Letters in Applied NanoBioScience
Open-Access Journal (ISSN: 2284-6808)

Article
Volume 14, Issue 3, 2025, 146
https://doi.org/10.33263/LIANBS143.146

Multifunctional Barium-Nickel Ferrite Nanoparticles: Structural Characterization and Antibacterial Mechanisms

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Received: 27.06.2024; Accepted: 11.04.2025; Published: 6.09.2025

Abstract: The provided abstract discusses two different studies related to the properties and applications of nanoparticle ferrites. The first study investigated the X-ray diffraction (XRD) analysis of $BaNi_2Fe_{16}O_{27}$ samples and their Zn-substituted counterparts. The study found that the replacement of Ni ions with Zn ions resulted in a rise in the lattice constants and a rise in a and c. This is a result of the crystal lattice expanding as a result of the larger ionic radius of Zn^{2+} ions. Additionally, the investigation verified that the samples had formed W-type with a single-phase crystalline formation in a hexagonal arrangement. In the second investigation, zinc-ion-doped barium-nickel ferrite nanoparticles were examined for their antibacterial properties. The investigation revealed that the nanoparticles demonstrated suppression of microorganisms that are two gram-positive and two gram-negative, with a higher impact on *Pseudomonas aeruginosa*. The antibacterial activity was related to the nanoparticle size, microstructure, and particular area on the surface, allowing for greater microbial surface contact and leading to greater H_2O_2 generation and increased antimicrobial activity. The study also discussed the underlying antimicrobial mechanism, which includes the generation of intracellular reactive oxygen species, disruption of cell membranes, and protein leakage. NPs have appealing antibacterial capabilities because of their higher specific surface area and improved particle surface reactivity brought about by their smaller particle size. The results of these investigations improve our knowledge of the characteristics and potential applications of nanoparticle ferrites in nanotechnology and biomedical fields.

Keywords: nanoparticle ferrites; gram-positive; gram-negative; antibacterial activity; antimicrobial mechanism; biomedical applications.

1. Introduction

The application of nanoparticles in the medical sciences, particularly in the areas of anticancer, antifungal, antivirus, and antibacterial applications, has been a subject of recent research. The overuse of antibiotics has led to a reduction in their effectiveness against bacterial pathogens, prompting researchers to explore alternative approaches such as the use of nanoparticles of ferrites as antibacterial agents [1]. Metal oxides, including zinc (Zn), nickel (Ni), and barium (Ba), have been extensively studied for their ferromagnetic characteristics and potential use in biomedical applications. These materials have shown promise in various applications, such as cancer therapy, antibacterial activity, and cancer diagnostics. Ferrites, specifically metal ferrite nanoparticles, are attractive for biomedical applications due to their unique properties, including a wide surface area, biocompatibility, small size, and superior magnetic characteristics. The large surface area of these nanoparticles allows for interaction with bacterial cells, leading to significant antibacterial activity. The high biocompatibility and antibacterial properties of these materials make them promising candidates for various biomedical uses [2,3]. `

Size alterations in nanoparticles can result in altered chemical, structural, optical, and electrical characteristics, opening up new possibilities for their use [4].

For instance, reducing nanoparticles to a nanometer size has been found to increase their antibacterial activity. In antibacterial applications, nanoparticles with reduced toxicity, improved stability, decreased resistance, and good selectivity are desirable. A recent focus on the use of nanoparticles in medicine has led to extensive research on the potential use of zinc-doped barium-nickel ferrites as antibacterial agents. Barium ferrite, a ferromagnetic material, possesses exceptional magneto-crystalline anisotropy, high magnetic saturation, good electrical resistance, and exceptional chemical stability [5,6]

The magnetic characteristics of these materials are strongly influenced by their synthesis routes, with common examples including co-precipitation, sol-gel synthesis, polarizable complex method, and ceramic process. The crystal structure of barium hexaferrites is entirely determined by the distribution of cations, and recent research has focused on replacing Ba^{2+} or Fe^{3+} sites with ions such as Ce^{3+}, Co^{2+}, Ni^{2+}, and Zr^{4+} [7]. Studies have demonstrated the potential of zinc-doped barium-nickel ferrites as antibacterial agents, with significant antibacterial activity reported in recent research. The larger surface area and small size of nanoparticles enhance their antibacterial effectiveness against both gram-positive and gram-negative bacteria. The potential applications of zinc-doped barium-nickel ferrites as antibacterial agents are significant, and further research in this area holds promise for the development of effective antibacterial treatments. Cations such as Cu^{2+}, Zn^{2+}, and Ba^{2+} have been identified as essential for human health and good antibacterial sanitizers. These cations bind to bacterial cell walls, leading to DNA degradation, inhibition of protein synthesis, and ultimately the lysis of bacterial cells [8-10].

