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Antibacterial Efficacy of Iron-Doped Zinc Oxide Nanoparticles for the Control of Hospital-Acquired Infections

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Hydrothermal; magnetic properties; nanoparticles, iron doped zinc oxide; antibacterial

ABSTRACT

Hospital-acquired infections represent a significant challenge in healthcare settings, often leading to increased morbidity, mortality, and healthcare costs. The growing issues of antimicrobial-resistant bacteria highlight the urgent need for novel approaches to control infections. Recent advancements in nanotechnology have introduced metal oxide nanoparticles as promising antimicrobial agents. In this study, the hydrothermal synthesis of iron-doped zinc oxide nanoparticles for the development of an antimicrobial surface is motivated by their potential application in mitigating hospital-acquired infections. The scientific community has been interested in these nanoparticles due to their potential use in biomedical applications. A low molarity iron (Fe) and zinc (Zn) solutions were used for the sample preparation. The concentration of dopant (Fe) was varied at weight percentages of 1-5wt%. X-ray diffraction (XRD) analysis demonstrated the formation of a wurtzite hexagonal structure of ZnO across all dopant concentrations. Increasing the dopant concentration caused a decrease in crystallinity, which in turn reduced the crystallite size of the nanoparticles. Vibrating sample magnetometer (VSM) analysis demonstrated that all of the synthesized samples exhibited soft ferromagnetic behavior. Dielectric studies showed normal dispersion behavior in both the dielectric constant and the tangent loss. The Cole-Cole plots displayed only a single semicircle, indicating that grain boundaries have strong resistance. The highly efficient iron-doped zinc oxide nanoparticles demonstrate significant antimicrobial potential, making them a promising candidate for application in reducing bacterial contamination on hospitals surfaces, which can contribute to the prevention of hospital-acquired infections.

1. INTRODUCTION

Hospital-acquired infections (HAIs) are infections that patients acquire during their stay in healthcare facilities, typically within 48 hours of admission, which were neither present nor incubating at the time of admission. The rise of antimicrobial resistance has rendered many traditional antibiotics ineffective, necessitating alternative strategies to combat

microbial pathogens. As a result, it is of the utmost importance to develop new materials that are not only more efficient but also exhibit enhanced photocatalytic and antibacterial capabilities. Infectious illnesses, particularly those of intracellular nature, are widely recognized for their challenging treatment protocols (Matthews *et al.*, 2010; Raza *et al.*, 2019), despite the enormous progress that has

been made in the production of antibiotics. The primary causes of difficulty include transport across cell membranes, restricted cellular activity, potential toxicity of antimicrobial agents to healthy tissues, and the development of acquired resistance in pathogenic bacteria (Mandell *et al.*, 2001; Deotale *et al.*, 2010; Wright, 2010). In an effort to combat these issues, researchers have developed novel antibacterial agents based on nanoscale materials. When compared to the bulk form, nanoparticles (NPs) are a superior delivery vehicle for antibacterial agents, owing to a high level of reactivity and an enormous surface-to-volume ratio (Reddy *et al.*, 2007; Mukherjee *et al.*, 2011).

Because of their ability to inhibit the growth of microbes, many NPs are being put to use in the fight against germs that are resistant to pharmacological treatment (Rai *et al.*, 2009). Inorganic metal oxide NPs have been extensively investigated for their applications in nanomedicine, particularly for disease biomarkers and antimicrobials (Adams *et al.*, 2006; Reddy *et al.*, 2007; Jahanshahi and Babaei, 2008; Sobha *et al.*, 2010). Some examples of these NPs include zinc oxide (ZnO), magnesium oxide (MgO), titanium dioxide (TiO₂), and silicon dioxide (SiO₂). The antibacterial activity exhibited by these NPs is significant. Inorganic NPs have been observed to provide enhanced effectiveness against antibiotic-resistant microbial pathogens. Additionally, these NPs exhibit reduced toxicity, possess heat resistance properties, and provide essential mineral components required by cells in human beings (Ohira *et al.*, 2008; Zakaria *et al.*, 2010; Brar *et al.*, 2023). Bio-inspired nano-architectonics, as predicted by Ariga *et al.* (2014), are state-of-the-art technology for the administration of drugs. One option to improve its metabolization and biodistribution of medicine is by making use of the polymeric based NP drug distribution technology (Chu *et al.*, 2013).

Rocha *et al.* (2023) extensively explored the utilization of spherically shaped co-doped and ZnO doped NPs with Fe and praseodymium (Pr) and as a result, the materials showed potential of applications where harmful microbes need to be eliminated. Sun *et al.* (2024) successfully synthesized Fe-doped ZnO NPs, exhibiting significant antibacterial activity against *Escherichia coli* with a minimum inhibitory concentration (MIC) of 0.15 mg mL⁻¹. The production of ZnO NPs doped with varying concentrations of rare-earth ions of cerium (Ce) and ytterbium (Yb) and the evaluation of their antibacterial and anticancer properties have been presented by Hannachi *et al.* (2022). Tasnim *et al.* (2023) studied the antimicrobial potential of metal doped FeO NPs. The findings revealed the efficacy of these NPs in inhibiting the growth of microorganisms, indicating their potential as a new antibacterial agent. ZnO NPs doped with Yb and Ce expands the fatal outcomes on microbial and cancer cells. The chemical naphthalocyanine, which is encased in the water-soluble polymer dendrimer, has been shown to be effective in the elimination of ovarian cancer tumors as well as other cancer cells (Taratula *et al.*, 2015). There have also been reports in the published literature about the utilization of NPs in the maritime and food processing industries (Feng *et al.*, 2014).

