Antibacterial Performance and Mechanistic Investigation of Cu_2O Nanoparticles for Textile Applications

Junyi Fan

Faculty or Science, Sichuan Agricultural University, Ya'an, 625014, China
Email: fjy202305880@stu.sicau.edu.cn
Manuscript received July 4, 2026; accepted August 1, 2026; published September 23, 2026

***Abstract*—As bacterial resistance rises, developing safe and effective antibacterial materials is a key challenge for public health and functional textiles. Cuprous oxide (Cu_2O) has attracted considerable attention due to its excellent antibacterial activity, low cost, and environmental friendliness. In this study, Cu_2O nanoparticles were synthesized and systematically evaluated for their antibacterial performance and underlying mechanisms. Their morphology, crystal structure, and composition were characterized using scanning electron microscopy (SEM), elemental mapping, X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS). Antibacterial activity was assessed against representative bacterial strains at different concentrations and on textile substrates. Mechanistic studies included biofilm inhibition, nucleic acid leakage, and redox-related assays. The results demonstrated that Cu_2O nanoparticles exhibited concentration-dependent antibacterial effects, effectively inhibiting bacterial growth on textiles, while causing significant membrane disruption and intracellular nucleic acid leakage. These findings indicate that the antibacterial activity primarily arises from cell membrane damage and intracellular leakage, with redox processes contributing to enhanced inactivation. This work provides mechanistic insights into Cu_2O-based antibacterial materials and supports their application in functional textiles.**

***Keywords*—Cu_2O, Antibacterial materials, Membrane disruption, Intracellular nucleic acid leakage, Functional textiles**

I. Introduction

Bacterial contamination on textile surfaces has become an important concern in healthcare and daily-life applications because microorganisms can adhere to fabrics and proliferate under favorable conditions. Such contamination may lead to unpleasant odors, material degradation, and potential risks of cross-infection [1-3]. Thus, the development of antibacterial textile materials has attracted increasing attention in recent years. To improve antibacterial performance, antimicrobial agents have been studied for textiles. Among them, metal and metal oxide nanoparticles have shown considerable potential because of their broad-spectrum antibacterial activity and physicochemical stability [1, 2]. Copper-based nanomaterials, especially cuprous oxide (Cu_2O) nanoparticles, have received attention due to their low cost, abundance, and antibacterial properties [3-5]. Prior studies showed that Cu_2O nanoparticles could inhibit bacterial growth through mechanisms such as membrane disruption, intracellular leakage, metal ion release, and oxidative stress generation [6-8]. However, the dominant antibacterial pathway of Cu_2O nanoparticles remains unclear, particularly in textile-related systems. In addition, studies on the application of Cu_2O nanoparticles in antibacterial textile materials are still limited [7].

This study focused on the synthesis of Cu_2O nanoparticles and the evaluation of their antibacterial performance in both aqueous suspensions and textile materials. It also examined the antibacterial mechanism, with particular emphasis on membrane disruption and the leakage of intracellular contents [9]. The Cu_2O nanoparticles were prepared via a reduction process under alkaline conditions and then characterized using established physicochemical techniques [9, 10]. Their antibacterial efficacy was then tested against representative bacterial strains, while mechanistic analyses assessed membrane integrity and the release of intracellular substances [9, 11]. These results provide insights into the antibacterial behavior of Cu_2O nanoparticles and support their potential use in antimicrobial textiles, directly facilitating the creation of long-lasting, effective, and economically viable materials for healthcare and consumer use.

II. Literature Review

Due to their gentle texture, comfort, capacity to retain moisture, and compatibility with biological tissues, cotton fabrics are among the most widely used textile materials [11]. However, traditional cotton fabrics with a single function are increasingly insufficient to meet the rising demand for high-performance and multifunctional textile products. As a result, surface modification technologies have been widely explored to impart additional functionalities to cotton textiles, including antibacterial, self-cleaning, hydrophobic, catalytic, and biomedical properties [6, 7]. Chemical grafting of small molecular groups, polymers, and nanoparticles onto cotton surfaces has become one of the most effective strategies for functional textile modification [9].

Among these approaches, nanotechnology has attracted considerable attention in textile engineering because nanomaterials possess unique physicochemical properties that are difficult to achieve using conventional materials [12]. The size, morphology, and surface chemistry of nanomaterials can be precisely controlled, enabling improved interaction with microorganisms and enhanced antibacterial performance [12-14]. In antibacterial applications, nanomaterials may exert intrinsic antimicrobial activity through several pathways, including bacterial membrane disruption, nutrient deprivation, photocatalytic antibacterial effects, and immune-related regulation [13, 15].

In addition, nanomaterials can function as delivery carriers that improve the permeability, sustained release behavior, and

targeting ability of antimicrobial agents or polymers. Such characteristics may boost antibacterial stability and improve antibacterial efficiency while reducing the required dosage [15]. More importantly, nanomaterials can be designed to exhibit broad-spectrum antibacterial activity, thereby reducing the likelihood of bacterial resistance development [13, 16]. In addition to their antibacterial properties, nanomaterials can offer other functionalities, including catalytic degradation, hemocompatibility, antifouling effects, enhancement of cell proliferation, and coagulation-related capabilities [17].