The antibacterial efficacy of ferrite nanoparticles is influenced by their size. Ultrafine magnetic nanoparticles have been shown to readily infiltrate bacterial cells, interact with the membranes of cells, induce oxidative stress, and cause DNA damage. The toxicity of ferrite nanoparticles against bacteria also hinges upon surface manipulation, inherent structural, chemical, and physical characteristics, as well as on doping agents utilized for dispersing the NP. Studies have demonstrated that the antibacterial effectiveness of ferrite nanoparticles is independent of their size. For instance, research on cobalt ferrite nanoparticles has shown size-dependent antimicrobial properties, highlighting the importance of nanoparticles' size in their antibacterial effectiveness. Studies on metal-substituted spinel ferrite nanoparticles, such as nickel ferrite doped with titanium (Ti) and copper (Cu), have also revealed that the size and composition of the nanoparticles significantly impact their antibacterial activity, with smaller nanoparticles exhibiting enhanced antibacterial properties. Additionally, research on nickel ferrite doped nanoparticles of α-alumina indicates that nanoparticle size influences their antibacterial effects, with ultrafine magnetic nanoparticles demonstrating the ability to infiltrate bacterial cells and induce oxidative stress, leading to DNA damage. These findings collectively support the notion that the size of ferrite nanoparticles is a critical determinant of their antibacterial activity [11-13].

The integration of magnetic materials with inherent antibacterial properties holds promise for biomedical applications. A specific study aimed to synthesize zinc-metal doped $BaNi_{x-2}Zn_xFe_{16}O_{27}$ nanoparticles, with varying values of x (0.0, 0.4, 0.8, 1.2, 1.6, and 2), to evaluate their potential for antibacterial applications. The results demonstrated significant antimicrobial activity of the developed zinc-doped barium nickel ferrite nanoparticles against Staphylococcus aureus and Escherichia coli bacterial strains [14].

2. Materials and Methods

The study employed the ceramic approach to synthesize barium-nickel base nanoparticles of ferrite doped with zinc. Based on their molecular weight ratio, the starting components Barium carbonate (BaCo3), zinc oxide (ZnO), nickel oxide (NiO), and iron oxide (Fe_2O_3) were interlarded together to form different compositions of $BaNi_{2-x}Zn_xFe_{16}O_{27}$. The synthesis procedure for the preparation of nanoparticles is described in detail elsewhere [14,15].

To assess the antibacterial efficacy of the nanoparticles, both dimethyl sulfoxide (DMSO) and complexes were employed against two types of bacteria: The aeruginosa bacterium as gram-negative and the bacterium *B. subtilis* as gram-positive. The agar well diffusion method was utilized, whereby a pure isolate with 24-hour growth was cultured on Muller-Hinton Agar plates using a sterile swab to achieve complete coverage. Subsequently, after the plates had dried, an antiseptic cork punch with an 8 mm diameter was employed to create wells in each agar plate. A micropipette was used to apply 20 µL of each compound, at a concentration of 200 µg/mL, into the wells on the Muller-Hinton Agar plate. Following the application, the plates were allowed to rest for at least 1 hour to ensure adequate diffusion, after which, for twenty-four hours, they were incubated at 37℃. The plates were incubated for twenty-four hours at 37℃. In the agar well diffusion methodology is significant for several reasons. Firstly, this temperature and duration are optimal for the growth of a wide range of pathogenic and non-pathogenic bacteria commonly used in laboratory settings. This allows for the accurate assessment of the antibacterial activity of the compounds being tested. Additionally, this duration allows for the observation of any potential bacteriostatic or bactericidal effects of the compounds, as well as the measurement of the diameter of the inhibition zones.

