

Joyshree Maji

Department of Physics, Asansol Engineering College, India

Scientific paper

ISSN 0351-9465, E-ISSN 2466-2585

<https://doi.org/10.62638/ZasMat1662>Zastita Materijala 67 ()
(2026)

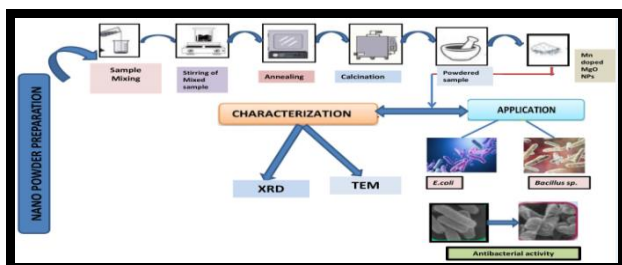
Exploring Mn-doped MgO nanoparticles: A soft chemical route to enhanced electrical and antibacterial functionality

ABSTRACT

Mn-doped MgO nanoparticles (8 nm crystalline size) were synthesized using a simple soft chemical method. Their antibacterial activity against both gram-positive and gram-negative pathogens was evaluated using MIC, live count, and agar cup assays. The AC conductivity and dielectric properties were measured at different temperatures, and the charge transport mechanism was investigated using the CBH model. Transmission electron microscopy (TEM) revealed cell wall disruption in pathogens treated with Mn-doped MgO nanoparticles. Antibacterial activity increased with nanoparticle concentration. These nanomaterials show promise as antibacterial agents for medical applications, pending successful *in vivo* trials.

Key words: Mn doped MgO, Nanoparticle, Antibacterial activity, Super oxide Radical, sol-gel mechanism, Cell wall disruption

Graphical abstract



1. INTRODUCTION:

Nanotechnology, focusing on particles between 1 and 100 nm, is a rapidly expanding field. This growth is driven by the unique physical and chemical properties of nanoparticles, including their distinct electrical, chemical, optical, thermal, and biological interactions [1,2]. A key area of interest is their antibacterial activity [1]. Traditional antibiotics face challenges due to multidrug-resistant bacterial strains. This has spurred the development of nanomedicine, which leverages nanomaterials (within the nanometer range) due to their size compatibility with biological systems [3,4,5]. Nanoparticles can be engineered for specific functions like targeted drug delivery and even remotely stimulated [4,5].

*Corresponding authors: Joyshree Maji

E-mail: joyshree.phy@aecwb.edu.in

Paper received: 06. 12. 2025.

Paper corrected: 24. 04. 2026.

Paper accepted: 26. 04. 2026.

They've shown promise as antimicrobial agents, even against antibiotic-resistant bacteria [6,7], and are also being explored for anticancer therapy [8], with some already developed for *in vivo* applications [9]. Beyond therapy, nanoparticles are enhancing medical imaging. Fluorescent nanoparticles (like quantum dots) and metallic nanoparticles provide improved contrast over traditional methods [10,11]. Metallic nanomaterials are specifically utilized in X-ray imaging and intravascular detection [12]. Metal oxide nanoparticles, including magnesium oxide (MgO), are drawing significant interest for their diverse electrical, magnetic, and antibacterial properties [13]. Among these, MgO nanoparticles stand out due to their low cost and abundance, making them particularly appealing for use in nanomedicine and FDA-regulated products [14,15]. Scientists employ various synthesis techniques like sol-gel, hydrothermal, and vapor-phase deposition to engineer a range of MgO nanostructures, including thin films, nanowires, flower-like structures, nanorods, nanobelts, and nanoparticles [16-22]. MgO nanoparticles are effective against both Gram-positive and Gram-negative bacteria.

This study investigates the antibacterial activity of Mn-doped MgO nanoparticles against *E. coli* and *Bacillus sp.*, synthesized using the sol-gel technique. The synthesized nanomaterials were characterized using various techniques. The high surface-to-volume ratio of nanoparticles plays a crucial role in enhancing their antibacterial performance.