ZnO NPs stand out from other types of metal oxide NPs due to the myriads of advantageous features that they possess (Ghule *et al.*, 2006; Matei *et al.*, 2008). The aforementioned characteristics encompass notable attributes such as exceptional chemical and physical strength, robust catalytic efficacy, significant antibacterial potential, and outstanding light absorption capabilities within the ultraviolet (UV) and infrared (IR) spectra. Moreover, NPs of ZnO have been identified as extremely efficient photocatalysts for the degradation of hazardous organic pollutants in the environment (Gouvea *et al.*, 2000; Lai *et al.*,



2011). Introduction of imperfections in pure ZnO NPs is commonly achieved using different techniques, including the selection of appropriate approaches to synthesize (Pawinrat *et al.*, 2009; Li and Wang, 2010), the utilization of mixed catalysts (Cho *et al.*, 2011; Qin *et al.*, 2011), and an introduction of acceptable metal ion deficiencies through doping (Ye *et al.*, 2006; Li *et al.*, 2011). The utilization of a variety of transition metal ions has resulted in an enhancement of the kinetics of charge transfer at the interface of ZnO NPs (Anandan *et al.*, 2007; Lu *et al.*, 2008; Ullah and Dutta, 2008; Akhavan and Ghaderi, 2009). ZnO NPs are put to use in a wide variety of various sectors. It plays an important role in the manufacturing of a variety of products, including plastic and rubber, as well as paint, cosmetics, electronics, and pharmaceuticals. In addition to this, it is regularly discovered in products like baby powder, shampoos that treat dandruff, and topical medication ointments for various skin disorders (Hughes and Mclean, 1988). Adhesive tape made of zinc oxide is also used as an elastic bandage by athletes to safeguard their delicate tissues during workouts (Hu and Zhang, 2006). The use of these elements to disinfect and purify water has also been effective (Li *et al.*, 2008). In this study, Fe-doped ZnO NPs synthesized utilizing the sol-gel approach were analyzed for their antibacterial properties.

2. EXPERIMENTAL DETAILS

2.1 Material and Method

The long-term exposure to GHGs poses devastating impacts on humans as: 1) fatal lung diseases and pulmonary edema due to sulfur oxides and nitrogen oxides, 2) cardiovascular diseases, and 3) hyperventilation, asphyxia, and cellular anoxia (Hassan *et al.*, 2021). Burning of fossil fuels to meet the energy demands gravitate to release colossal amounts of GHGs like CO₂, CO, SO₂, NO₂, and

CH₄, and impose egregious impacts on climate (Martins *et al.*, 2021; Kumar *et al.*, 2022). Nitrogen and sulphur oxides convert into respective acidic forms after dissolving in clouds and in turn cause acid rain and snow. According to the 2015 modeled data of ambient air pollution, loss of life expectancy (LLE) strongly exceeds due to air pollution (Hassan *et al.*, 2021). Developed countries have their main focus on how to minimize the utilization of fossil fuels and lessen the carbon programs in the power sector, while in the developing countries, usage of fossil fuels is continuously increasing with no technologies to mitigate detrimental impacts. Thus, the rate of GHGs emission is more in those power sectors and ultimately cause damage to environmental sustainability (Karmaker *et al.*, 2020).

2.1.1 Synthesis Details

In the context of synthesizing NPs of Fe-doped ZnO, (where Fe = 1-5wt%), a straightforward, cost-effective, and low-temperature process known as sol-gel was utilized. As precursors, we employed zinc acetate [Zn(CH₃COO)₂·2H₂O] and iron nitrate [Fe(NO₃)₃·9H₂O], both of which are of research-grade quality. Both precursors had a purity level of 99.99% and did not require any additional purification before usage. Before making the final ZnO sol, two solutions, designated solution A and solution B, were made in order to facilitate the creation of undoped ZnO sols. Zinc acetate was dissolved in deionized water to make Solution A at room temperature, with constant stirring. Iron nitrate was employed as the precursor for the formation of FeO solution. Prior to its utilization in the synthesis process, iron nitrate was dissolved in a mixture of ethanol and deionized water. In order to obtain Fe-doped ZnO sol, FeO sol was gradually added to the ZnO sol until it reached the desired concentration while the mixture was constantly stirred. The amount of Fe in the final product ranged from 1wt%-5wt%. After that, the



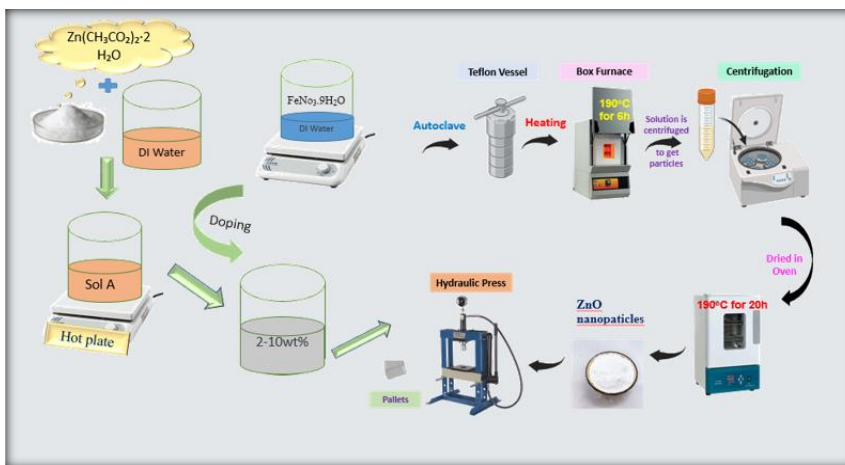


Figure 1. Synthesis detail of iron doped zinc oxide nanoparticles varying dopant concentration (1-5wt%)

solution was transferred to a container made of Teflon, which is thereafter inserted into an autoclave. At last, the autoclave is placed inside the box furnace and then it's heated to 150°C and maintained there for 20 hrs. Synthesis detail are shown in Figure 1.

