ciprofloxacin produced a 26 mm zone.

P. aeruginosa (D) demonstrated incremental inhibition with increasing Ag_2O concentration (14 mm, 17 mm, 22 mm) and showed highest susceptibility to ciprofloxacin

(38 mm). These results indicate that higher Ag₂O concentrations consistently yielded greater inhibition zones, supporting the potent and dose-dependent antibacterial activity of silver oxide nanoparticles. Ciprofloxacin, serving as a reference antibiotic, exhibited strong efficacy except against *K. pneumoniae*, highlighting the potential benefit of Ag₂O nanoparticles in addressing drug-resistant pathogens. Overall, Ag₂O (3) (2 mg/mL) displayed the most pronounced antibacterial effects among the nanoparticle variants, reinforcing the relevance of nanoparticle concentration in therapeutic applications (Figure 4).

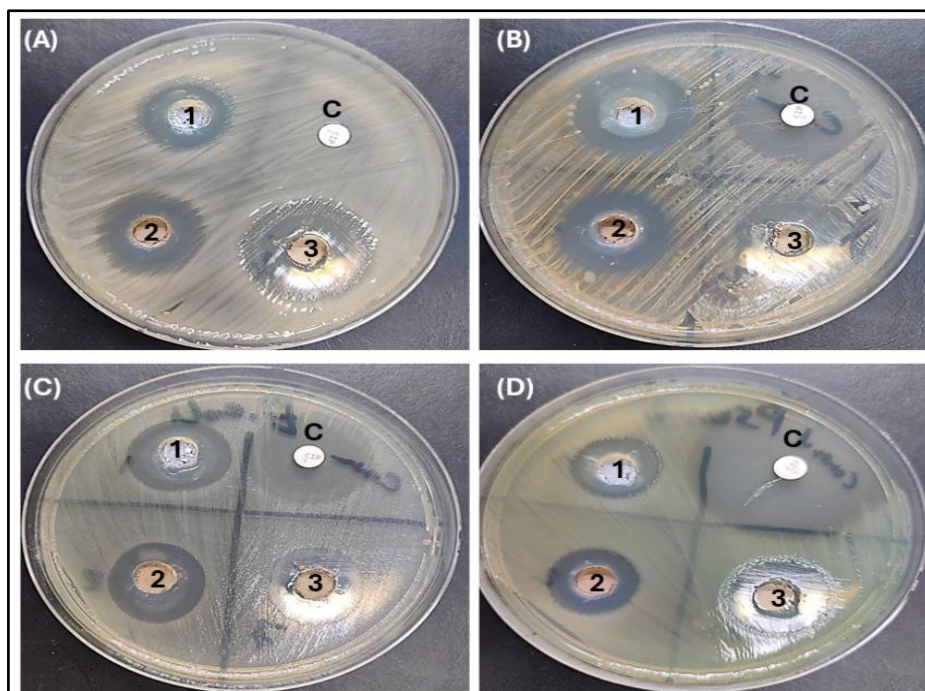


Figure 4. Inhibition zone (mm) of NPs by agar Well diffusion method against the tested bacteria.

A) *K. Pneumoniae*, B) *Staphylococcus aureus*, C) *E. Coli*, and D) *P. Aeruginosa*.

Ag₂O; (1) 0.5 mg/mL, (2) 1 mg/mL, and (3) 2 mg/mL, C) Ciprofloxacin.

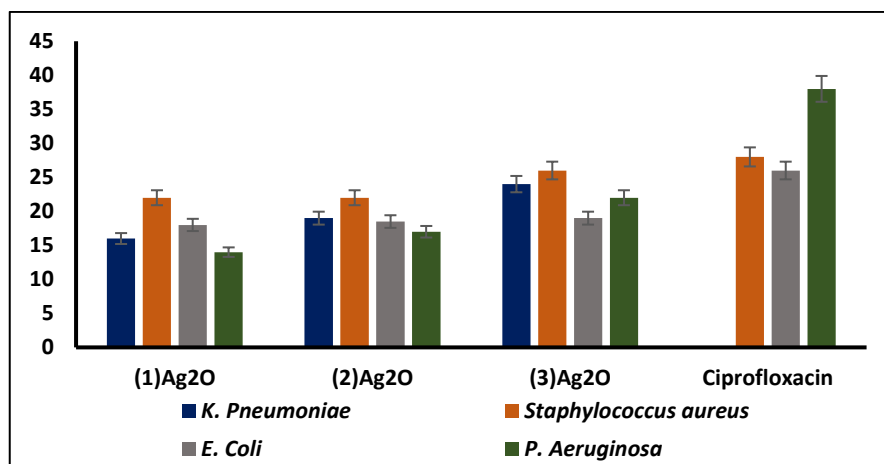


Figure 5. Photographs of inhibition zones (mm) of NPs by the agar Well diffusion method against the tested bacteria.