Furthermore, this standard incubation period ensures that the results obtained are consistent and comparable with those of other studies, thereby facilitating the interpretation and validation of the findings. All compounds' antibacterial activity was assessed by calculating the diameter of the inhibitory zones encircling the wells. This measurement provided an estimate of the extent of bacterial growth inhibition. The test was performed in triplicate and the mean diameter of the inhibition area was found in order to have a reliable assessment evaluation of the antibacterial effect.

3. Results and Discussion

The $BaNi_2Fe_{16}O_{27}$ samples showed well-ordered crystalline structures of hexagonal W-type, a single-phase crystalline structure, according to X-ray diffraction (XRD) examination. Lattice parameters such as a and c increased when Zn was substituted for Ni, and this is because the higher ionic radius of Zn^{2+} ions caused the crystal lattice to expand. The rise of the lattice constant is consistent with earlier research and Vagurd's law. The samples' creation of the W-type hexagonal structure is further supported by the c/a values that fit within the acceptable range. Using the formula $V= 0.8666*a^2c$, the unit cell volume, V, was estimated from the XRD data, and results are presented in Table 1. These results advance our knowledge of $BaNi_2Fe_{16}O_{27}$'s structural characteristics and possible uses in nanotechnology [16]. The crystalline structure and phase identification of the $BaNi_{2-x}Zn_xFe_{16}O_{27}$ samples with varying zinc content (x = 0.0, 0.4, 0.8, 1.2, 1.6, and 2) are presented in Figure 1, which shows their corresponding XRD patterns compared to the reference JCPDS card (00-54-0097).