2.2 Antibacterial Activity

The Fe-doped ZnO NPs were tested for their antibacterial properties against *E. coli*. Petri dishes that had been autoclaved were filled with twenty milliliters of Muller-Hinton agar (MHA) and allowed to solidify. *E. coli* culture was streaked on these plates, and wells were created. Different dilutions of Fe-doped zinc NPs were distributed into the. The plates were then placed in an incubator at 37°C for 24 hr. Following the incubation, measurements of the zones of inhibition were taken (mm).

3. CHARACTERIZATIONS

For structural and phase analysis, Rigaku X-ray diffractometer was used with Cu K α radiations (1.5406Å) for angle range of $2\theta^\circ = 30-80^\circ$. Vibrating Sample Magnetometer (VSM) Lakeshore's 7407 was employed for magnetic properties analysis. Precision Impedance

Analyzer 65000B was employed for the analysis of dielectric and complex impedance.

4. RESULTS

4.1 XRD Analysis

The XRD analysis (Figure 2) of hydrothermally synthesized Fe-doped ZnO NPs (1–5 wt%) confirmed the retention of the wurtzite hexagonal structure up to 4 wt% doping. Peaks corresponding to standard ZnO planes showed slight broadening and shifting due to Fe³⁺ incorporation, indicating successful substitution of Zn²⁺ without altering the crystal structure. The smaller ionic size of Fe³⁺ and its effect on lattice distortion contributed to reduced crystallinity and crystallite size (Figure 3). At 5 wt% doping, minor peaks of FeO emerged, suggesting excess Fe leads to secondary phases and further distortion, thereby reducing crystallinity and affecting the growth dynamics of the NPs.

Equation 1 and 2 (Ameur *et al.*, 2021) were used to calculate the crystallite size (nm) and dislocation density of ZnO NPs that include Fe.

$$t = \frac{0.9\lambda}{\beta \cos \theta} \dots\dots 1$$

$$\delta = \frac{1}{t^2} \dots\dots 2$$

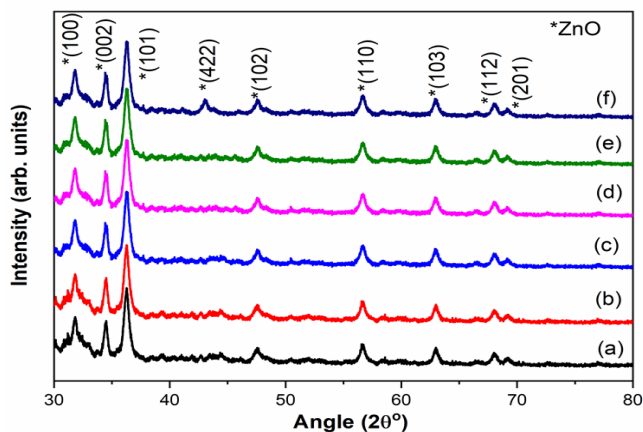


Figure 2. XRD Pattern of (a) undoped and (b-f) iron doped zinc oxide nanoparticles at various dopant concentrations (1-5wt%)

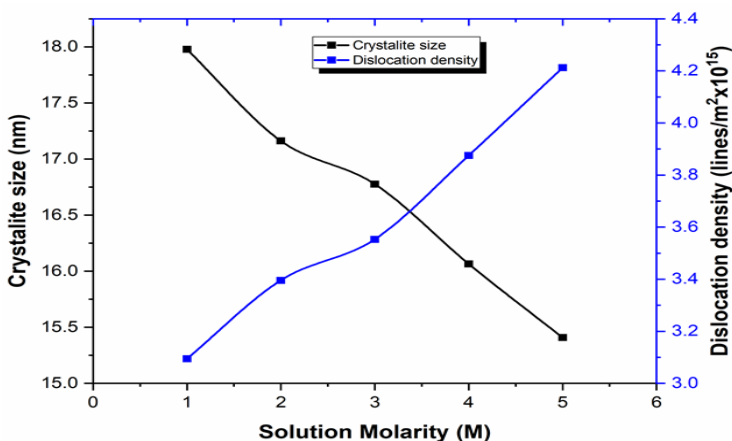


Figure 3. Variation in crystallite size and dislocation density at various dopant concentration (1-5wt%)

The average size of crystallites is represented by the variable t . The symbol λ stands for the wavelength of the X-rays used in X-ray diffraction, which is $1.54050 \text{ \AA}$ in this case. The FWHM, or full width at half maximum, is represented by the symbol β . The angle Bragg is represented by the symbol θ .

4.2 Magnetic Analysis

The study explores how Fe doping affects the structural and magnetic properties of ZnO NPs. As Fe concentration increased, the crystallite size decreased due to the smaller ionic radius

of Fe^{3+} compared to Zn^{2+} . This size reduction correlates with an increase in dislocation density, peaking at 5 wt% doping. Magnetic measurements showed a slight but noticeable enhancement in saturation magnetization and coercivity with higher Fe content (Figure 4). The observed increase in room temperature ferromagnetism is attributed to reduced spacing between Fe ions, strengthening the ferromagnetic interactions. Overall, Fe doping improved both structural defects and magnetic behavior in ZnO NPs.