The development of antibacterial materials has attracted increasing research attention because microbial contamination remains a major concern in healthcare products, biomedical materials, and textile applications [1-3]. Textile surfaces provide favorable environments for bacterial adhesion and proliferation, which may result in odor formation, material deterioration, and increased risks of infection transmission [1]. Conventional antibacterial treatments based on organic antimicrobial agents and antibiotics often suffer from limited durability and reduced long-term effectiveness, leading researchers to explore alternative inorganic antibacterial materials [2, 13].

Among various antimicrobial materials, metal and metal oxide nanoparticles have been widely investigated due to their unique physicochemical properties and broad-spectrum antibacterial activity [1, 13]. Silver-, zinc-, and copper-based nanoparticles are among the most commonly studied systems [9-12]. While silver nanoparticles exhibit potent antibacterial activity, they tend to be relatively costly, while copper-based nanomaterials provide benefits such as lower cost, greater abundance, and inherent redox properties [1, 13].

Cu_2O nanoparticles have gained attention as effective antibacterial agents due to their reported activity against both Gram-positive and Gram-negative bacteria [8, 15-17]. Prior studies demonstrated that Cu_2O nanoparticles could inhibit bacterial growth and biofilm formation through several possible pathways. These mechanisms include direct interaction with bacterial membranes, release of copper ions, oxidative stress generation, and leakage of intracellular components [14, 17].

Although studies concerning copper-based antibacterial mechanisms remain relatively limited, two major antibacterial pathways have been widely proposed for copper-containing nanoparticles and copper oxide systems. First, copper nanoparticles may directly interact with microbial cell surfaces because bacterial membranes contain functional groups such as amino and carboxyl groups. Microorganisms with higher densities of these functional groups on their cell surfaces may exhibit stronger affinity toward copper nanoparticles, resulting in enhanced antibacterial activity [14]. Second, free Cu^{2+} ions released from copper-based nanoparticles may induce the generation of reactive oxygen species (ROS), which can inhibit DNA replication and amino acid synthesis in microorganisms [12, 14].

Membrane disruption has been considered an important antibacterial pathway because nanoparticle interaction with bacterial cell surfaces may increase membrane permeability and compromise cellular integrity [14]. Reactive oxygen species generated during redox processes may further contribute to bacterial inactivation through oxidative damage to intracellular biomolecules [13, 17].

In addition, recent research has investigated the integration of metal oxide nanoparticles into functional coatings and textile materials to improve sustained antibacterial activity [2, 4, 7, 15, 16]. Despite increasing interest in Cu_2O-based antibacterial systems, the dominant antibacterial mechanism of Cu_2O nanoparticles remains under discussion, especially in textile-related applications where nanoparticle-surface interactions may influence antibacterial activity [17]. Thus, further investigation is still required to clarify the antibacterial behavior of Cu_2O nanoparticles and their suitability for antibacterial textile applications.

III. Materials and Methods

A. Materials

Copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$), L-ascorbic acid, and sodium hydroxide were purchased from Chengdu Kelong Chemical Co., Ltd. (Chengdu, China). Beef extract, peptone, and agar (all BR grade), and sodium chloride (NaCl, 99%), which were used in the preparation of solid culture medium, were provided by Beijing Aoboxing (Beijing, China). All reagents were of analytical grade and used without further purification, and deionized water was used throughout the experiments.

B. Synthesis and Fabrication

The preparation of Cu_2O nanoparticles through a facile and efficient reduction strategy is shown in Fig. 1. Specifically, 1.2785 g of copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$) was dissolved in 50 mL of deionized water under magnetic stirring. The solution was kept in an oil bath at 80 °C and stirred for 10 min to ensure complete dissolution.

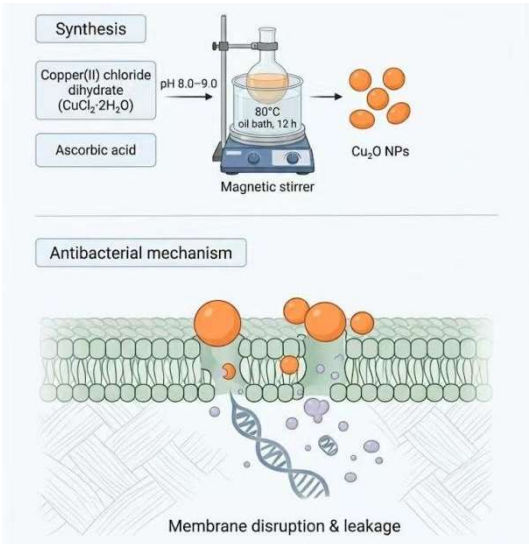


Fig. 1. Synthesis and antibacterial mechanism of Cu_2O NPs.

Subsequently, 50 mL of L-ascorbic acid aqueous solution (100 mmol/L) was added dropwise under continuous stirring. After complete addition, the pH of the reaction mixture was adjusted to 8.0–9.0 using 1 mol/L NaOH solution.