2.1: Materials

Magnesium Nitrate [$\text{Mg}(\text{NO}_3)_2 \cdot \text{H}_2\text{O}$] (MERK, India), Sodium hydroxide palate [NaOH] (MERK, India), Ferric Nitrate [$\text{Mg}(\text{CO}_3)_2 \cdot \text{H}_2\text{O}$] (MERK, India), Citrate acid [$\text{C}_6\text{H}_8\text{O}_7$] (MERK, India), and Ethylene glycol [$\text{C}_2\text{H}_6\text{O}_2$] (MERK, India) were used as precursor materials. The chemicals have been used without any further purification. In this work two bacterial pathogens, *E. coli*. and *Bacillus sp.* were collected from the Botany Department, B.B College, Asansol, West Bengal, India.

2.2. Synthesis of nanoparticle:

Mn-doped MgO nanoparticles with different dopant concentrations were synthesized by sol-gel process. For synthesize the Mn doped MgO nanoparticles, initial solution was prepared by mixing the appropriate molar ratios of $\text{Mg}(\text{NO}_3)_2 \cdot \text{H}_2\text{O}$ and $\text{Mn}(\text{CO}_3)_2 \cdot \text{H}_2\text{O}$ in deionized water. Then, citrate acid ($\text{C}_6\text{H}_8\text{O}_7$) and ethylene glycol ($\text{C}_2\text{H}_6\text{O}_2$) were added to the mixed solution to form a clear solution and the mixed solution was initially processed by adding components until a clear solution formed. This solution was then heated to 100°C to create a gel. The resulting gel underwent a two-step heating process: first, it was heated at 350°C for 3.5 hours, and subsequently, it was calcined at 550°C for 30 minutes. The crushed samples were annealed at various temperatures for 3.5 h.

2.3. Characterization

2.3a. Micro Structural Characterization

X-ray diffraction (XRD) confirmed the formation of Mn-doped MgO nanocrystals at concentrations of 0.5%, 1.0%, and 1.5%. XRD patterns were collected using a PANalytical XPert Pro diffractometer with Ni-filtered $\text{Cu-K}\alpha$ radiation ($\lambda = 1.54 \text{ \AA}$) in the 2θ range of 20° to 80° . HRTEM (JEOL 2011) was utilized to assess the particle size, crystallinity, and morphology of the nanocrystals. Sample preparation involved ultrasonically dispersing ground nanocrystals in ethanol, followed by depositing a drop onto a 300-mesh carbon-coated copper grid.

The morphology of bacterial pathogens, specifically *E. coli* and *Bacillus sp.*, was also investigated using TEM at 200 kV. Before TEM analysis, liquid cultures of *E. coli* and *Bacillus sp.* were exposed to their respective Minimum Inhibitory Concentrations (MICs) of $2.75 \mu\text{g/ml}$ and

$1.75 \mu\text{g/ml}$. Untreated cultures served as controls for comparison. Measurements of the dielectric constant and AC conductivity were conducted across a temperature range of 313 K to 473 K and a frequency range of 20 Hz to 10 MHz. An Agilent E4980ALCR meter was used for these measurements.

The dielectric constants $\epsilon'(f)$ were calculated according to the following equation (1):

$$\epsilon'(f) = \frac{C_p t}{s \epsilon_0} \quad (1)$$

Where t and s are the width and surface area of the experimental sample disk respectively and ϵ_0 is the permittivity of free space.

2.3b. Antibacterial assay and Minimum Inhibitory Concentration (MIC):

The antibacterial efficacy of Mn-doped MgO nanoparticles was evaluated against *E. coli* and *Bacillus sp.* using a dual approach: the agar-cup diffusion method and the live count technique.