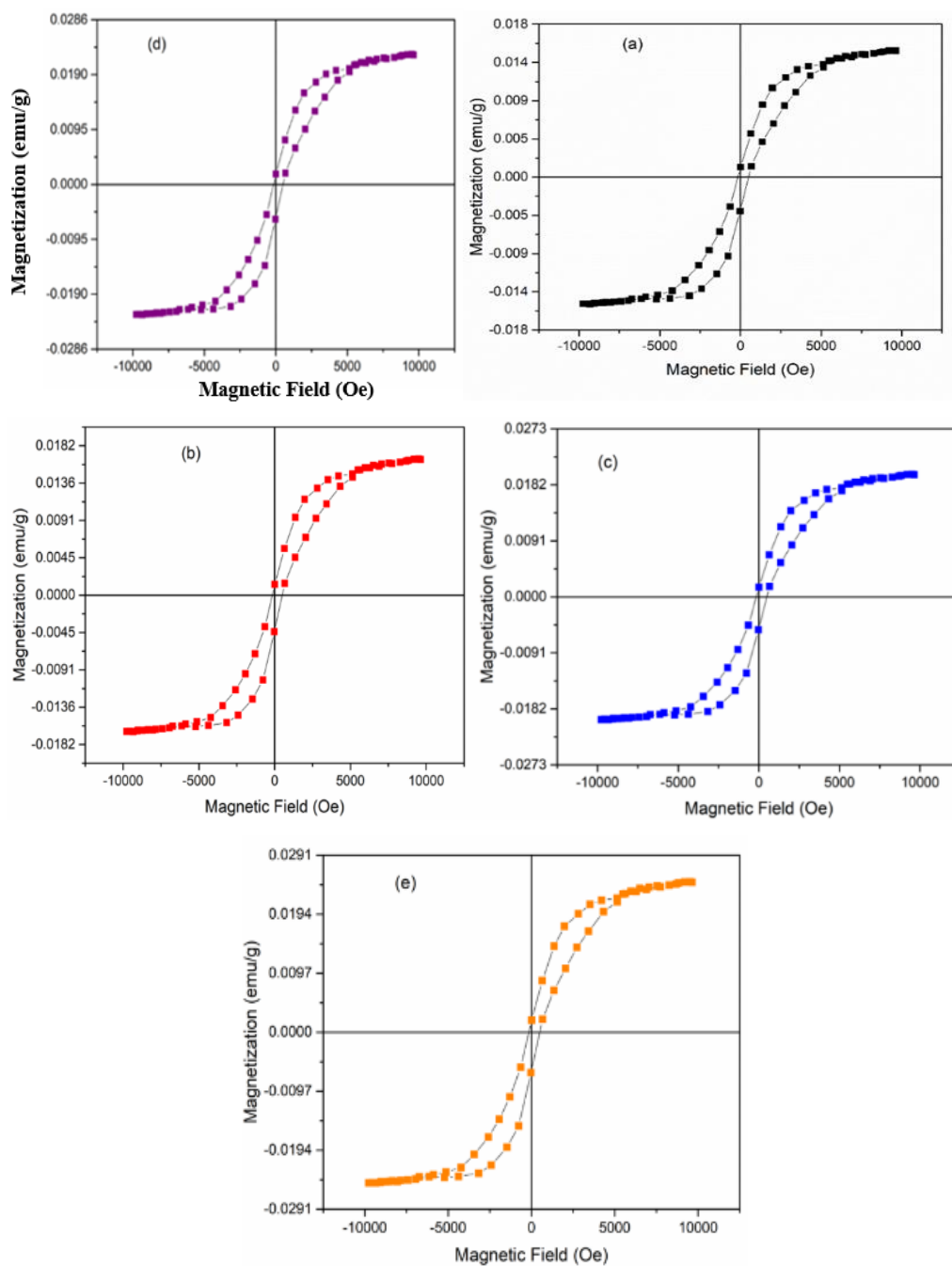


Figure 4. M-H loop for Fe dopant concentration of ZnO nanoparticles (a) 1wt% (b) 2wt% (c) 3wt% (d) 4wt% (e) 5wt%



Table 1. Saturation magnetization and coercivity of Fe doped ZnO nanoparticles

Dopant concentration	Saturation Magnetization (emu/g)	Coercivity (Oe)
1 wt%	0.016	718
2 wt%	0.017	735
3 wt%	0.0189	633
4 wt%	0.0198	753
5 wt%	0.024	762

4.3 Dielectric Analysis

Dielectric relaxation in materials was analyzed using impedance spectroscopy (figure 5-6), which distinguishes between grains, grain boundaries, and electrode interfaces through real and imaginary impedance components. An equivalent parallel RC circuit model helps

describe these regions. Ideally, Cole–Cole plots exhibit three semicircles for grains, grain boundaries, and electrode contact. However, in Fe-doped ZnO NPs, only one semicircle was observed, indicating significant resistance at grain boundaries. This semicircle, seen in Figure 7(a–e), suggests dominant grain boundary effects. The electrode’s role appears at low frequencies, grain effects at high frequencies, and grain boundaries in the mid-frequency range, emphasizing Fe’s impact on electrical behavior as observed in figure 8.