The reaction mixture was kept at 80 °C for 12 h, and the precipitate was then collected by centrifugation (8000 rpm, 5

min), washed with deionized water three times, and dried under vacuum at 60 °C to produce Cu_2O nanoparticles.

The synthesized Cu_2O nanoparticles were applied to cotton fabrics via a dip-coating method for antibacterial performance evaluation. As such, a series of Cu_2O nanoparticle dispersions with different concentrations (0, 0.25, 0.5, and 1 mg/mL) were prepared in deionized water. For each dispersion, ten pieces of pretreated cotton fabric (1 × 1 cm²) were immersed in 50 mL of the solution. The system was maintained in an oil bath at 45 °C for 2 h to facilitate the deposition of Cu_2O nanoparticles onto the cotton fibers.

After treatment, the fabrics were removed and thoroughly rinsed with deionized water to remove loosely bound particles, followed by drying under ambient or controlled conditions to obtain Cu_2O-loaded cotton samples.

C. Physicochemical Characterization

The physicochemical properties of the Cu_2O nanoparticles and Cu_2O-loaded fabrics were characterized using a range of analytical techniques. Morphology, size, and fabric structure were examined with a Zeiss Sigma300 scanning electron microscope (SEM), while energy-dispersive spectroscopy (EDS) mapping of CeO_2 particles was conducted on an FEI Tecnai G2 F20 TWIN transmission electron microscope. Powder X-ray diffraction (XRD) patterns of Cu_2O were recorded with an X-ray diffractometer (DX-2700, Dandong, China), and X-ray photoelectron spectroscopy (XPS) data were collected using a Thermo Fisher ESCALAB 250Xi instrument. In addition, fluorescence spectra were measured with a PerkinElmer fluorescence spectrometer (Llantrisant, UK), and dynamic light scattering (DLS) as well as zeta potential measurements were conducted using a Zetasizer NANO ZS. Finally, photographic images of the samples were captured using an iPhone.

D. Evaluation of Antibacterial Activity

The antibacterial activity of Cu_2O nanoparticles (Cu_2O NPs) was evaluated using the plate counting method. Bacterial suspensions were incubated with Cu_2O NPs at different concentrations for a specified period, followed by colony counting to determine the minimum inhibitory concentration (MIC) and antibacterial rate.

Solid and liquid culture media were prepared as follows. For the solid medium, 1 g peptone, 0.5 g beef extract, 0.5 g NaCl, and 2 g agar were dissolved in 100 mL ultrapure water; for the liquid medium, 1 g peptone, 0.5 g beef extract, and 0.5 g NaCl were dissolved in 100 mL ultrapure water. All materials, including 1.5 mL microcentrifuge tubes, culture media, spreaders, and pipette tips (1000 μL and 200 μL), were sterilized by autoclaving.

After sterilization, the materials were transferred to a laminar flow hood and allowed to cool at room temperature for 30 min. The molten agar medium was then poured into Petri dishes and solidified for approximately 3 h before being inverted and labeled.

Bacterial strains (Escherichia coli and Staphylococcus aureus) were activated by inoculating 100 μL of stock culture into 50 mL of liquid medium and incubating at 37 °C with shaking at 150 rpm for 24 h. The activated cultures were then stored at 4 °C. Subsequently, the bacterial suspensions were diluted to 10^{-6}.

For the antibacterial assay, 80 μL of diluted bacterial suspension was mixed with 80 μL of liquid medium (control group) or 80 μL of nanoparticle suspension (experimental group). The mixtures were incubated at 37 °C with shaking at 150 rpm for 2 h. After incubation, aliquots were spread onto agar plates and further incubated at 37 °C. Colonies of E. coli were counted after 36 h, while S. aureus colonies were counted after 24 h. All biological waste was sterilized before disposal.

The antibacterial performance of cotton fabrics loaded with copper-based nanoparticles was evaluated. Cu_2O NPs and $CuCl_2 \cdot 3Cu(OH)_2$ nanoparticles were deposited onto pretreated cotton fabrics via a dip-coating method, following the same procedure described previously. The treated fabrics were then immersed in 160 μL of liquid culture medium containing bacterial suspensions and incubated under the same conditions as described above. After incubation, the bacterial solutions were spread onto agar plates, and colony formation was assessed to evaluate antibacterial activity.

E. Membrane Integrity and Biofilm Analysis

Membrane integrity and intracellular component leakage were assessed after treatment with (Cu_2O nanoparticles (Cu_2O NPs) using a protein leakage assay and biofilm disruption analysis.

For the protein leakage assay, bacterial suspensions (80 μL) were mixed with an equal volume of Cu_2O NPs suspension and incubated at 37 °C for 12 h under gentle agitation, while PBS served as the control. After incubation, samples were centrifuged at 12,000 rpm for 10 min, and the supernatants were collected. Protein concentration was determined using a BCA assay. Briefly, 20 μL of each supernatant was added to a 96-well plate, followed by 200 μL of BCA working reagent. After incubation at 37 °C for 30 min in the dark, the absorbance was measured at 562 nm. A standard curve was established using protein standards (0-0.5 mg/mL).