For the agar-cup assay, nanoparticle suspensions were prepared at concentrations of 0, 1.5, 2.5, 3.5, 4.5, 5.5, and $6.5 \mu\text{g/ml}$. The diameter of the inhibition zone around each cup was measured to quantify antimicrobial effect. The live count technique was utilized to precisely determine the Minimum Inhibitory Concentration (MIC) of the nanoparticles. In this procedure, bacterial cultures were treated with the same range of Mn-doped MgO nanoparticle concentrations (0, 1.5, 2.5, 3.5, 4.5, 5.5, and $6.5 \mu\text{g/ml}$), then replicated in three sets, and subsequently plated onto nutrient agar plates.

3. RESULTS AND DISCUSSION

3.1. Microstructural characterization

XRD analysis [Figure 1(a-c)] of Mn-doped MgO nonmaterial at 0.5 wt%, 1.0 wt%, and 1.5 wt% showed a crystalline structure with an average crystallite size of 7.20 nm. All major diffraction peaks corresponded to the standard FCC phase of MgO (JCPDS card no. 78-0430), confirming the high crystallinity of the synthesized nanoparticles. This result is consistent with previously reported data for Mn-doped MgO nanoparticles. Images captured by TEM of the 0.5 wt%, 1.0 wt% and 1.5 wt% Mn doped MgO nanoparticles are shown in Figure 2 (a)-(c).

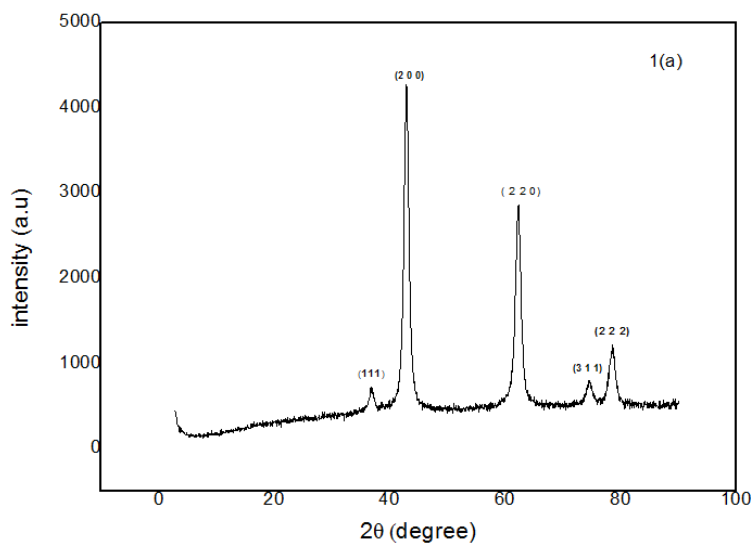


Figure 1(a)

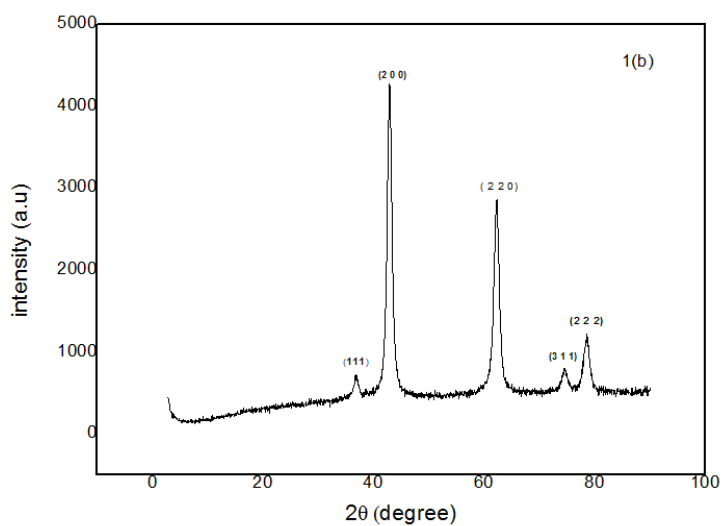


Figure 1(b)