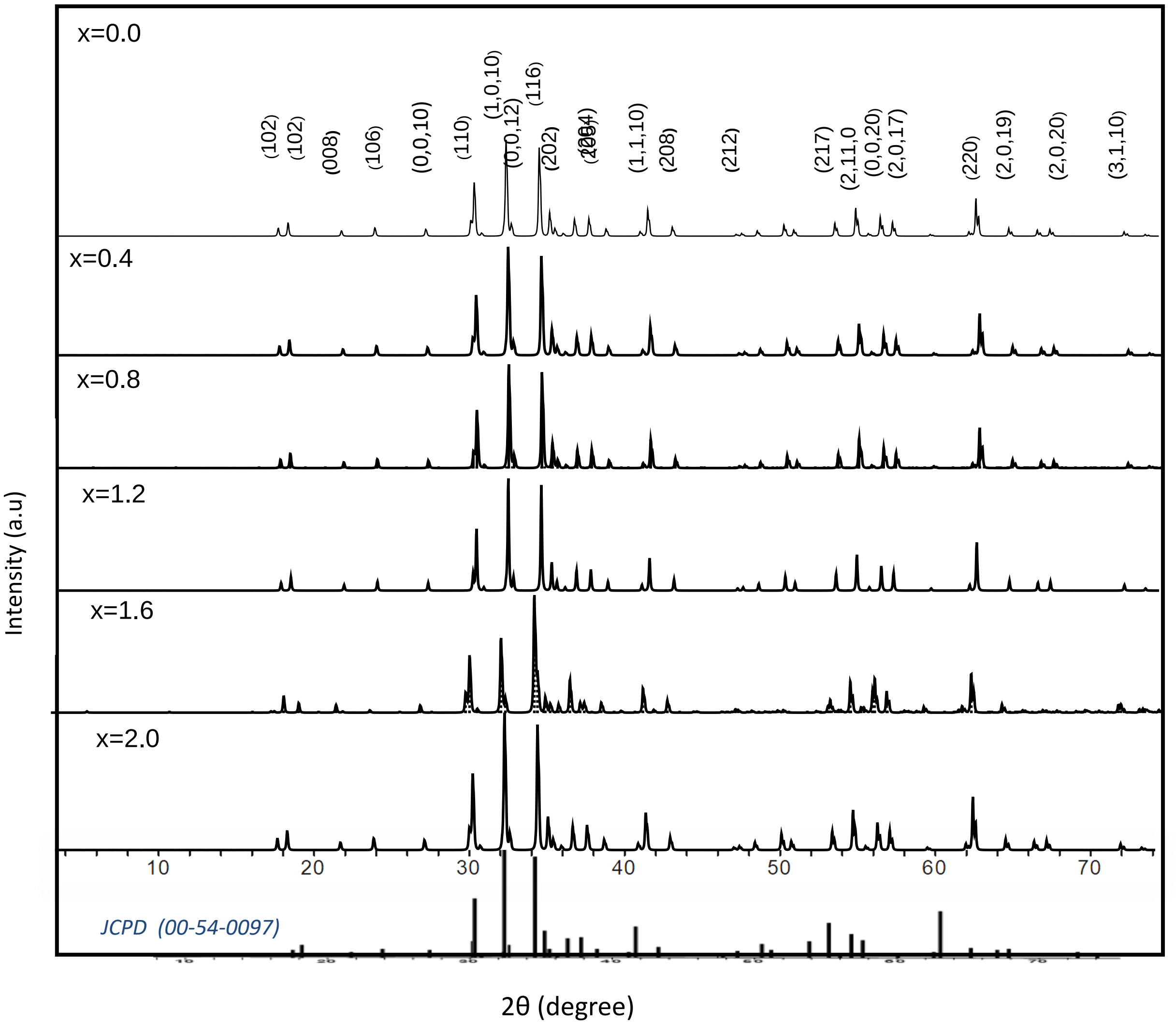

Figure 1. XRD pattern of $BaNi_{2-x}Zn_xFe_{16}O_{27}$ (x= 0.0, 0.4, 0.8, 1.2, 1.6, and 2) with 2θ (degree) JCPD card (00-54-0097)

The presence of well-defined hexagonal W-type single-crystalline structures in samples of BaNi2Fe16O27 was confirmed by the XRD analysis indicated in Figure 1. Substitution of Ni by Zn caused the lattice peaks to shift to the left of the chart, signifying an increase in lattice parameters a and c. The increase in lattice parameters is due to the fact that higher-ionic-radius Zn^{2+} ions replaced lower-ionic-radius Ni^{2+} ions in the crystal lattice, thereby causing it to expand.The X-ray diffraction (XRD) analysis of the prepared sample revealed that using non-magnetic ions for doping changed the typical crystallite's diameter and amount of surface area, resulting in an increased specific area of the surface. More contact with the microbial surface is possible due to this large specific surface area, which is significant for antimicrobial properties. The nanoparticles' tiny size and high specific surface area, along with the hexagonal structure, enable more contact with the microbial surface, leading to greater H_2O_2 generation and increased antimicrobial activity [17,18]. The size of nanoparticle ferrites is significant for their antimicrobial properties. Smaller nanoparticles have a greater effect on cell uptake and toxicity, leading to increased antibacterial activity. Metal ferrite nanoparticles, including cobalt ferrite and nickel ferrite, have substantial antibacterial activities, and their biocompatibility makes them appropriate for antibacterial uses. The specific surface area of iron oxide nanoparticles is high, allowing for interaction with the bacterial surface, and their small size enables faster particle uptake by bacterial cells.

Table 1. Microstructural parameters: lattice constant, volume, density, particle size, and specific surface area.

Compositions (x)	a (nm)	c (nm)	Volume (nm^3)	X-ray density (g/cm^3)	particle size (nm)	SSA (m^2/g)
0	0.5975	3.2734	1.01273	5.298	35.531	31.873
0.4	0.5976	3.2737	1.01316	5.29	35.181	32.239
0.8	0.5978	3.2759	1.01452	5.2498	35.814	31.912
1.2	0.598	3.2784	1.01597	5.2492	36.376	31.422
1.6	0.5981	3.2877	1.01919	5.2434	36.501	31.349
2	0.5997	3.2899	1.02534	5.216	36.664	31.374

The antibacterial activity of ferrites is partially shown for tests at different concentrations. The nanoparticles' small dimensions and increased specific area of the surface allow for more interaction with the microbiological surface, which is significant for antimicrobial properties [19]. Nanoferrites' antibacterial activity is attributed to the cations' affinity to proteins. The internalization and biological activity of nanoparticles, including their bactericidal potential, can be impacted by a number of variables, including charge on the surface, size, and form. Notably, nanoparticles with a smooth surface have a higher probability of interacting with the bacterial cell wall. Furthermore, spherical nanoparticles with smaller sizes have demonstrated enhanced antibacterial activity, surpassing that of larger counterparts [1-3; 19,20]. Therefore, the diffraction peaks' shift to the left when Zn is substituted for Ni in the $BaNi_2Fe_{16}O_{27}$ structure is significant as it correlates with the modification of the typical surface area and size of crystalline particles, all of which are related to the antimicrobial properties of the nanoparticles.