For biofilm formation and disruption analysis, Escherichia coli and Staphylococcus aureus were diluted to 10^{-6} and cultured in 96-well plates at 37 °C for 48 h to allow biofilm development, with the medium refreshed every 24 h. The supernatant was then removed, and Cu_2O NP suspension (1 mg/mL) was added. Following treatment, wells were gently washed with PBS to remove planktonic cells.The remaining biofilms were fixed with methanol for 15 min and dried at 60 °C. Then, 0.1% crystal violet was added and incubated for 30 min, followed by washing with PBS. The bound dye was dissolved in ethanol, and the absorbance was measured at 570 nm. All experiments were performed in triplicate.

IV. Results and Analysis

A. Morphology and Surface Characterization

The morphology and composition of the as-prepared Cu_2O nanoparticles were studied by SEM and EDS, as shown in Fig. 2. The SEM image in Fig. 2a shows that the nanoparticles form aggregated clusters, likely due to their high surface energy.

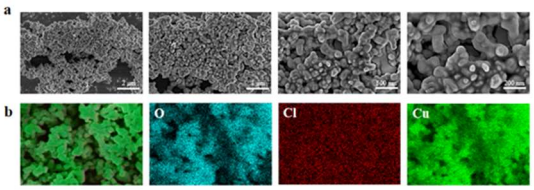
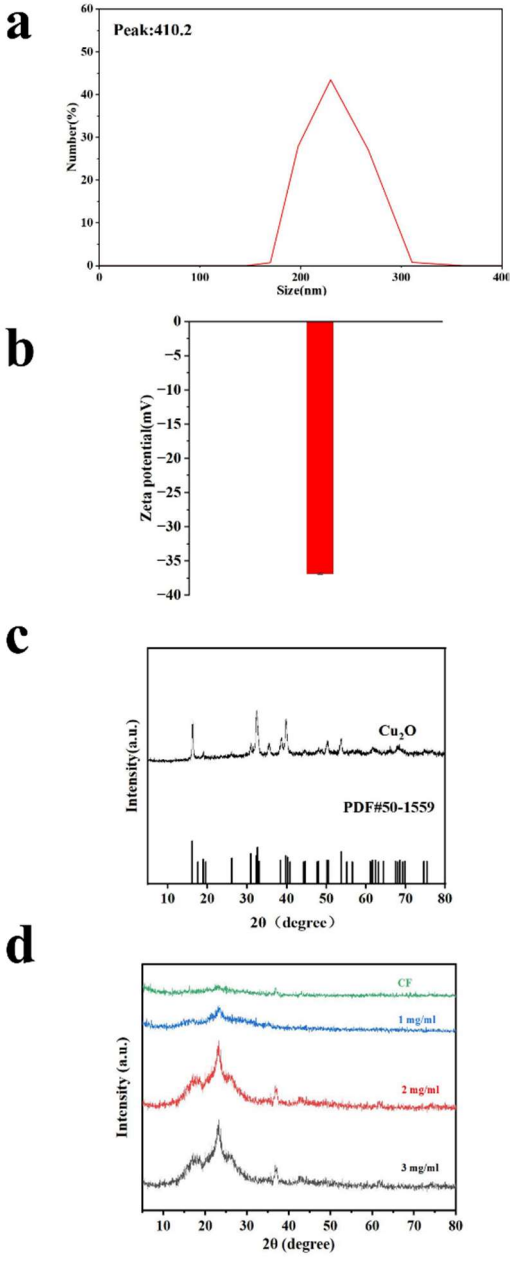


Fig. 2. Morphological and compositional characterization of copper oxide nanoparticles. (a) SEM images of copper oxide nanoparticles at different magnifications. (b) Corresponding EDS elemental mapping images showing the spatial distribution of constituent elements.

The corresponding EDS spectrum and elemental mapping in Fig. 2b confirm that Cu and O are the dominant elements. The Cu and O signals are uniformly distributed throughout the aggregated structures, indicating the successful formation of a homogeneous Cu_2O phase. The atomic ratio of Cu to O is close to 2:1, which is consistent with the stoichiometry of Cu_2O. In addition, a trace amount of Cl (~1.3 at%) is detected, likely from residual precursor species, and is considered negligible for the overall composition.