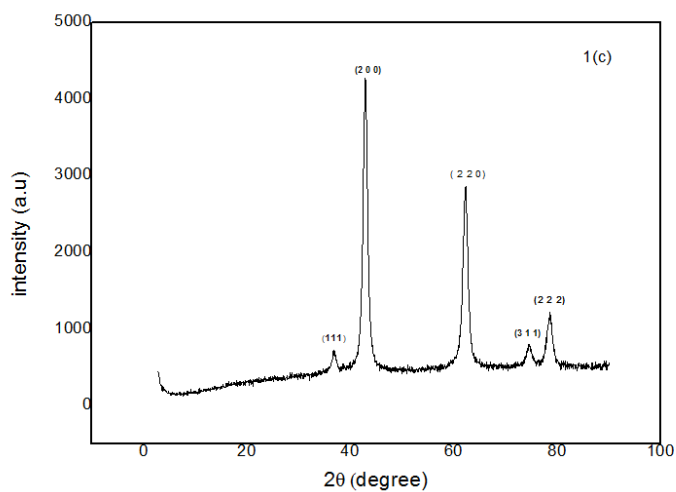


Figure 1(c)

Figure 1. (a) The X-Ray diffraction pattern of 0.5wt% Mn doped MgO nanoparticles, (b) The X-Ray diffraction pattern of 1.0wt% Mn doped MgO nanoparticles, (c) The X-Ray diffraction pattern of 1.5wt% Mn doped MgO nanoparticles

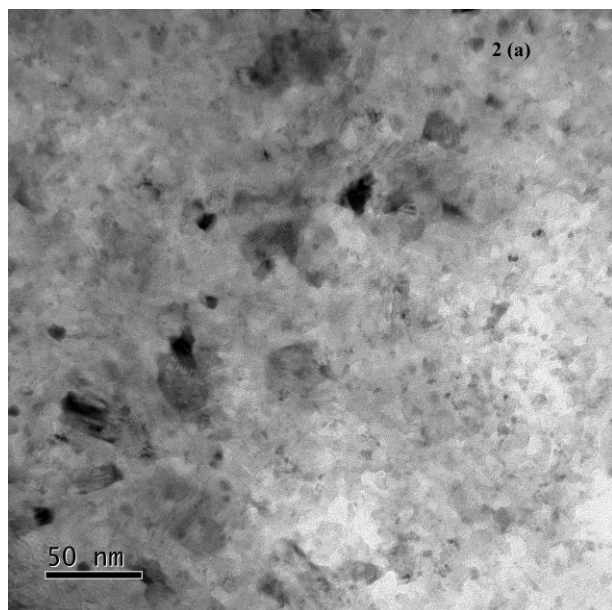


Figure 2(a)

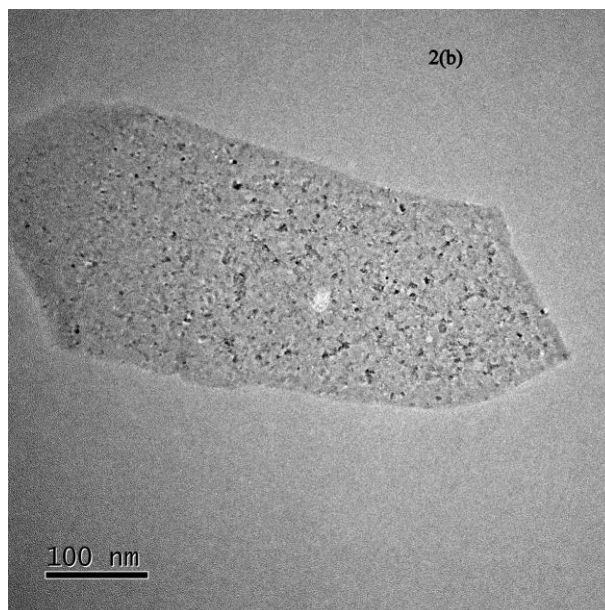


Figure 2(b)

