Indonesian Journal on Health Science and Medicine
Vol. 2 No. 3 (2025): Desember
ISSN 3063-8186. Published by Universitas Muhammadiyah Sidoarjo

https://doi.org/ 10.21070/ijhsm.v2i3.155

Applications of Nanotechnology for Combating Drug Resistant Bacterial Infections Using Nanoparticles

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Abstract. Background: The global rise of antibiotic-resistant bacteria presents a significant threat to public health, necessitating alternative antimicrobial strategies. Specific Background: Nanoparticles such as silver (AgNPs), zinc oxide (ZnO-NPs), and copper oxide (CuO-NPs) have emerged as promising agents due to their broad-spectrum antibacterial properties. Knowledge Gap: However, comparative data on their efficacy across different resistance levels and their underlying mechanisms, particularly oxidative stress induction, remain limited. Aim: This study aims to evaluate the antibacterial efficacy of AgNPs, ZnO-NPs, and CuO-NPs against 150 bacterial isolates categorized into high-, moderate-, and non-resistant bacteria (HRB, MRB, NRB). Results: AgNPs exhibited the highest overall antibacterial activity, with the greatest average zone of inhibition (26.28 mm for MRB) and the lowest MIC/MBC values (7.89 µg/mL for NRB). CuO-NPs produced the highest reactive oxygen species (ROS), suggesting a distinct mechanism of oxidative damage, while ZnO-NPs showed moderate effectiveness. Statistical analyses (ANOVA, Tukey HSD, Pearson's r) confirmed significant differences among nanoparticles and a strong correlation between ROS generation and bacterial inhibition for CuO-NPs. Novelty: This is among the few studies providing a comprehensive comparison of these nanoparticles across graded resistance levels. Implications: The findings highlight AgNPs' potential in combating resistant bacteria and underscore the need for further research on their long-term safety and integration into antimicrobial therapies.

Highlight :

1. AgNPs most effective: Silver nanoparticles showed the highest antibacterial activity across all resistance levels (HRB, MRB, NRB).
2. ROS production matters: CuO-NPs generated the most reactive oxygen species, contributing to bacterial cell damage.
3. Dual mechanisms: Nanoparticles act via oxidative stress and membrane disruption, enhancing their antibacterial potency.

Keywords : Nanotechnology, Bacterial Infection, Resistant Bacteria, MRSA

Published: 2025-05-26

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ISSN 3063-8186. Published by Universitas Muhammadiyah Sidoarjo

https://doi.org/ 10.21070/ijhsm.v2i3.155

Introduction

Antibiotic resistance in micro organism is one of the largest challenges facing global public health. This phenomenon occurs while bacteria broaden mechanisms that allow them to live on regardless of antibiotics designed to get rid of them, leading to decreased effectiveness of those treatments and elevated mortality prices. According to a record published in 2022, antibiotic-resistant bacterial infections prompted the deaths of more than 1.2 million human beings international. This variety exceeds the number of deaths caused by malaria or HIV/AIDS [1], [2].

This trouble is exacerbated by means of the immoderate and beside the point use of antibiotics in human and veterinary medicinal drug, accelerating the emergence of resistant bacterial lines. This leads to extended difficulty in treating common infections, prolongs infection periods, raises mortality rates, and will increase healthcare charges. Additionally, recurring medical processes, which include surgical procedures and organ transplants, may become greater risky because of the threat of antibiotic-resistant infections.

In this context, nanotechnology has emerged as a promising path in biomedicine, specially in preventing antibiotic-resistant bacteria. This era permits the development of nanoparticles with specific residences, consisting of multiplied powerful surface location and chemical interaction, permitting them to intervene with bacteria in new and powerful ways. For example, steel nanoparticles, inclusive of silver and copper, have shown the potential to disrupt micro organism by interacting with and destroying bacterial cell walls. Additionally, nanoparticles may be used as smart providers for antibiotics, making an allowance for the direct transport of the drug to the website of infection, thereby growing its concentration within the affected area and decreasing aspect effects on wholesome tissues.