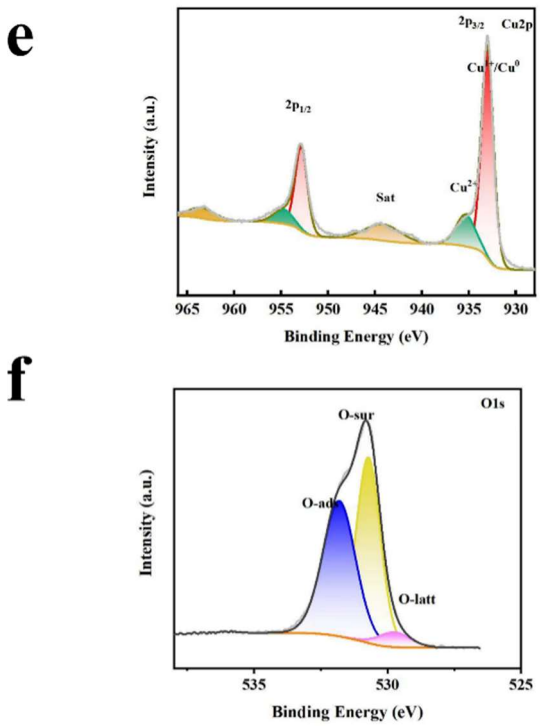


Fig. 3. Characterization of Cu_2O nanoparticles and Cu_2O-modified fabrics. (a) Hydrodynamic size distribution of Cu_2O nanoparticles. (b) Zeta potential of Cu_2O nanoparticles. (c) XRD pattern of Cu_2O nanoparticles. (d) XRD patterns of pristine fabric and Cu_2O-loaded fabrics. (e) High-resolution Cu 2p XPS spectrum of Cu_2O nanoparticles. (f) High-resoluti on O 1s XPS spectrum of Cu_2O nanoparticles.

The colloidal stability and surface charge of the Cu_2O nanoparticles were further characterized by Zeta potential and particle size distribution measurements. As shown in Fig. 3a, the nanoparticles exhibit a Zeta potential of –36.88 ± 0.13 mV in aqueous solution. This highly negative value indicates strong electrostatic repulsion, which effectively prevents aggregation and ensures good colloidal stability. The narrow, symmetric distribution further suggests a uniform surface charge. The particle size distribution in Fig. 3b confirms a relatively narrow size range and good nanoparticle dispersion.

The surface chemical states of Cu_2O loaded on fabrics at different concentrations (1, 2, and 3 mg/mL) were analyzed by X-ray photoelectron spectroscopy (XPS), as shown in Fig. 3c. The XPS spectra confirm the presence of Cu and O elements, with binding energies characteristic of Cu^+ species, consistent with the Cu_2O phase. As the loading concentration increases, the intensity of the Cu 2p peaks rises, indicating a higher amount of Cu_2O deposited on the fabric surface. No obvious Cu^{2+} satellite peaks are observed, thus suggesting that copper mainly exists in the Cu^+ state after immobilization. The crystal structure and phase purity of the as-prepared Cu_2O nanoparticles were characterized by X-ray diffraction (XRD). As shown in Fig. 3c, the XRD pattern exhibits distinct diffraction peaks at 2θ values of 29.6°, 36.5°, 42.4°, 61.5°, and 73.7°, which correspond to the (110), (111), (200), (220), and (311) crystal planes of cubic-phase Cu_2O, respectively. These peaks match the standard JCPDS card No. 05-0667. The sharp, intense diffraction peaks show that the synthesized Cu_2O nanoparticles are highly crystalline. No additional peaks corresponding to impurities like CuO or Cu were detected, confirming the high phase purity. These results indicate that phase-pure, well-crystallized Cu_2O nanoparticles were

successfully synthesized.

The crystal structure and phase composition of the pristine and modified fabrics were investigated by X-ray diffraction (XRD). As shown in Fig. 3d, the pristine fabric (CF) exhibits its characteristic diffraction peaks. After modification with Cu_2O, new diffraction peaks appear at $2\theta = 36.5°$, 42.4°, and 61.5°, corresponding to the (111), (200), and (220) crystal planes of cubic Cu_2O (JCPDS No. 05-0667), respectively. The intensity of these characteristic Cu_2O peaks gradually increases with increasing Cu_2O concentration from 1 mg/mL to 3 mg/mL, indicating a higher loading amount of Cu_2O on the fabric surface. This concentration-dependent enhancement confirms the successful deposition of Cu_2O nanoparticles onto the fabric substrate.

The chemical states of Cu in the as-prepared samples were investigated by X-ray photoelectron spectroscopy (XPS), as shown in Fig. 3e. The Cu 2p spectrum exhibited two main peaks located at approximately 932.5 eV and 952.3 eV, corresponding to Cu $2p_{3/2}$ and Cu $2p_{1/2}$, respectively. The Cu $2p_{3/2}$ peak could be deconvoluted into two components, which were attributed to Cu^+/Cu^0 and a minor amount of Cu^{2+} species. Notably, the dominant peak centered at ~932.5 eV was characteristic of Cu^+, indicating that copper exists mainly in the Cu_2O state. Meanwhile, the weak contribution of Cu^{2+} at a slightly higher binding energy suggested partial surface oxidation of Cu^+ to Cu^{2+}, which is commonly observed due to exposure to air. Besides, a satellite peak (Sat) was observed in the range of 940–945 eV, further supporting the presence of Cu^{2+} species. The XPS results indicated that the synthesized nanoparticles were mainly composed of Cu^+ (Cu_2O), with a small amount of Cu^{2+} on the surface, which may play a role in surface reactivity and antibacterial activity.