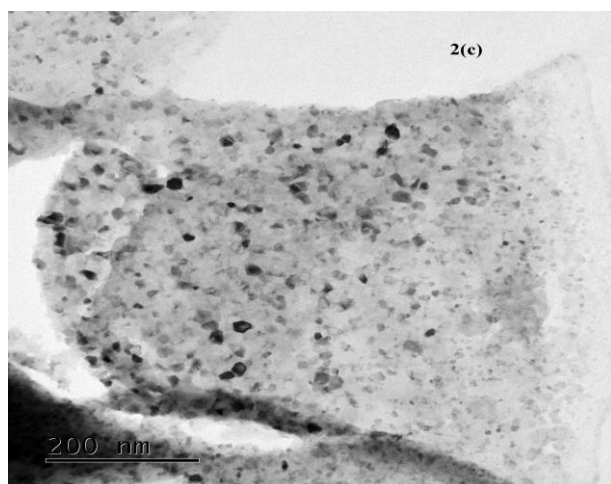


Figure 2(c)

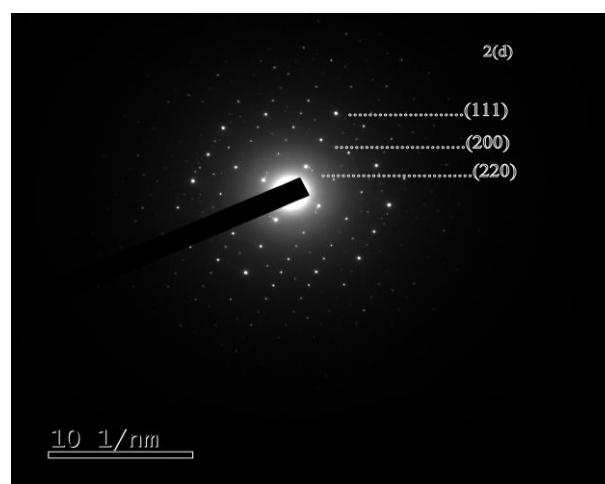


Figure 2(d)

Figure 2. (a) Transmission electron micrograph of 0.5 wt% Mn doped MgO nanoparticle, (b) Transmission electron micrograph of 1.0 wt% Mn doped MgO nanoparticle, (c) Transmission electron micrograph of 1.5 wt% Mn doped MgO nanoparticle, (d) Selected area diffraction patterns of Mn doped MgO nanoparticles from TEM Image

The average particle size of 0.5 wt%, 1.0 wt% and 1.5 wt% concentration is detected to be 8.75 nm, 7.24 nm and 7.86 nm respectively. The XRD patterns of Mn-doped MgO nanoparticles are shown in Figure 1. All the samples exhibit the reflections corresponding to cubic MgO phase. As the Mn content increases, one observes that the diffraction peaks shift slightly in the position indicating evidence of doping. For MgO nanoparticle xrd patterns are 28.3° , 32.8° , and 39.5° , which correspond to the (111), (200), and (220) planes. But as we are doping with Mn

doped MgO we can observe the change in peak position. 38.2° , 43° and 64.3° which correspond to the (111), (200), and (220) planes. Therefore, the average crystalline particle size of Mn doped MgO nanoparticle is calculated 6.40 nm approximately. Synthesized Mn doped MgO nanoparticles seem to be cubical shape and regular crystal structures without any perceptible pores. Figure 2(d) exhibits the SAED pattern with some clear diffraction points again proved the formation of different concentration of Mn doped MgO crystalline nanoparticles.