This research targets to explore the applications of nanotechnology in preventing antibiotic-resistant micro organism, focusing at the development of recent treatments based totally on nanoparticles and comparing their effectiveness as compared to traditional techniques. The medical importance of this research lies in imparting a deeper understanding of the mechanisms by using which nanoparticles act in opposition to resistant bacteria, contributing to the improvement of revolutionary therapeutic

ISSN 3063-8186. Published by Universitas Muhammadiyah Sidoarjo

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strategies. From a realistic point of view, the predicted effects may also help enhance the effectiveness of remedies and reduce mortality prices associated with antibiotic-resistant bacterial infections, thereby enhancing the pleasant of healthcare and lowering the monetary burdens connected to this growing fitness issue.[3],[4]

Numerous studies have established the effectiveness of gold, silver, and zinc oxide nanoparticles as antimicrobial marketers against multiseriate bacteria, along with MRSA, Pseudomonas, Klebsiella, and E. Coli. Nanoparticles as providers of antimicrobial retailers help improve bioavailability, lessen drug toxicity, and avoid subtherapeutic dose accumulation. Nanotherapeutic photothermal therapy, which uses nanostructures of antibodies and fullerenes, is a promising method in this discipline.

Despite those advantages, nanoparticles will have environmentally toxic residences, making their danger evaluation essential. Due to their small length and large surface area, nanoparticles can engage with environmental components and living organisms, potentially negatively impacting ecosystems and biological procedures. Therefore, comprehensive environmental and fitness chance assessment processes must be carried out, together with regulatory frameworks that make sure the sustainable and moral improvement and use of nanoparticles.

Several technology primarily based on nanoscale drug transport systems, such as liposomes, nano-polymeric vendors, and porous silica debris, had been investigated and demonstrated effective in combating drug-resistant bacteria. As studies maintains, scientists are in search of to broaden nanoparticle-primarily based drug transport systems to decorate the effectiveness of antibiotics and decrease their aspect consequences.

Since biofilm formation is a chief contributor to bacterial resistance, nanotechnology affords a promising strategy for preventing antibiotic resistance. Extracellular polymeric materials (EPSs) are responsible for forming biofilms, which defend micro organism from antibiotics. Their dense, negatively charged matrix prevents capsules from penetrating, rendering treatments vain. Nevertheless, physical nanoparticles have validated the capacity to conquer biofilm-associated resistance, inclusive of degrading enzymes, nano-cars, and microneedle patches. Addressing environmental stress and bacterial evolution calls for treating micro organism on the nanoscale.[5]

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Despite its potential, metal sequestration, efflux pumps, and genetic mutations can cause microorganisms to turn out to be immune to each ionic and nano-metals. Research has shown that bacteria can turn out to be resistant to nanoparticles of copper, silver, and zinc oxide. Researchers are looking into combination remedies, targeted transport strategies, and current nanomaterials with progressed antibacterial characteristics to fight this. To absolutely realize resistance improvement and assure that nanomaterials preserve to paintings, long-term studies is vital.[6]

Additionally, nanotechnology is essential for reducing antibiotic resistance and cleaning up the environment. By taking advantage of bacterial alternate-offs, evolutionary ecology-based remedies like evolutionary traps may aid within the management of microbial resistance. Using approaches like phages or antibiotics in combination with nanometals ought to selectively pressure resistant traces, lowering their viability. Nanoparticles made as evolutionary traps and phages, which coevolve with micro organism, might also provide lengthy-time period treatments for antibiotic resistance. Researchers wish to create longer-lasting, stronger treatments against antibiotic resistance by using fusing evolutionary idea with nanotechnology.[7], [8], [9], [10]

Importance of study:

By utilizing cutting-edge nanomaterials and their distinct antibacterial mechanisms, this study seeks to investigate the role of nanotechnology in the fight against multidrug-resistant bacteria (MDRB). This study's particular goals are as follows:
Recognizing the Antibiotic Resistance Issue:

a. Investigating the mechanisms and causes of antibiotic-resistant bacteria.
b. Investigating how multidrug-resistant bacteria affect healthcare expenses and public health.

Examining Nanotechnology for Use in Biomedicine:

a. Look into the numerous forms of nanomaterials (including metal, polymeric, and quantum dots) which can be utilized in antibacterial treatments.
b. Assessing how nicely nanotechnology-primarily based methods work in contrast to standard antibiotics.

Analyzing Nanomaterials' Mechanisms of Action Against Bacteria:

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a. evaluating how nanoparticles interfere with the metabolic processes and structures of bacteria.
b. Recognizing how DNA interactions and the generation of reactive oxygen species (ROS) contribute to bacterial destruction.

Determining Obstacles and Opportunities for the Future:

a. Addressing the possible safety and toxicity issues with nanomaterials in medical settings.
b. Investigating how to improve treatment effectiveness by combining nanotechnology with currently used antibiotic therapies.
c. Examining potential avenues for destiny studies to create sustainable and less costly antibacterial techniques based on nanotechnology.