The antibacterial performance of barium-nickel nanoferrite powder was assessed against Bacillus subtilis and other Bacillus speciessubtilis, *Bacillus strains* that possess Gram-positive bacteria, using the agar well diffusion method, and Gram-negative bacteria, *Pseudomonas aeruginosa*, were identified. The study aimed to develop nanotechnology-based antibacterial agents to mitigate the growth and impact of these harmful bacteria in water systems. The optimal concentration of the Barium-Nickel nanoferrites powder was determined by varying its mass concentration ratio to the solvent (DMSO) to achieve the most effective antibacterial activity. The measurement of the diameter of inhibition is displayed in Table 2, while the area of inhibition is displayed in Figure 2 as a result of the antibacterial activities.

The antibacterial effects of zinc-ion-doped Ba-Ni nanoferrites against Bacillus subtilis (gram-positive) were assessed based on the area and diameter of the inhibition zone. Additionally, utilizing three different quantities, the minimal inhibitory concentration (MIC) was ascertained. Among the samples tested, which (Zn = 0.4) at a 3 mL volume exhibited the highest antibacterial activity versus Bacillus subtilis, resulting in an inhibition zone diameter of 18.2 mm. This is due to the large surface area and small particle size.

The antibacterial facet of zinc oxide nanoparticles (ZnO NPs) is due to their high surface area and small size,which allows them to effectively inhibit the growth of various bacteria. The study of ZnO NPs against bacterial strains such as *E. coli*, *P. aeruginosa*, *S. aureus*, and others has demonstrated their robust antibacterial activity [3,5,18,21]. The high surface area-to-volume ratio of ZnO NPs enables them to act as effective antimicrobial agents, making them a focus of research in this field. The impact of the size of particles on ZnO antibacterial activity has been studied, and improved antibacterial action has been found to be correlated with reduced particle sizes [22]. Therefore, the ZnO sample with a particle size of 0.4 at a 3 mL volume exhibiting the highest antibacterial activity against *Bacillus subtilis* is consistent with the findings related to the impact of particle size on antibacterial activity.

These research results have potential applications in medicine. It is commonly known that *B. subtilis* can contaminate hospital implants, which can result in dangerous infections [23]. In the second order, the sample (Zn0.8), with a 16.8 mm zone of obstruction, the test specimen $BaNi_{1.2}Zn_{0.8}Fe_{16}O_{27}$ had considerably better antibacterial activity at concentrations of 1.5 and 3 mg/mL, as shown in Figure 2 and Table 2. The results of this study agreed with the research results of Reddy et al. [24], indicating that *B. subtilis* and *E. coli* were detected at 1 mg mL^{-1} and 3.4 mg mL^{-1}, respectively [25].