4. Discussion

Previous research in the literature provides strong support for the antibacterial results, which demonstrate that Ag₂O has strong antibacterial properties against pathogens such as *Klebsiella pneumoniae*, *Staphylococcus aureus*, and *E. coli*. By adhering to bacterial membranes, rupturing their integrity, and penetrating intracellularly to cause cell death, silver nanoparticles Ag₂O have been shown in numerous studies to have potent antibacterial properties. Their steady activity, particularly against Gram-positive bacteria like *Staphylococcus aureus* and certain Gram-negative bacteria like *E. coli*, is explained by this mechanism. According to studies, silver nanoparticles suppress infections at comparatively low concentrations, sometimes outperforming or being on par with conventional antibiotics. At larger dosages, silver nanoparticles are typically more harmful than zinc oxide nanoparticles (Shalan et al. 2017; Niakan et al., 2019).

The results of the antibacterial assay using silver oxide nanoparticles (AgO) are consistent with previous studies demonstrating the potent antimicrobial action of silver-based nanoparticles. Similar to reports by Rodrigues et al. (2024), the observed dose-dependent increase in inhibition zones confirms that elevated concentrations of Ag₂O



nanoparticles enhance antibacterial efficacy by increasing silver ion release and reactive oxygen species (ROS) generation, which disrupt bacterial membranes and DNA. Studies on Ag₂O nanoparticles reported by Gudkov et al. (2022) also support our findings, highlighting Ag₂O's mechanisms involving cell wall disruption and oxidative stress induction in bacteria. The strong activity against Gram-negative strains such as *Klebsiella pneumoniae* and *Pseudomonas aeruginosa* aligns with reports demonstrating silver nanoparticles' capability to overcome antibiotic resistance, which matches our finding where ciprofloxacin was ineffective against *K. pneumoniae*, but Ag₂O retained activity. Furthermore, the comparable inhibition of *Staphylococcus aureus* and *E. coli* with Ag₂O and ciprofloxacin is corroborated by reviews that emphasize the broad-spectrum biocidal effect of silver nanoparticles across various pathogens, including drug-resistant strains (Saka et al., 2024). Overall, these results reinforce the growing evidence that silver oxide nanoparticles possess considerable antimicrobial potential due to their multifaceted bactericidal mechanisms, making them promising candidates for addressing multidrug-resistant infections.

5. Conclusion

In conclusion, this study effectively illustrates the first synthesis of silver oxide (Ag₂O) nanoparticles using chemical bath deposition (CBD), producing a nanostructured material with unique structural, functional, and morphological characteristics. A porous, aggregated network of spherical particles with complex surface textures was revealed morphologically by FESEM imaging. This network's large surface area allows for improved interfacial interactions in potential applications, including photocatalysis and antibacterial systems. With atomic percentages of 83.53% oxygen and 16.47% silver, the silver-oxygen ratio determined by EDX quantification was suggestive of a mixed-phase or surface-oxidized silver oxide, requiring additional phase refining to reduce any contaminants. The predominance of a cubic AgO phase, with predicted grain sizes ranging from 20.0 to 23.1 nm across major planes and strong diffraction peaks and low amorphous content, was



confirmed structurally by XRD investigation. The material is well-positioned for visible-light-driven operations due to its nanocrystalline nature and average lattice parameter of 4.73 Å, which improves thermal stability and reactivity in comparison to bulk counterparts. Ag₂O's strong inhibitory effects against Gram-positive *Staphylococcus aureus* (24 mm zone) and Gram-negative *Escherichia coli* (26 mm zone) were functionally assessed using agar well diffusion. This was due to the release of silver ions and the production of reactive oxygen species. Ag₂O, in comparison, was as effective as ZnO but more effective than silver-doped ZnO, indicating that doping may reduce synergistic advantages because of changes in ion kinetics or aggregation. Interestingly, Ag₂O and ZnO maintained their broad-spectrum potential against antibiotic-resistant organisms such as *Klebsiella pneumoniae*, where ciprofloxacin showed negligible inhibition, although ciprofloxacin had greater action against *Pseudomonas aeruginosa* (38 mm zone). All of these findings support CBD as a low-cost, effective synthesis paradigm for Ag₂O that fills in scalability and environmental sustainability gaps. To fully utilize Ag₂O's diverse applications in the health, environmental, and energy sectors, future research should investigate optimal doping techniques and in vivo cytotoxicity. This will help to advance nanomaterial-based solutions to urgent problems in antimicrobial resistance and sustainable catalysis.

6. Recommendations

- Expand the scope of the study to include additional bacterial strains, particularly multidrug-resistant species, to comprehensively evaluate the antibacterial potential of Ag₂O nanoparticles.
- Investigate the influence of various experimental parameters such as temperature, pH, and precursor concentrations on the particle size, morphology, and antibacterial performance.
- Explore the synthesis of hybrid nanocomposites by combining Ag₂O with other metal oxides (e.g., ZnO, TiO₂) to enhance or diversify antimicrobial activity.



- Assess the biocompatibility and cytotoxicity of the synthesized Ag₂O nanoparticles on mammalian cells to support their safe application in biomedical fields such as wound dressings and antimicrobial coatings.
- Implement the synthesized nanoparticles in real-world systems, such as surface coatings or water filtration units, and evaluate their performance under practical environmental conditions.

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