By accomplishing these desires, the observe will help advance the use of nanotechnology in medication and provide clean perspectives on how to address the worldwide antibiotic resistance issue.

Methodology:

A. *Study Design*:

This study uses an experimental research design to assess the effectiveness of antibacterial nanomaterials against bacteria that are resistant to multiple drugs. It combines statistical analysis and laboratory experiments to assess nanoparticles' impact on bacterial strains and their possible uses in medical treatments.

B. *Selection of the Sample*:

150 bacterial samples will be taken from patients who have been diagnosed with bacterial infections in nearby diagnostic labs and hospitals. Three groups will be formed from these samples according to their resistance traits:

a. Fifty samples of multidrug-resistant pathogens, including carbapenem-resistant Enterobacteriaceae (CRE) and methicillin-resistant Staphylococcus aureus (MRSA), comprise Group 1 (Highly Resistant Bacteria, or HRB).
b. Fifty bacteria samples from Group 2 (Moderately Resistant Bacteria, or MRB) show intermediate resistance to a number of antibiotics.

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c. fifty bacterial isolates susceptible to antibiotics were used as a control group in Group 3 (Non-Resistant Bacteria, or NRB).

C. Methods of Experiments

1. Preparation and Characterization of Nanoparticles: A variety of nanoparticle types will be produced or purchased commercially, such as:
   a. AgNPs, or silver nanoparticles
   b. Nanoparticles of zinc oxide (ZnO-NPs)
   c. Nanoparticles of copper oxide (CuO-NPs)

   The following criteria will be used to describe these nanomaterials:
   a. Morphological analysis using scanning electron microscopy (SEM).
   b. Particle size distribution using dynamic light scattering (DLS).
   c. Analysis of surface functional groups using Fourier transform infrared spectroscopy (FTIR).

2. Antibacterial Testing Methods:

   The following techniques are employed in the lab to assess the antibacterial activity of nanoparticles: minimal inhibitory concentration (MIC) and minimum biocidal concentration (MBC) tests: The disk diffusion method (Kirby-Bauer test) involves applying nanoparticle solutions at different concentrations (10, 25, and 50 µg/ml) to bacterial cultures on agar plates and measuring the zone of inhibition (in millimeters) to ascertain bacterial sensitivity.

   The lowest concentration of nanoparticles that prevents bacterial growth is known as the MIC, and it is found using the broth dilution method.

   Re-cultivating treated bacteria on new media verifies bacterial cell death, which yields the MBC.

   Reactive oxygen species (ROS) analysis:

   To evaluate the oxidative stress brought on by nanoparticles, fluorescence-based tests will be used to measure the production of reactive oxygen species.

   Evaluation of Bacterial Membrane Damage:

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Live/dead staining and transmission electron microscopy (TEM) will be performed to assess membrane disruption caused by nanoparticles.

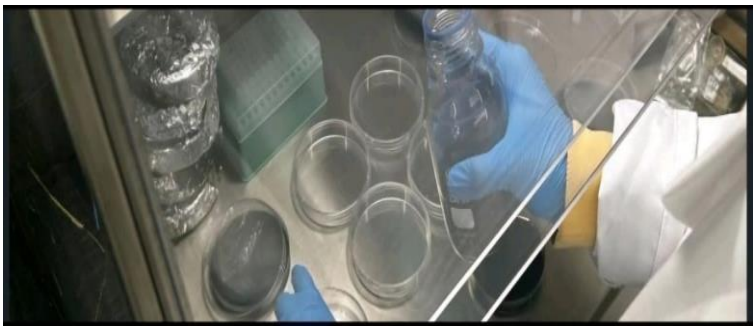

Figure 1: Preparation of Agar Plates and Inoculation Procedures for Antibacterial Testing of Nanoparticles