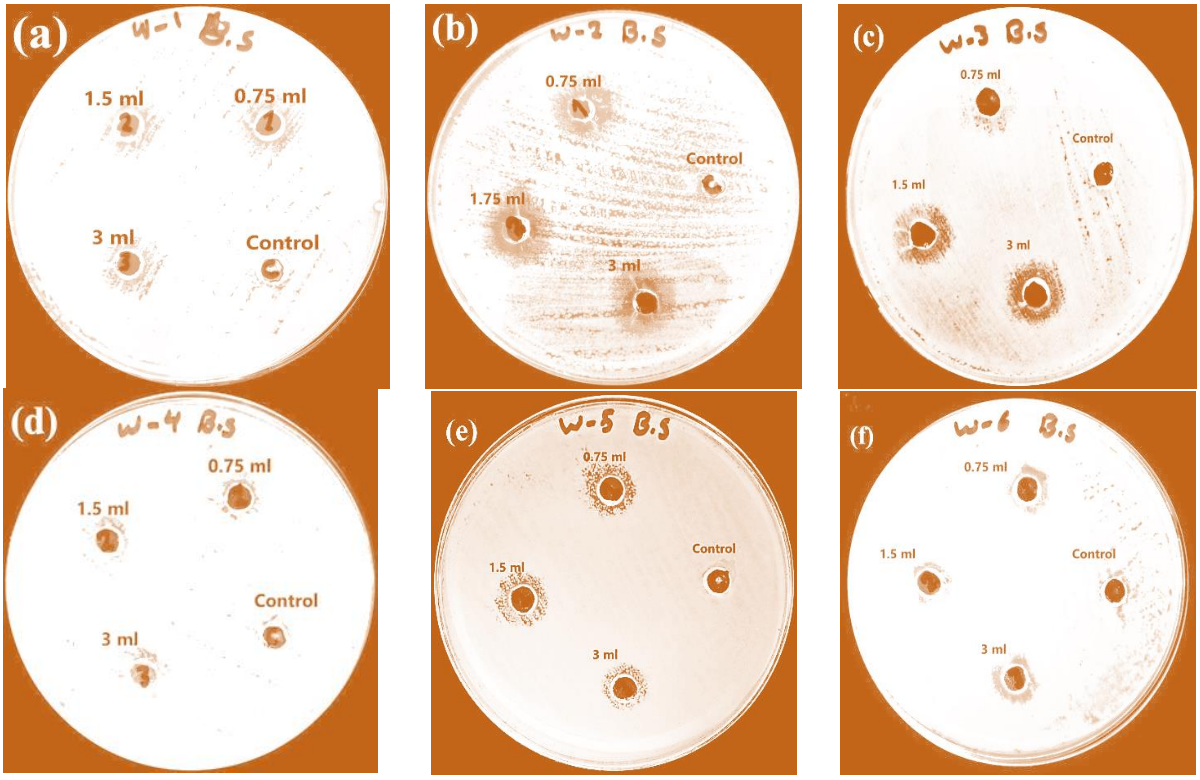

Figure 2. Zones of inhibition *Bacillus subtilis*.

Table 2. Diameter zones of inhibition of *Bacillus subtilis*.

Concentration	**0.75 ml**	**1.5 ml**	**3 ml**
Compositions (x)	**Diameter zones of inhibition mm**		
0	15	15.2	14
0.4	17	16	18
0.8	15	17	17
1.2	9	12	14
1.6	13	14	12
2	14	15	17

Additionally, $BaZn_2Fe_{16}O_{27}$ at a volume concentration of 3 mg/mL reveals a 16 mm zone of obstruction. The results indicated that the nanoparticle size, crystal size, and the presence of specific ions influenced the antibacterial activity against *Bacillus subtilis* [26].

The study conducted further investigation on the antibacterial activity of zinc-ion-doped Barium-Nickel ferrite (Ba-Ni-ZnO) nanoparticles, particularly against *Pseudomonas aeruginosa* and *Bacillus subtilis*. The results demonstrated that the sample with a zinc (Zn) concentration of 0.4 at a 3 mg/mL volume exhibited significant antibacterial activity, resulting in a substantial inhibition zone of 30 mm against *Pseudomonas aeruginosa*, as shown in Figure 3 and Table 3. These findings highlight the influence of specific ions and the characteristics of the nanoparticles, such as their surface area and particle size, on their antibacterial efficacy [27-29].

The study also discussed the mechanisms of antibacterial properties of the prepared nanoferrite samples, such as the generation of reactive oxygen species (ROS) and chemical reaction of metal ions with the membranes of bacteria.. The search results provided additional information about the ability of zinc oxide nanoparticles to damage bacterial cell walls, prevent bacterial cell formation, and block protein synthesis, thereby enhancing their antibacterial activity[21, 27-28].

The antibacterial properties of the zinc-ion-doped barium-nickel ferrite nanoparticles were investigated for potential use in water treatment, aiming to address common infections caused by hazardous bacteria in polluted water systems. The study demonstrated significant antibacterial efficacy against *Pseudomonas aeruginosa* and *Bacillus subtilis*, with the sample $BaNi_{1.6}Zn_{0.4}Fe_{16}O_{27}$ showing the most effective antibacterial activity. The findings also emphasized the influence of nanoparticle size, surface area, and the presence of specific metal ions on the nanoparticles' antimicrobial qualities[27,30]. In summary, the results of the study provided valuable insights into the significant antibacterial activity of the zinc-ion-doped barium-nickel ferrite nanoparticles against both gram-positive and gram-negative bacteria, highlighting their potential for various biomedical applications as effective antibacterial agents.