The O 1s spectrum of the sample was presented in Fig. 3f. The spectrum could be deconvoluted into three distinct components. The peak centered at ~530.0 eV was assigned to lattice oxygen (O_latt), corresponding to the Cu-O bonds in the Cu_2O crystal structure. The peak at ~531.2 eV was attributed to surface adsorbed oxygen species (O_ads), such as hydroxyl groups or chemisorbed oxygen. The higher binding energy peak at ~532.0 eV was associated with surface oxygen species (O_sur), which might arise from oxygen defects or adsorbed water molecules.

The presence of surface-adsorbed oxygen and oxygen-related defects indicated a relatively active surface, which could facilitate interfacial interactions and contribute to the enhanced antibacterial performance.

B. Concentration-Dependent Antibacterial Performance

The antibacterial activity of Cu_2O nanoparticles was systematically evaluated against Gram-negative Escherichia coli (E. coli) and Gram-positive Staphylococcus aureus (S. aureus) using the spread plate method. As shown in Fig. 4a and Fig. 4b, the control group (0 μg/mL) exhibited dense bacterial colonies on both E. coli and S. aureus plates, indicating normal bacterial growth. With increasing Cu_2O concentration from 62.5 to 500 μg/mL, a progressive reduction in the number of colonies was observed for both bacterial strains. Fig. 4b clearly demonstrates that the antibacterial inhibition rate increased in a concentration-dependent manner. When the concentration reached 1000 μg/mL (1 mg/mL), the inhibition rate approached nearly 100% against both E. coli and S. aureus, with almost no bacterial colonies detected. This shows that Cu_2O anoparticles exhibit strong concentration-dependent antibacterial activity, achieving nearly complete bacterial killing at this concentration.

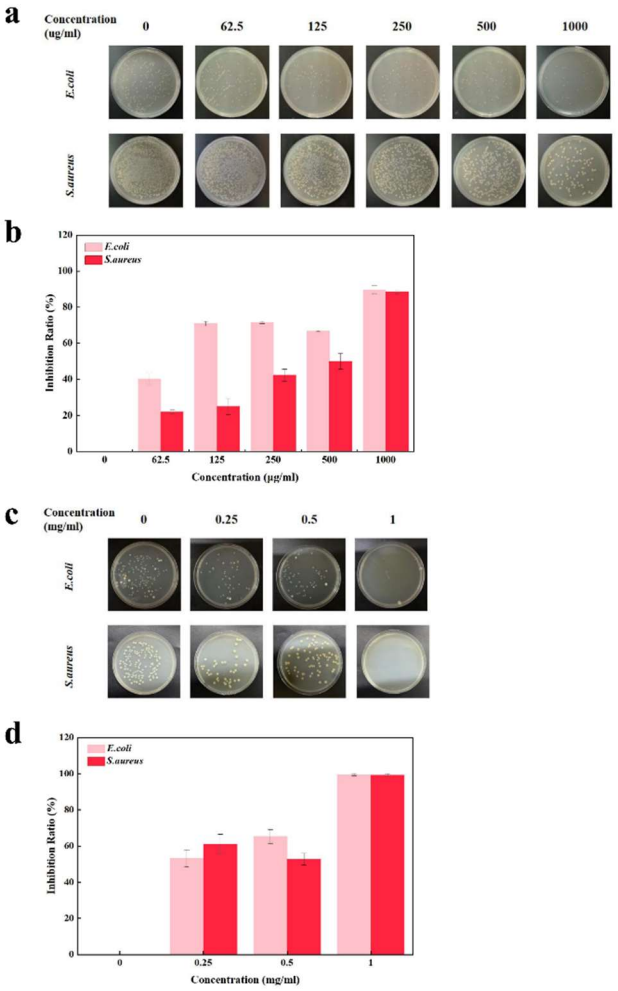


Fig. 4. Antibacterial performance evaluation of Cu_2O nanoparticles. Antibacterial activity of Cu_2O nanoparticle suspensions at various concentrations (0, 62.5, 125, 250, 500, and 1000 μg/mL) against E. coli and S. aureus. (b) Corresponding quantitative analysis presented as bar charts. (c) Antibacterial activity of fabrics loaded with different concentrations of Cu_2O nanoparticles (0.25, 0.5, and 1 mg/mL) against E. coli and S. aureus. (d) Corresponding quantitative analysis shown as bar charts.

To explore their potential for practical applications, Cu_2O nanoparticles were immobilized onto fabric substrates, and the antibacterial performance of the resulting Cu_2O-coated fabrics was evaluated at concentrations of 0.25, 0.5, and 1 mg/mL, as shown in Figs. 4c and 4d. The modified fabric exhibited effective antibacterial activity against both E. coli and S. aureus, significantly reducing bacterial survival compared to the unmodified control. Although complete sterilization was not achieved under the tested conditions (the highest inhibition rate on fabric was slightly lower than that of free nanoparticles), the retained antibacterial function confirms that Cu_2O nanoparticles can be successfully loaded onto fabric surfaces while maintaining their bioactivity.