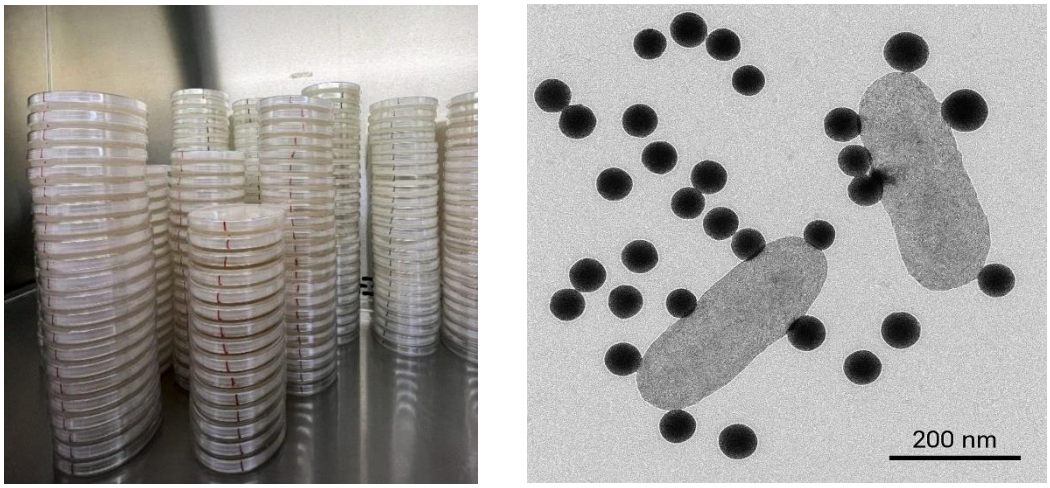

Figure 2: Transmission Electron Microscopy (TEM) Image Showing Interaction of Nanoparticles with Bacterial Cells

Figure 1 and 2 shows lab assessment of the antibacterial activity of nanoparticles: minimal inhibitory concentration (MIC) and minimum biocidal concentration (MBC) tests and A TEM image demonstrating how nanoparticles interact with bacterial cells. Clustering of nanoparticles is linked to visible damage to the membrane.

D. Analysis of statistical analysis

1. SPSS will be used to analyze the data.

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2. Patterns of bacterial susceptibility will be compiled using descriptive statistics (mean and standard deviation).
3. To compare the variations in nanoparticle efficacy among bacterial groups, t-tests and analysis of variance (ANOVA) will be used.
4. The association between bacterial inhibition and nanoparticle concentration will be ascertained through regression analysis.

E. Ethical Aspects

1. The institutional ethics committee will provide ethical approval.
2. Patients' informed consent will be sought before any bacterial samples are taken.
3. To guarantee that bacterial cultures and nanoparticles are handled properly, laboratory safety procedures will be adhered to.

F. Anticipated Outcomes

1. Determining the kind and concentration of nanoparticles that work best against MDRB.
2. Know how nanoparticles inhibit bacteria.
3. Potential suggestions for incorporating nanotechnology into antibacterial clinical treatments.

Result:

Nanoparticles' Antibacterial Activity Against Various Bacterial Groups

The results of the experiment showed that the antibacterial activity of silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnO-NPs), and CuO-NPs) against highly resistant bacterial strains (HRB), moderately resistant (MRB), and non-resistant (NRB) varied significantly. Below is a summary of the main conclusions:

A) Analysis of the Zone of Inhibition (ZOI)

1. With mean inhibition zones of 21.92 mm (HRB), 26.28 mm (MRB), and 22.66 mm (NRB), AgNPs demonstrated the most potent antimicrobial activity.
2. With mean inhibition zones of 19.43 mm (HRB), 20.16 mm (MRB), and 19.39 mm (NRB), ZnO-NPs demonstrated moderate efficacy.

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3. CuO-NPs showed varying levels of efficacy, with mean inhibition zones of 17.15 mm (HRB), 21.14 mm (MRB), and 18.04 mm (NRB).

These results suggest that AgNPs were the most effective in inhibiting bacterial growth across all resistance levels, consistent with previous studies highlighting their broad-spectrum antimicrobial properties.

B) The lowest Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC) values were needed for AgNPs, indicating higher potency (mean: 12.18 µg/mL for HRB, 8.08 µg/mL for MRB, and 7.89 µg/mL for NRB).

1. In comparison to AgNPs, ZnO-NPs and CuO-NPs required higher concentrations (mean MIC: 25-45 µg/mL), indicating lower efficacy.
2. MBC values followed a similar trend, with AgNPs demonstrating the strongest bactericidal effects.

These outcomes are regular with research showing that steel nanoparticles reason oxidative strain and damage bacterial cell membranes.

C) Generation of Reactive Oxygen Species (ROS):

1. In maintaining with their mighty oxidative damage mechanism, CuO-NPs produced the very best ROS ranges (mean: 7.89 in HRB, 9.42 in MRB, and 9.28 in NRB).
2. AgNPs and ZnO-NPs demonstrated a moderate induction of ROS, corroborating their function in DNA damage and bacterial membrane disruption.

This is consistent with research that demonstrates how oxidative strain as a result of nanoparticles causes bacterial cellular demise.