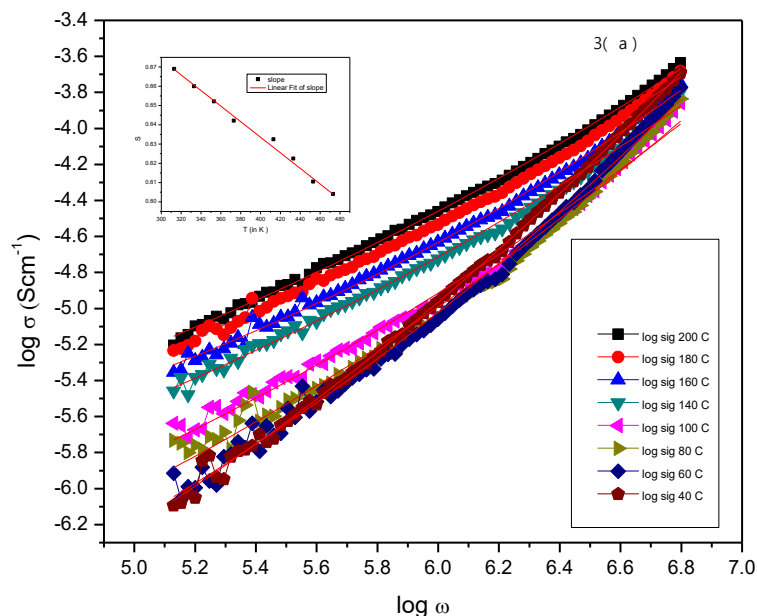


Figure 3(a)

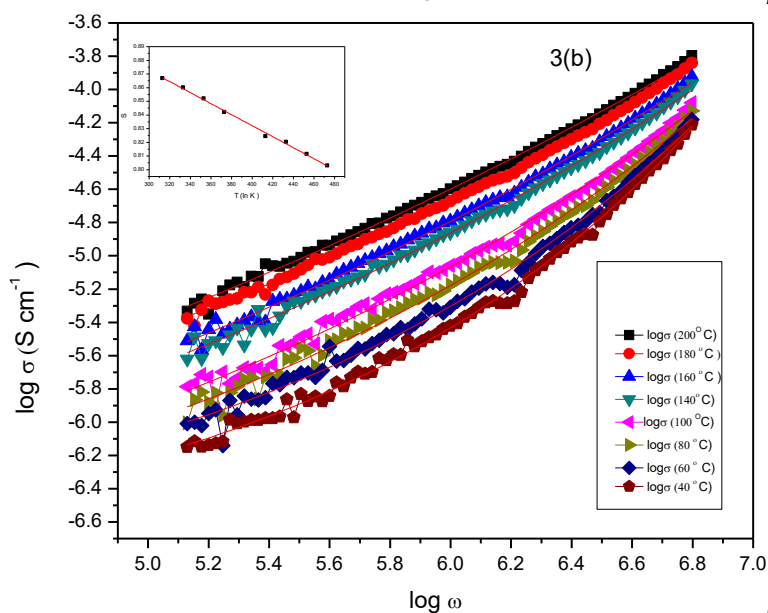


Figure 3(b)

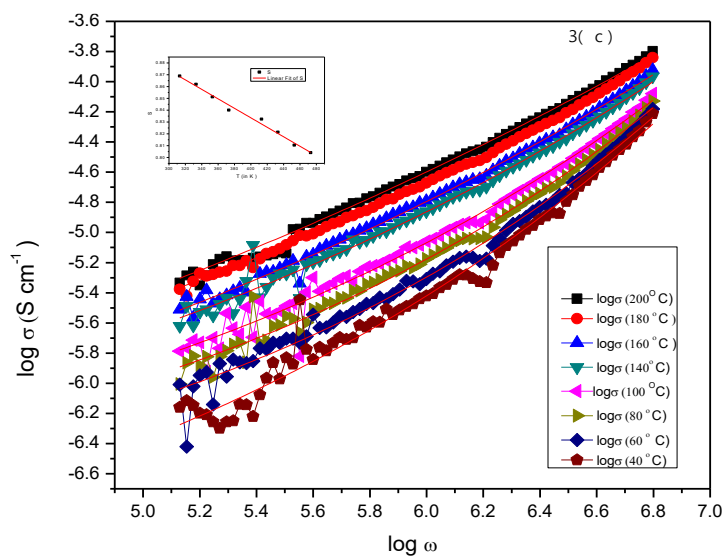


Figure 3(c)