In summary, Cu_2O nanoparticles demonstrate excellent antibacterial performance against both Gram-negative and Gram-positive bacteria, with a near-complete killing effect at 1

mg/mL. When immobilized onto fabric, the nanoparticles still retain strong antibacterial activity, highlighting their great potential for use in antibacterial coatings and functional textiles. These results confirm that Cu_2O nanoparticles are effective antibacterial agents both in free form and when deposited on fabric surfaces.

C. Antibacterial Mechanism Investigation

The crystal violet staining results in Fig. 5a revealed that Cu_2O nanoparticles effectively inhibited biofilm formation. And biofilm biomass decreased markedly in treated groups compared with the control, suggesting that Cu_2O interferes not only with planktonic bacteria but with early-stage biofilm development.

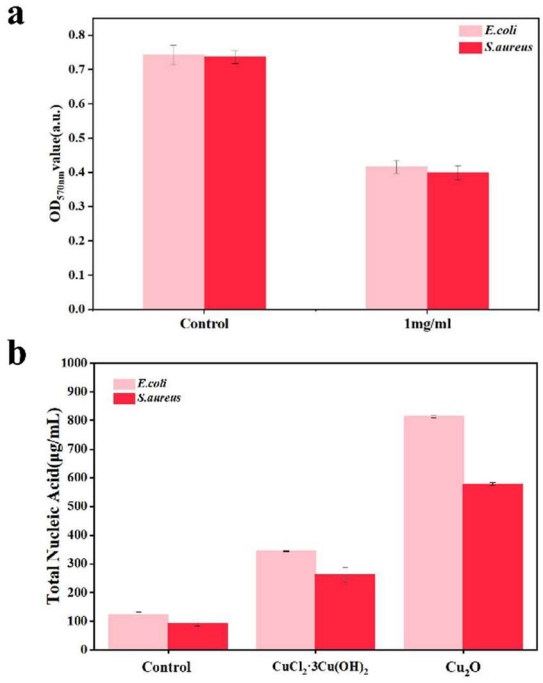


Fig. 5. (a) Crystal violet staining results and (b) nucleic acid leakage analysis of Cu_2O nanoparticle-treated bacteria, demonstrating their biofilm formation and membrane disruption abilities.

In addition, the nucleic acid leakage analysis in Fig. 5b exhibited a significant increase in absorbance at 260 nm in nanoparticle-treated groups, indicating disruption of bacterial membrane integrity and release of intracellular components. Membrane damage appears to be a major factor in bacterial inactivation, as direct interaction between Cu_2O nanoparticles and bacterial cell envelopes likely causes structural destabilization, altered permeability, and eventual cell death.

Based on the results, the antibacterial mechanism of Cu_2O nanoparticles can be summarized as follows. First, direct contact between nanoparticles and bacterial surfaces disrupts the membrane. As a result, increased membrane permeability leads to leakage of nucleic acids and other intracellular components. In addition, surface redox activity may generate localized oxidative stress, further aggravating cellular damage. Together, these effects result in bacterial inactivation. Overall, membrane damage and intracellular leakage appear to be the primary antibacterial pathways, while redox-related processes play a supporting role.

V. Conclusion

This paper presents the synthesis, characterization, and antibacterial evaluation of Cu_2O nanoparticles, as well as their application on textile substrates. The nanoparticles were successfully synthesized and thoroughly characterized, showing well-defined morphology, uniform elemental distribution, and excellent colloidal stability, making them suitable for biomedical and textile-related applications. Antibacterial tests demonstrated potent, dose-dependent activity against both Gram-negative Escherichia coli and Gram-positive Staphylococcus aureus, with significant inhibition also observed on textile surfaces. Mechanistic studies revealed that bacterial inactivation primarily resulted from disruption of membrane integrity, leading to intracellular nucleic acid leakage, while moderate redox activity contributed synergistically rather than serving as the dominant pathway. Furthermore, Cu_2O nanoparticles were successfully loaded onto fabric surfaces, and the resulting coated textiles retained strong antibacterial function, highlighting the feasibility of developing functionalized fabrics for infection control and hygienic applications. Overall, this study systematically established the preparation, characterization, antibacterial evaluation, and mechanistic analysis of Cu_2O nanoparticles, confirming their effective antibacterial performance in both solution and textile systems and highlighting membrane disruption followed by intracellular leakage as the primary antibacterial pathway.

However, several limitations should be acknowledged. First, the long-term stability of Cu_2O nanoparticles on textile substrates under real usage conditions, such as repeated washing, mechanical abrasion, and prolonged environmental exposure, was not fully evaluated. Second, although the antibacterial mechanism was primarily attributed to membrane disruption, the detailed contribution of copper ion release and reactive oxygen species generation was not quantitatively distinguished. Third, the study mainly focused on laboratory bacterial models, and more complex real-world microbial environments were not included.

Future research should focus on improving the durability and binding stability of Cu_2O nanoparticles on textile surfaces through advanced surface engineering strategies such as crosslinking, polymer encapsulation, or hierarchical coating design. In addition, more in-depth mechanistic studies combining quantitative ROS detection, ion release analysis, and molecular-level bacterial response profiling are recommended to further clarify the antibacterial pathways. Finally, future work should extend to practical application scenarios, including long-term washing durability tests and multi-species microbial environments, to better evaluate the real-world applicability of Cu_2O-functionalized antibacterial textiles.