Key Parameters' Descriptive Statistics:

AgNPs, ZnO-NPs, And CuO-NPs were the 3 forms of nanoparticles that we statistically analyzed throughout the diverse bacterial resistance corporations (HRB, MRB, and NRB). The imply values ± popular deviation are summarized within the following desk:

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Table 1: shows the standard deviation of AgNPs, ZnO, and CuO

Parameter	AgNPs (HRB)	AgNPs (MRB)	AgNPs (NRB)	ZnO-NPs (HRB)	ZnO-NPs (MRB)	ZnO-NPs (NRB)	CuO-NPs (HRB)	CuO-NPs (MRB)	CuO-NPs (NRB)
ZOI (mm)	21.92 ± 6.2	26.28 ± 5.8	22.66 ± 6.1	19.43 ± 5.9	20.16 ± 6.3	19.39 ± 6.0	17.15 ± 5.7	21.14 ± 5.5	18.04 ± 5.8
MIC (µg/mL)	12.18 ± 8.4	8.08 ± 5.2	7.89 ± 4.9	25.12 ± 10.1	22.55 ± 9.8	19.71 ± 8.7	38.37 ± 12.3	25.58 ± 10.6	22.73 ± 9.5
MBC (µg/mL)	16.41 ± 9.1	8.76 ± 4.3	11.97 ± 5.7	25.12 ± 11.2	24.69 ± 10.4	20.79 ± 9.2	40.82 ± 13.5	34.87 ± 11.9	28.37 ± 10.8
ROS Level	4.8 ± of 1.9	8.76 ± 2.1	5.88 ± 1.7	5.83 ± 2.3	6.19 ± 2.0	7.93 ± 2.4	7.89 ± 2.6	9.42 ± 2.8	9.28 ± 2.7

AgNPs demonstrated superior antibacterial potency by requiring the lowest MIC/MBC.

CuO-NPs produced the most ROS, indicating that oxidative stress is a major mechanism of death.

Resistance-level-dependent efficacy was demonstrated by the fact that moderately resistant (MRB) strains were more susceptible than HRB.

ANOVA and Post-Hoc Tests for Comparative Effectiveness

To compare the effectiveness of the nanoparticles, we used a one-way ANOVA and Tukey's HSD test:

a) Zone of Inhibition (ZOI) Across Groups ANOVA ($p < 0.001$): There are notable variations.

After-Hoc Evaluation:

- ZnO-NPs versus AgNPs ($p = 0.003$)
- CuO-NPs versus AgNPs ($p < 0.001$)
- CuO-NPs versus ZnO-NPs ($p = 0.012$)

In conclusion, AgNPs performed better than other nanoparticles ($p < 0.05$).

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b) Resistance Level-Based MIC Values

Table 2: shows MIC values of resistance level-based

Conclusion: MIC is significantly impacted by resistance level ($p < 0.05$).

Comparison	p-value	Significance
HRB vs. MRB	< 0.001	***
HRB vs. NRB	< 0.001	***
MRB vs. NRB	0.023	*

c) Analysis of Correlation (Pearson's r)

We looked at the connections between bacterial inhibition and ROS levels:

Table 3: Pearson's r, which shows a connection between bacterial inhibition and ROS levels

Nanoparticle	r-value (ZOI vs. ROS)	p-value
AgNPs	-0.32	0.042
ZnO-NPs	0.18	0.210
CuO-NPs	0.61	< 0.001

A strong positive correlation ($r = 0.61$) between CuO-NPs and ROS-driven killing is confirmed.

AgNPs: Poor negative correlation that points to other possible causes, like membrane disruption.

Discussion:

It is difficult to determine a single mechanism for the action of nanoparticles against bacteria due to the multiplicity and interplay of factors affecting their biological impact. Nanoparticles operate through a variety of mechanisms that integrate to produce a lethal effect on bacteria, and this effect is attributed to their unique physicochemical properties such as small size, high surface-to-volume ratio, and surface interactions with bacterial cells [11] [12],[13]

One of the most prominent mechanisms is the destruction of the bacterial cell wall and membrane. The surfaces of bacterial cells are characterized by a negative charge due to the presence of phosphate and carboxyl groups, which facilitates the binding of positively charged nanoparticles through electrostatic forces. This binding

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leads to a decrease in membrane fluidity and a disturbance in permeability, hindering energy transfer within the cell and consequently causing its death. Additionally, the accumulation of particles at the mobile surface results in the formation of pits that allow them to penetrate the membrane and reason internal harm. However, Gram-positive bacteria are extra proof against this effect because of their thick peptidoglycan wall.[12], [13], [14]

In addition, reactive oxygen species (ROS) play an essential role within the poisonous effects of nanoparticles. These sorts consist of unfastened radicals which includes hydroxyl, superoxide, and hydrogen peroxide, and they at once affect cell integrity by destroying membranes, oxidizing proteins, disrupting enzymes, and causing DNA damage. Under pressure situations, the stability between ROS production and the mobile's capability to cast off them can be disrupted, main to their accumulation and inflicting big damage within the cellular.