The antibacterial properties of barium-nickel ferrite nanoparticles, particularly when doped with zinc ions, have been examined for use in the biological sciences and the treatment of water. The results of the study demonstrated that the nanoparticles exhibited relatively strong antibacterial action against microorganisms classified as bacteria-positive and gram-negative bacteria, with the sample $BaNi_{1.6}Zn_{0.4}Fe_{16}O_{27}$ showing the most effective antibacterial activity. The study also discussed the mechanisms of antibacterial activity, highlighting the influence of nanoparticle characteristics, such as size, surface area, and the presence of specific metal ions, on their antibacterial properties.

According to the search findings, zinc-doped barium-nickel ferrite nanoparticles have potent Antimicrobial capabilities versus *Escherichia coli* and *Staphylococcus aureus*, among other gram-positive and gram-negative pathogens. The results also imply that these nanoparticles' larger surface area and small crystallite size may increase surface reactivity, which boosts antibacterial activity. These results highlight the potential of these nanoparticles for various biomedical applications. The studies provide valuable insights into the antibacterial properties of zinc-doped barium-nickel ferrite nanoparticles and their potential for addressing bacterial contamination in diverse settings, including water systems.

In comparison to traditional antibiotics, the antibacterial properties of barium-nickel ferrite nanoparticles, especially when doped with zinc ions, show promise because of their possible use in the purification of water and biomedical sciences. The increased surface area of the nanoparticles is responsible for their enhanced antibacterial action and very small crystallite size, and their significant antibacterial effects make them promising candidates for various practical applications, including the development of novel water treatment technologies and biomedical products with enhanced antibacterial properties. More study is required to comprehend and maximize the potential uses of these nanoparticles completely.

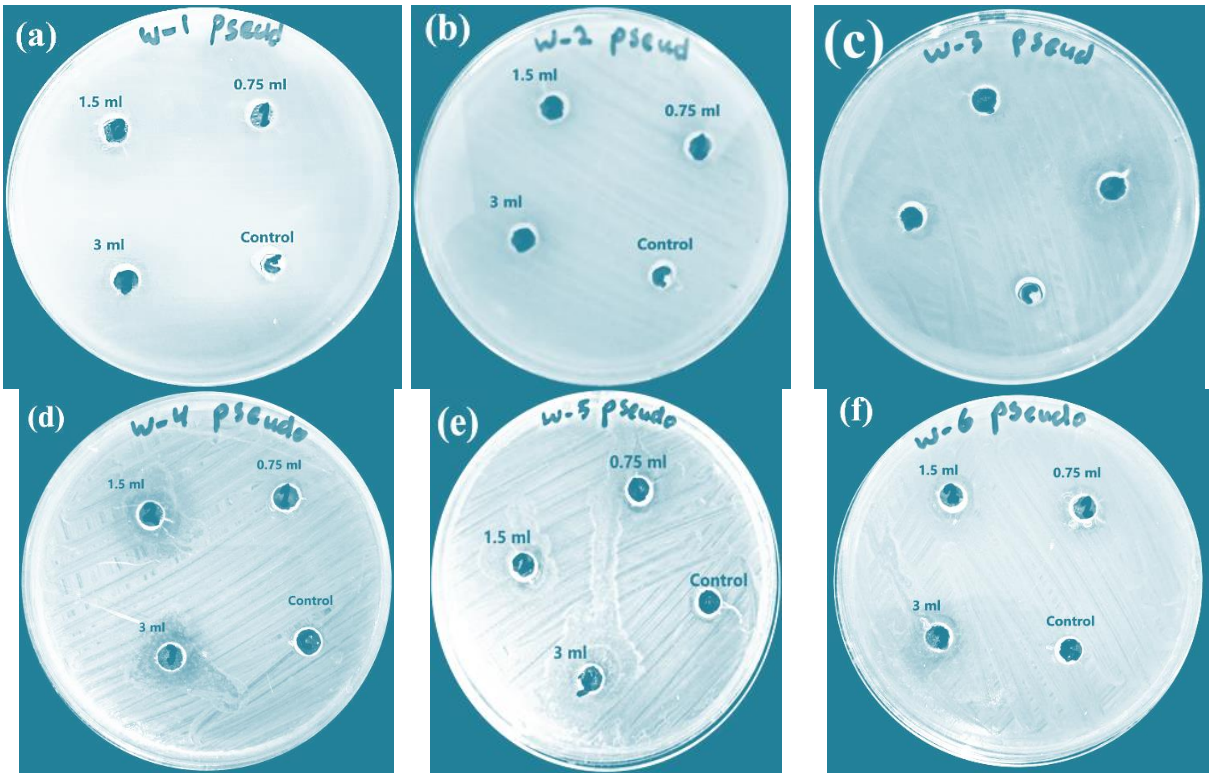

Figure 3. Zones of inhibition of *Pseudomonas aeruginosa*.