Equation 3 (Bazazi *et al.*, 2018) was utilized in order to arrive at the dielectric constant.

$$\epsilon' = \frac{C_p d}{A \epsilon_0} \dots\dots\dots 3$$

The symbol ϵ' represents the dielectric constant. The symbol C_p represents the value of the parallel plate capacitance. In this context, "d" stands for film thickness. Area A and permittivity ϵ_0 of free space are defined.

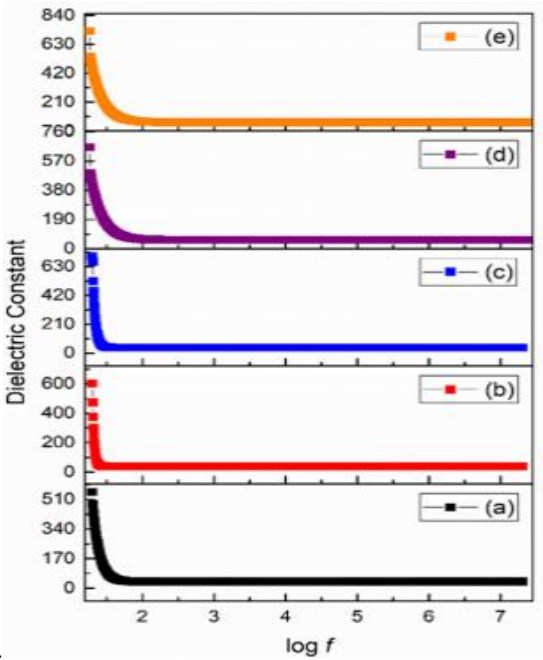


Figure 5. Dielectric constant of iron doped zinc oxide nanoparticles with variation in dopant concentration (a-e:1-5wt%)

Calculating the amount of energy loss (δ) requires utilising the formula found in Equation 4.

$$\tan\delta = 1 / 2\pi R_p f C_p \dots\dots 4$$

In which the parallel resistance R_p and capacitance C_p were represented.

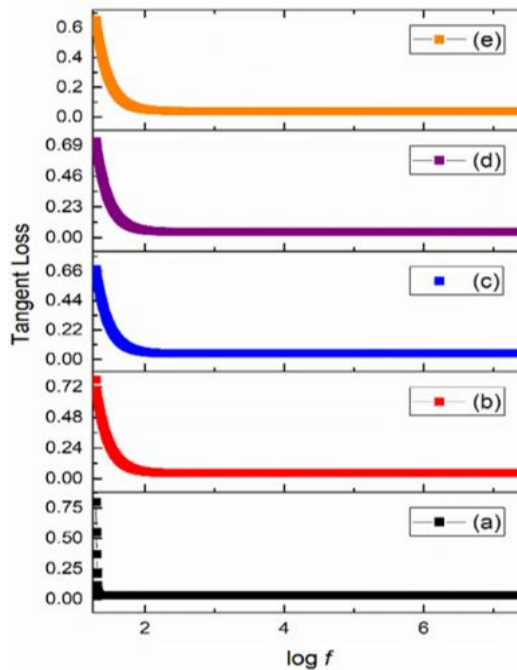


Figure 6. Tangent loss of iron doped zinc oxide nanoparticles with variation in dopant concentration (a-e: 1-5wt%)

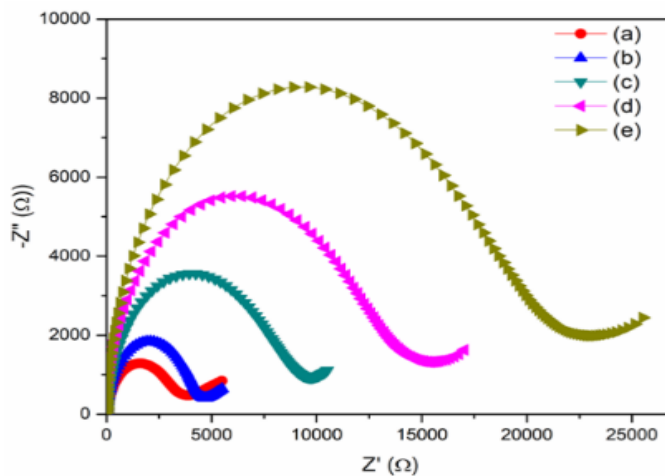


Figure 7. Cole cole plot of iron doped zinc oxide nanoparticles with variation in dopant concentration (a-e: 1-5wt%)



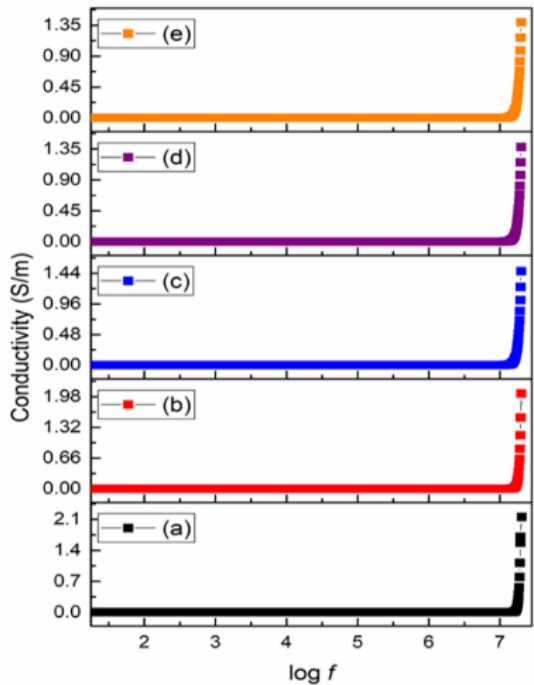


Figure 8. Conductivity of iron doped zinc oxide nanoparticles with variation in dopant concentration (a-e:1-5wt%)