Conflict of Interest

The author declares no conflict of interest.

References

[1] M. Godoy-Gallardo, U. Eckhard, L. M. Delgado, Y. J. D. de Roo Puente, M. Hoyos-Nogués, F. J. Gil, and R. A. Perez, "Antibacterial approaches in tissue engineering using metal ions and nanoparticles: From mechanisms to applications," *Bioactive Materials*, vol. 6, no. 12, pp. 4470–4490, 2021.

[2] B. F. Finina and A. K. Mersha, "Nano-enabled antimicrobial thin films: Design and mechanism of action," *RSC Advances*, vol. 14, pp. 5290–5308, 2024.
[3] C. A. Michael, D. Dominey-Howes, and M. Labbate, "The antimicrobial resistance crisis: Causes, consequences, and management," *Frontiers in Public Health*, vol. 2, 145, 2014.
[4] R. Lu, X. Zhang, X. Cheng, Y. Zhang, X. Zan, and L. Zhang, "Applications of nanomaterials in antibacterial functional textiles," *Frontiers in Chemistry*, vol. 8, 583484, 2020.
[5] N. Li, L. S. Taylor, M. G. Ferruzzi, and L. J. Mauer, "Influence of formulation and processing variables on stability and functionality of nanomaterials," *Journal of Agricultural and Food Chemistry*, vol. 60, pp. 12531–12539, 2012.
[6] Y. Yang, Y. Zhang, L. Wang, Z. Miao, K. Zhou, Q. Yang, J. Yu, X. Li, and Y. Zhang, "Antibacterial property of oxygen-terminated carbon bonds," *Advanced Functional Materials*, vol. 2200447, pp. 1–11, 2022.
[7] W. Li, X. Wang, Y. Wu, M. Chen, and Z. Li, "One-step spontaneous grafting via diazonium chemistry for the fabrication of robust bionic multifunctional superhydrophobic fabric," *Surface and Coatings Technology*, vol. 407, 126802, 2021.
[8] J. Y. Park, S. Lee, Y. Kim, and Y. B. Ryu, "Antimicrobial activity of morphology-controlled Cu_2O nanoparticles: Oxidation stability under humid and thermal conditions," *Pharmaceuticals (Basel)*, vol. 15, no. 8, 968, 2022.
[9] A. Saka, S. R. Dey, L. T. Jule, R. Krishnaraj, R. Dhanabal, N. Mishra, and N. Nagaprasad, "Investigating antibacterial activity of biosynthesized silver oxide nanoparticles using Phragmanthera macrosolen L. leaf extract," *Scientific Reports*, vol. 14, 26850, 2024.
[10] D. Dharmaraj, M. Krishnamoorthy, K. Rajendran, K. Karuppiah, J. Annamalai, K. R. Durairaj, P. Santhiyagu, and K. Ethiraj, "Antibacterial and cytotoxicity activities of biosynthesized silver oxide (Ag_2O) nanoparticles using Bacillus paramycoides," *Journal of Drug Delivery Science and Technology*, vol. 61, 102111, 2021.
[11] S. V. Gudkov, D. A. Serov, M. E. Astashev, A. A. Semenova, and A. B. Lisitsyn, "Ag_2O nanoparticles as a candidate for antimicrobial compounds of the new generation," *Pharmaceuticals (Basel)*, vol. 15, no. 8, 968, 2022.
[12] M. Y. Alkawareek et al., "Synergistic antibacterial activity of silver nanoparticles and hydrogen peroxide," *PLoS One*, vol. 14, e0218763, 2019.
[13] D. Franco, G. Calabrese, S. P. P. Guglielmino, and S. Conoci, "Metal-based nanoparticles: Antibacterial mechanisms and biomedical application," *Microorganisms*, vol. 10, no. 9, 1778, 2022.
[14] S. Meghana, P. Kabra, S. Chakraborty, and N. Padmavathy, "Understanding the pathway of antibacterial activity of copper oxide nanoparticles," *RSC Advances*, vol. 5, pp. 12293–12299, 2015.
[15] O. Długosz, K. Lis, W. Matyjasik, P. Radomski, J. Pulit-Prociak, and M. Banach, "Cu_2O nanoparticles deposited on Y_2O_3 and CuO: Synthesis and antimicrobial properties," *Journal of Cluster Science*, vol. 34, pp. 2153–2165, 2023.
[16] X. Ji, Y. Wu, Y. Han, B. Liang, Y. Cheng, J. Zheng, S. Guo, C. Li, and H. Xu, "Synergistic antibacterial study of nano-Cu_2O/CuO@Ag-tetracycline composites," *Materials Chemistry and Physics*, vol. 306, 127904, 2023.
[17] S. V. Gudkov, D. E. Burmistrov, P. A. Fomina, S. Z. Validov, and V. A. Kozlov, "Antibacterial properties of copper oxide nanoparticles (review)," *International Journal of Molecular Sciences*, vol. 25, no. 21, 11563, 2024.