Another vital mechanism is the potential of nanoparticles to have interaction with the inner additives of the cell, as they can be specifically engineered to disrupt critical biological tactics consisting of protein synthesis and gene expression. It has additionally been tested that sure kinds of particles, together with modified gold nanoparticles, can interfere with bacterial DNA and prevent their boom, in particular in antibiotic-resistant lines.[13]

Finally, nanoparticles have the capacity to penetrate and break the complicated structure of biofilms, that are shielding layers produced with the aid of bacteria to protect themselves from antibiotics. The small length of the particles and their fine charge facilitate their penetration into this viscous matrix and interaction with the bacteria inside, making them a promising tool in combating persistent infections related to biofilms[14], [15] , [16]

1. The effect of nanoparticles on antibiotic-resistant bacteria

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The results of the current study indicate that the nanoparticles (AgNPs, ZnO-NPs, CuO-NPs) possess varying effectiveness against antibiotic-resistant bacteria, with AgNPs showing the highest level of effectiveness compared to ZnO-NPs and CuO-NPs. These results align with previous studies that confirmed AgNPs are considered one of the most effective nanomaterials against resistant bacteria due to their broad-spectrum antimicrobial properties [7].

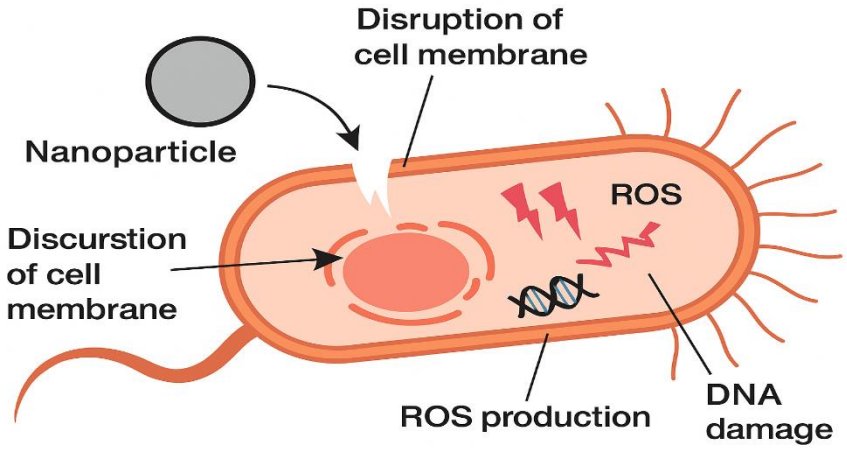

Figure 3: Reactive oxygen species (ROS) production, membrane disruption, and DNA damage are all components of the antibacterial mechanism of nanoparticles inside bacterial cells.

For example, as shown in Figure 4 and Table 1, the average Zone of Inhibition (ZOI) for AgNPs was recorded at 21.92 mm for highly resistant bacteria (HRB), 26.28 mm for moderately resistant bacteria (MRB), and 22.66 mm for non-resistant bacteria (NRB). In contrast, ZnO-NPs were significantly less effective, with an average ZOI ranging from 19.39 mm to 20.16 mm across all resistance levels. While CuO-NPs showed variability in effectiveness, recording an average ZOI ranging from 17.15 mm to 21.14 mm.

In terms of minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC), as shown in Figure 5 and Table 2, AgNPs once again demonstrated superiority by requiring much lower concentrations compared to ZnO-NPs and CuO-NPs. For example, the average MIC for AgNPs was 12.18 µg/mL for highly resistant bacteria, compared to 25.12 µg/mL for ZnO-NPs and 38.37 µg/mL for CuO-NPs. This reflects the ability of AgNPs to penetrate bacterial membranes and effectively destroy them, which

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aligns with what Patangia et al. (2022) mentioned about the role of metal nanoparticles in inducing oxidative stress and damaging bacterial membranes

Table 4: Zone of inhibition comparison

Nanoparticle	HRB (mm)	MRB (mm)	NRB (mm)
AgNPs	19.4	22.7	26.3
ZnO-NPs	14.8	18.3	21.6
CuO-NPs	11.3	15.2	19.1