Table 2. Comparison of Literature on zinc oxide nanoparticles

Literature	Bacterial Inhibition Rate	Doping of Fe	References
The structural, optical, and antibacterial properties of spherical ZnO NPs were investigated regarding the impact that Fe and Pr addition plays in these aspects.	33%	8wt%	(Rocha <i>et al.</i> , 2023)
The antibacterial activity of nanofibers coated with Fe-doped ZnO NPs, with weight percentages of 4, 8, and 12@PVA, was evaluated.	19mm	12wt%	(Sekar <i>et al.</i> , 2019)
5The study concentrates on the synthesis of ZnO NPs, which include Fe-doped ZnO (GZF).	20mm	5wt%	(Konieczny and Labisz, 2013)

4.4 Antibacterial Activity

Fe-doped ZnO NPs (1–5 wt% Fe) were tested for antibacterial activity against *E. coli* as shown in figure 9(i,ii), a common hospital pathogen. Results showed that increasing Fe

content enhanced bacterial inhibition, with 5 wt% showing the highest efficacy. This antibacterial effect is attributed to reactive oxygen species (ROS) generation, Zn^{2+} ion release, and nanoparticle morphology. ROS damage bacterial membranes and proteins,

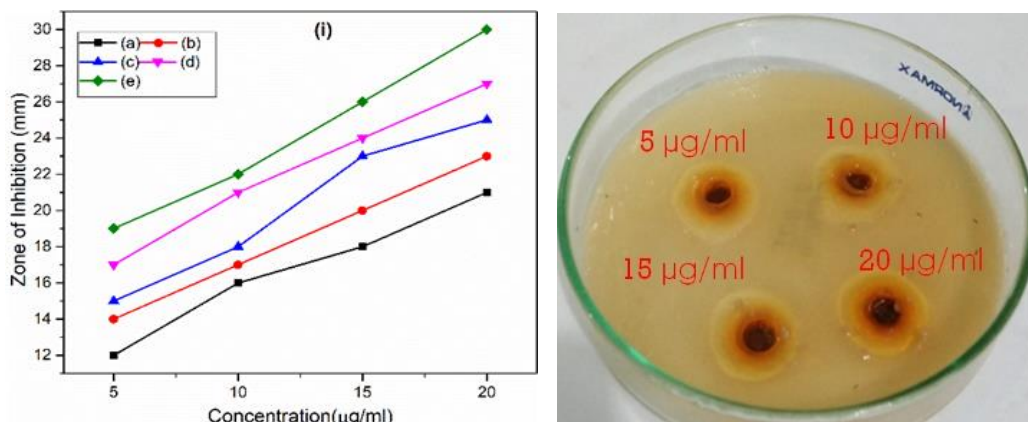


Figure 9. (i) Concentration-dependent antibacterial activity of Fe doped ZnO nanoparticles (a) 1 wt%, (b) 2 wt% (c) 3%, (d) 4%, (e) 5%, and (ii) a 5% weight-percentage-based inhibitory zone Nanoparticles of Fe-doped zinc oxide

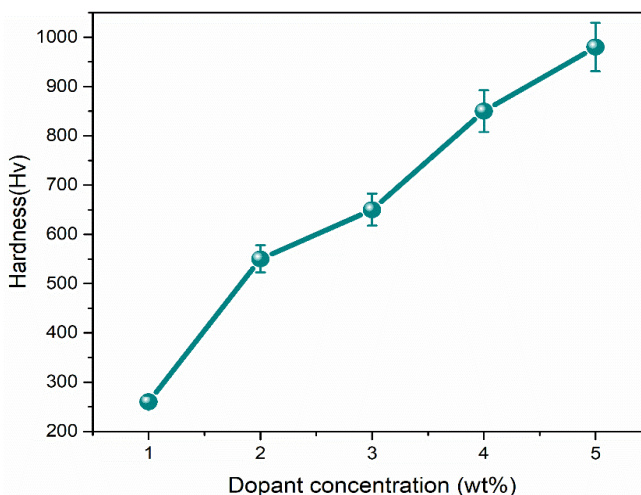


Figure 10. Hardness of Fe doped ZnO nanoparticles at various dopant concentration (1-5wt%)

while Zn^{2+} ions disrupt cellular functions. Fe doping further enhances this activity through defect generation. These properties suggest potential use of Fe-ZnO NPs in hospital sanitation.

4.5 Hardness Test

Mechanical strength is crucial for surface coatings, particularly in bioceramics. The optimized sample achieved a high hardness of approximately 980 Hv, indicating excellent durability. Strength in such materials is

influenced by factors like density, hardness, and fracture toughness. Smaller grain sizes increase the number of grain boundaries, enhancing hardness and strength. Additionally, features like grain boundary arrangement and triple junctions contribute significantly to the material's mechanical performance.