Table 3. Diameter zones of inhibition of *Pseudomonas aeruginosa*.

Concentration	**0.75 ml**	**1.5 ml**	**3 ml**
Compositions (x)	**Diameter zones of inhibition mm**		
0	21	25	20
0.4	20	25	30
0.8	13	19	20
1.2	12	18	20
1.6	13	18	22
2	12	13.5	16

4. Conclusions

The purpose of the study was to assess the bactericidal properties of zinc-doped barium-nickel ferrite nanoparticles against the gram-positive *B. subtilis* and gram-negative *P. aeruginosa* bacteria. Study results showed that the particles did not affect Bacillus subtilis growth. On Pseudomonas aeruginosa, however, they demonstrated a strong antibacterial action with a 30 mm inhibition zone diameter. The $BaNi_{1.6}Zn_{0.4}Fe_{16}O_{27}$ sample, which contained zinc at a concentration of 0.4, demonstrated the maximum inhibition zones against both Pseudomonas aeruginosa and Bacillus subtilis. The findings underscore the potential of these nanoparticles for biomedical applications, particularly in addressing bacterial contamination in water systems. The search results provide comprehensive insights into the antibacterial characteristics and potential of Zn ions-doped barium-nickel ferrite nanoparticles for medical applications. In addition, the study offered a tenable explanation for how Zn^{2+} NPs arise, which corroborated the findings. In conclusion, the work offers insightful information about the possible applications of barium-nickel ferrite nanoparticles doped with zinc ions as effective antibacterial agents for water treatment. The results are consistent with existing literature, which emphasizes the potential of these nanoparticles for various biomedical applications, including their significant antibacterial effects.

The antibacterial activity of nanoparticles is influenced by several factors, such as the size of the nanoparticle, surface area, and the presence of specific metal ions. In general, nanoparticles with smaller crystallite sizes exhibit higher activity against bacteria compared to those with larger crystallite sizes. Metal nanoparticles have been observed to interact with membrane proteins, causing damage to the bacterial membrane. Moreover, the biological interactions between nanoparticles and macromolecules can inhibit microbial growth. The metal content within the nanoparticle core is also a crucial determinant of their antibacterial activity. The search results provide a comprehensive overview of the antibacterial properties of metal-based nanoparticles, highlighting their potential for various biomedical applications. The studies emphasize the significance of comprehending the principles underlying metal nanoparticles' antibacterial activity, particularly in the context of addressing bacterial resistance and developing effective antimicrobial agents.

The creation of zinc-doped barium-nickel ferrite nanoparticles has proven to have potent antibacterial properties against the bacteria *Bacillus subtilis* as well as *P. aeruginosa*, among other bacteria. This significant antibacterial activity positions these nanoparticles as promising materials for various biomedical applications. The study provided valuable insights into the potential of these nanoparticles for various medical applications, including their significant antibacterial effects. All things considered, this fruitful investigation demonstrates that ZnO-NPs are promising candidates for additional antibacterial applications because of their broad suppression of growth caused by their smaller size and their low concentration.

Author Contributions

Methodology, S.H.K.; investigation, S.H.K. and A.H.A.-H.; formal analysis, S.H.K. and A.H.A.-H.; software, S.H.K. and A.A.M.O.; validation, S.H.K.; resources, A.H.A.-H.; data curation, A.H.A.-H.; writing—original draft preparation, A.H.A.-H. and A.A.M.O.; writing—review and editing, S.H.K. and A.H.A.-H.; visualization, A.A.M.O.; supervision, A.H.A.-H.All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

Funding

This research received no external funding.

Acknowledgments

The authors express their gratitude to Al-Razi University, Sana'a, Yemen, for providing invaluable technical support for using Labe and scientific assistance in determining the antibacterial properties.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper."

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