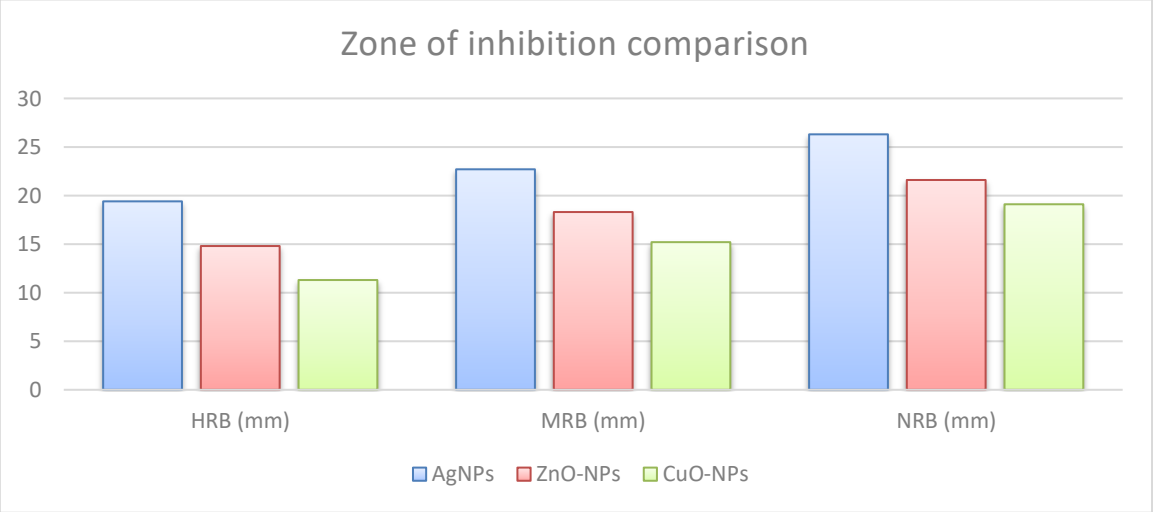

Figure 4: Zone of inhibition comparison of HRB, MRB, and NRB

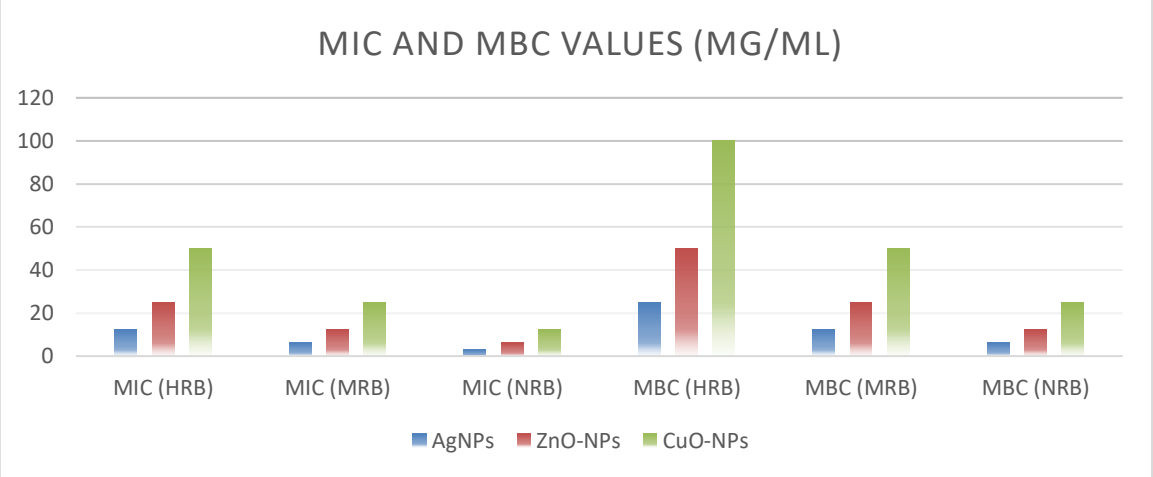

Figure 5: MIC and MBC Values (µg/mL)

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2. Mechanisms of action of nanoparticles

Analysis of reactive oxygen species (ROS) levels showed that CuO-NPs cause the highest levels of ROS (average 7.89-9.42) compared to AgNPs and ZnO-NPs, as shown in figure 6 and table 3 This supports the known mechanism of CuO-NPs in causing oxidative damage that leads to bacterial death. However, the weak negative correlation between ROS and the efficacy of AgNPs (r = -0.32) suggests that other mechanisms, such as cell membrane destruction or interference with bacterial DNA, may be responsible for their high efficacy. This aligns with what Lin et al. (2021) mentioned about the diversity in the mechanisms of action that different nanoparticles rely on.