5. DISCUSSION

Figure 2 depicts the X-ray diffraction (XRD) patterns of ZnO NPs doped with Fe at different

dopant concentrations of 1wt%-5wt%. These NPs were synthesized using the hydrothermal approach. The X-ray diffraction (XRD) pattern of ZnO (JCPDS 36-1451) reveals the presence of a wurtzite hexagonal structure. This is evidenced by the diffraction peaks observed at specific angles, namely $2\theta=32.1^\circ, 34.8^\circ, 36.8^\circ, 47.50^\circ, 56.7^\circ, 63.0^\circ, 36.8^\circ, 67.9^\circ, \text{ and } 68.9^\circ$. These peaks correspond to the diffraction planes (100), (002), (101), (102), (110), (103), (112), and (201) respectively, as illustrated in Figure 2(a)–(e). The observations that are displayed in Figure 2(a–e) demonstrate that the wurtzite crystal structure of ZnO has not undergone any apparent change as a result of the addition of dopants of Fe. This shows that up to a concentration of 4wt%, Fe atoms are able to successfully substitute zinc atoms within the ZnO lattice. The Fe-doped XRD peaks were broader when the Fe concentration was raised (Figure 2 e). There are two causes for this peak broadening; one is that Fe^{3+} is smaller than Zn^{2+} (0.064nm vs. 0.072nm) in terms of ionic size (Agarwal *et al.*, 2019). Incorporation of Fe into the crystalline structure of ZnO can be a second factor that prevents crystallization (Ahmed, 2017). The shifting of peak towards lower 2 theta angle showed the exact doping of Fe into Zn lattice. This is evidence that Fe^{3+} ions were successfully incorporated into the Zn lattice without causing a change in the cubic structure of ZnO. Consequently, a decrease in crystallinity was observed, accompanied by the emergence of small peaks corresponding to FeO (JCPDS 39-1346), upon increasing the doping concentration to 5 wt% (Figure 2 f). The increase in Fe doping results in the NPs exhibiting lower crystallinity and smaller crystallite size. This can be attributed to the distortion in the host lattice caused by the entrance of Fe atoms into the lattice site (Alshamsi and Hussein, 2018). This distortion is caused by the introduction of doping atom (Fe). As a result, the rate of nucleation slows

down while the growth rate quickens as the amount of Fe dopant increases.

Figure 3 illustrates that the correlation, with change in crystallite size and the dislocation density, is of interest. Crystallite size has been demonstrated to decrease when the concentration of Fe dopant in a material increases. This lower value of crystallite size can be attributed to the fact that the atomic ionic radii, i.e., $\text{Fe}^{3+} \sim 0.064 \text{ nm}$ are significantly lesser than those i.e. $\text{Zn}^{2+} \sim 0.072 \text{ nm}$ (Ashraf *et al.*, 2013; Akbar *et al.*, 2015). As can be seen in Figure 3, the relationship between dislocation density and crystallite size behaves counterintuitively. As the concentration of the dopant increases, there is a discernible upward trend in the dislocation density. The dislocation density reaches its greatest value in Fe-doped ZnO NPs when the dopant concentration is 5 wt% due to the presence of a stable phase.

Figure 4 (a–e) depicts the magnetic curves that were found at a variety of doping concentrations. When the concentration of the dopant (Fe) is increased from 1 to 5 weight percent (wt%), one can observe a slight change in the saturation magnetization and coercivity, as depicted in Table 1. However, this shift is not really noticeable at all. When the concentration of the dopant is raised, this shift becomes more apparent. The process that is dependent on the concentration of Fe can provide an explanation for the increase in ferromagnetism that happens at room temperature as a result of an increase in the amount of doping. This rise in ferromagnetism is caused by an increase in the amount of doping (Mior Idris, 2015). When there is a low concentration of Fe, such as 1wt% (Figure 4 a), the average spacing between Fe ions must be greater than when there is a higher concentration of Fe, such as 5wt% (Figure 4 e). When there is a significant distance between two Fe ions, the ferromagnetism interaction is relatively weak. As a consequence, an increase



in the amount of Fe present will cause the ferromagnetic connection between Fe ions to become more robust, which will lead to an increase in magnetic properties.

The concentration of the dopant has an effect on the magnetic properties of Fe-doped ZnO NPs. These properties include saturation magnetization and coercivity. As can be shown in Table 1, the saturation magnetization rises as the concentration of Fe increases, while it reaches its highest point at 5wt%. Indicating that there are complicated interactions between Fe ions and the ZnO matrix, the coercivity values fluctuate, with a considerable reduction occurring at 3 weight percent and a high occurring at 5wt%.

Because Fe is a deep acceptor in ZnO, it was also discovered that the number of Fe^{+2} ions increases when the concentration of Fe in the material increases. When iron replaces zinc in the lattice of ZnO, the valence state of the Fe ion changes to Fe^{+2} . Because of the increased incorporation of Fe ions in ZnO, the magnetism will be increased (Basnet and Chatterjee, 2020).

Voltage causes a transformation of the internal energy of the dielectric and the loss factor, leading to the production of heat. This is the form of energy that is released. Fe oxide NPs' dielectric constant (dielectric loss) and tangent loss (tan loss) are described and shown as functions of frequency in both the Figures 5(a-e) and 6(a-e), respectively. It is feasible to demonstrate, across the whole frequency spectrum, that both the dielectric constant and the tangent loss are significantly sensitive to changes in frequency. This sensitivity can be shown to apply to both the dielectric constant and the tangent loss. It is important to note in the Figures 5(a-e) and 6(a-e), the dielectric and tangent loss of Fe doped ZnO NPs both decrease as the frequency is raised. This is something that should be kept in mind. When we consider higher frequencies, we find that

this is the case. The presence of space charge carriers in Fe oxide NPs is what makes this particular kind of dispersion possible (Bardi *et al.*, 2009). The Fe-doped ZnO NPs that were synthesized with a dopant content of 5wt% exhibited the highest dielectric constant as well as the lowest tangent loss. Multiple polarization processes are responsible for the polarisation in a dielectric medium. The five types of polarization include polarization of space charges, polarization at the interface, dipolar in nature, electronically and cationic polarizariion (Chanu *et al.*, 2019). Figures 5(a-e) and 6(a-e)] figures show the distinctive nature of the NPs. This pattern of behaviour arises as a consequence of the orientational and dipole polarizations, both of which become predominant at greater frequencies i.e. $> \log f=5$. When the frequency is more than 1.5 MHz i.e. $> \log f= 5$, the mobility of the charge carrier begins to resonate alongside the fiels that is being applied. This happens when the frequency is increased. This occurs when the logarithm of the frequency is greater than five. When investigated at higher frequencies, the value of the dielectric constant was found to have grown as a consequence of this.

The phenomena of dielectric relaxation in materials is investigated by means of impedance spectroscopy. The ability to discriminate between grain, grain boundaries, and the electrode contact is helped by both real and imaginary impedance. The analogous parallel RC circuit is utilized so that the various regions of a material can be accurately described. The cole-cole plot of Fe-doped ZnO NPs is represented by Figure 7(a-e). This plot is between real and imaginary impedance and is formed of a single semicircle. In a perfect world, the Cole–Cole plots would contain three semicircles that corresponded to the grains, their boundary, and the electrode interface. The efficiency of the electrode is shown by the arc at low frequencies, that of the grains by the semicircle at high frequencies, and that of the

grain borders by the semicircle at mid-frequency regions (Pepperhoff and Acet, 2001). Figure 7(a-e) demonstrates Fe-doped ZnO NPs consisting a single semicircle in formation show substantial resistance at grain boundaries (Desai *et al.*, 2006).

At room temperature, the system's conductivity varies with frequency, as shown in Figure 8(a-e). At $\log f < 5$, the frequency dependence of conductivity is nearly zero. The presence of conductivity in this region is indicative of the presence of conduction between bound states, and it is feasible to refer to the conductivity in this region as conductivity similar to that of direct current (Jartych *et al.*, 2001; Jang *et al.*, 2015; Han *et al.*, 2018; Jin and Jin, 2019). When the logarithm of the frequency is greater than 5.0, a dispersion in the conductivity values can be seen in Figure 8(a-e). The phrase "a.c. conductivity" refers to the conductivity found in this location (Jaral *et al.*, 2015). A hopping-based conduction mechanism is present if there is a noticeable response of conductivity at higher frequencies. This suggests that there are multiple localized states.

Every single sample of Fe doped ZnO NPs varying levels of Fe as a dopant with 1%, 2%, 3%, 4%, and 5% by weight—were put to the test against *E. coli*, a common hospital pathogen. An experiment was carried out to examine the ability of generated NPs to suppress the growth of *E. coli*. Figure 9i (a-e) shows that an increase in the amount of Fe in the NPs results in an increased efficiency in the killing of *E. coli* (Kulkarni and Lokhande, 2003). The production of ROS, the release of Zn^{2+} ions, and the size and form of the synthesized NPs could all contribute to ZnO NPs' antibacterial effectiveness. Through a strong electrostatic contact between the negatively charged cell membrane and Zn^{2+} ions, ROS infiltrates these species and damage their cell membrane and cellular proteins. Consequently, the bacteria perish and the Zn^{2+} ions are liberated from the surface of the ZnO

NPs. This Zn^{2+} behaviour can also be explained in terms of defect generation; hence, Zn^{2+} ion defects boost the antibacterial activity of ZnO NPs (Chandramouli *et al.*, 2021). It was discovered that a sample containing 5wt% yielded the highest level of effectiveness, according to Figure 9i (a-e). Based on these findings, it was discovered that applying NPs to the hospital's surfaces may help to inhibit the growth of bacteria (Kumar *et al.*, 2011; Lin *et al.*, 2017; Boopathi *et al.*, 2024). Fe doped ZnO NPs are novel and highly effective, making them a promising choice for use in healthcare institutions to reduce bacterial contamination of frequently touched surfaces (Liang *et al.*, 2019). Table 2 provides a summary of some of the most important publications on these NPs. This demonstrates the influence that doping concentration has on the antibacterial activity of materials as well as the properties of certain materials.

When testing the durability of surface coatings, mechanical strength is a key metric to look for (Blundell, 2001). Several characteristics, including as density, hardness, and fracture toughness, are responsible for controlling and governing strength. There is a possibility that this phenomenon is caused by a variety of different elements, such as the aspect ratio of the microstructure, the arrangement of grain boundaries, and the triple junctions. Materials with smaller grains do, in fact, have a greater number of grain boundaries, and as a result, they have a higher value for their hardness and strength. In addition, grain boundaries are one of the places where important atom sites can be located (Sanaullah *et al.*, 2022). Figure 10 displays the highest hardness value of approximately 980 Hv for our optimized sample, which is excellent for coatings.

6. CONCLUSIONS

We've looked into the consequences of adding Fe as a dopant to ZnO made by the



hydrothermal approach. The Fe-doped ZnO that was created at a loading of 5wt% of NPs may enhance antibacterial activity while posing minimal toxicity. The novel and exceptionally efficient Fe-doped ZnO NPs suggest a promising candidate for implementation in hospital settings to reduce bacterial contamination associated with frequently handled surfaces.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Muhammad Tahir: Writing – review & editing original draft. Zaheer Hussain Shah: Conceptualization. Azqa Farrukh Butt: Formal Analysis. Muhammad Imran: Visualization

Ethics approval and Informed Consent

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Availability of Data

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