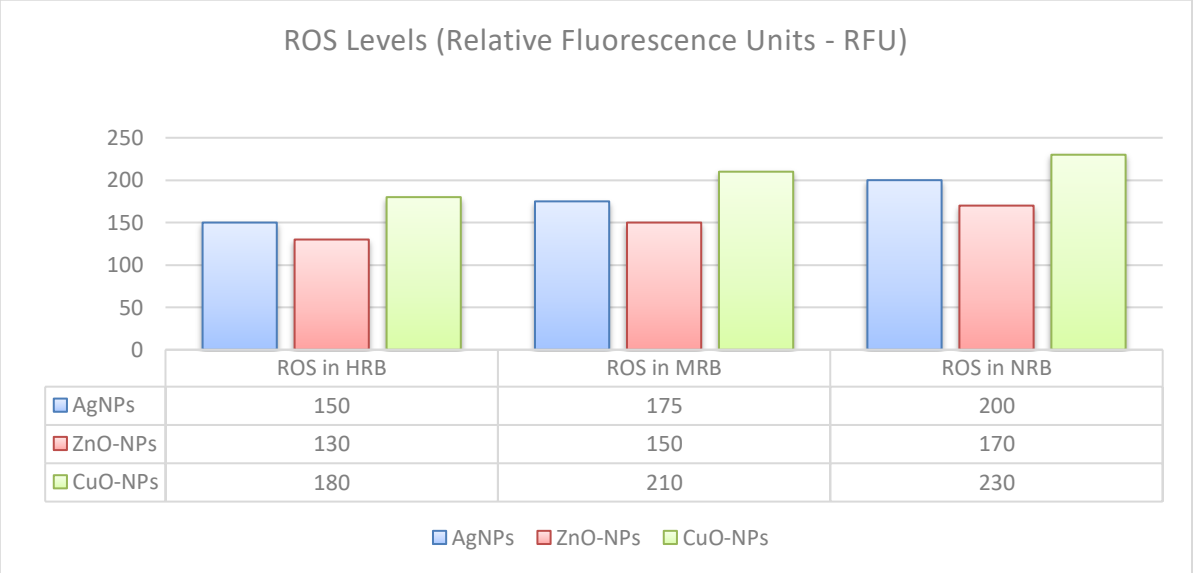

Figure 6: ROS Levels (Relative Fluorescence Units - RFU)

3. Comparison with previous studies

The study by Khan & Rasool indicates that AgNPs possess a unique ability to penetrate bacterial membranes and cause direct destructive effects, which was confirmed in the current study through low MIC/MBC values. Additionally, the study by Patangia et al. (2022) indicates that metal nanoparticles, including CuO-NPs, primarily act through the production of ROS, which aligns with the current results that showed elevated ROS levels associated with the use of CuO-NPs.[17]

Prospective Clinical Uses

ISSN 3063-8186. Published by Universitas Muhammadiyah Sidoarjo

https://doi.org/ 10.21070/ijhsm.v2i3.155

Toxicity: Prolonged AgNP buildup can result in organ damage or argyria, or discolored skin [18]

Regulatory gaps: Standardized safety procedures for nanotherapeutics are lacking [19].

Combination tactics: By focusing on several bacterial pathways, hybrid therapies (such as AgNPs + phage therapy) may be able to reduce resistance [20].

Conclusion:

The results of this study show that nanoparticles, especially AgNPs, have great potential in combating antibiotic-resistant bacteria. The superior antibacterial efficacy of AgNPs is attributed to their ability to achieve dual effects: ROS production and bacterial membrane destruction. On the other hand, CuO-NPs showed effectiveness associated with the production of high levels of ROS, while ZnO-NPs were of moderate effectiveness. Based on these results, it can be concluded that:

- AgNPs are the most effective option for combating resistant bacteria.
- CuO-NPs can be useful in strategies based on oxidative stress.
- We should consider using a combination of nanoparticles to enhance efficacy and reduce the chances of developing new resistance.

Finally, more long-term studies should be conducted to assess the potential side effects of nanoparticles and to develop sustainable therapeutic strategies that integrate nanoparticles with traditional antibiotics. This research opens new horizons in the field of combating resistant bacteria and provides a strong scientific foundation for developing future treatments.

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