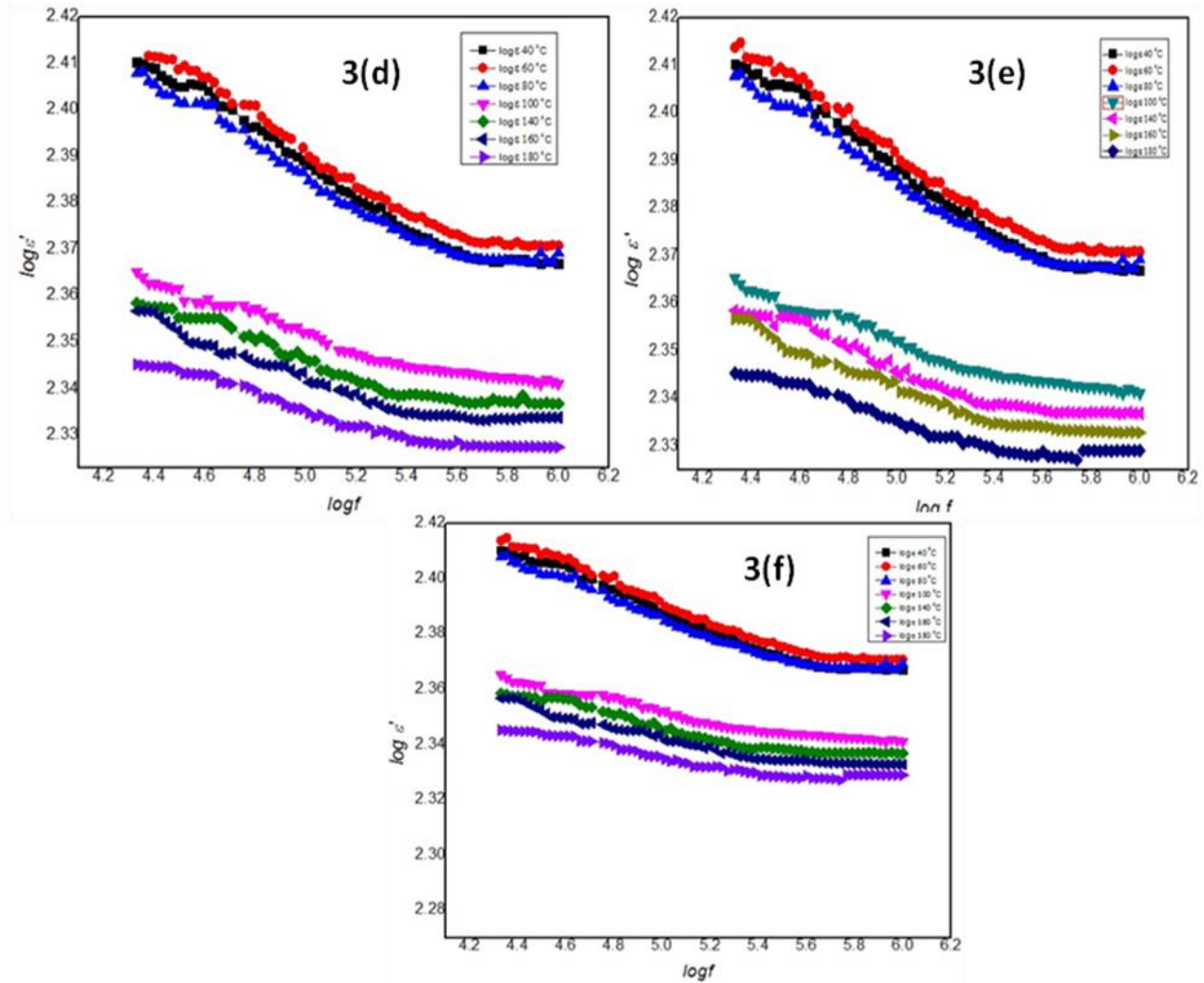


Figure 3. (a) Graph of a.c conductivity of 0.5 wt% Mn doped MgO nanoparticle, (b) Graph of a.c conductivity of 1.0 wt% Mn doped MgO nanoparticle, (c) Graph of a.c conductivity of 1.5 wt% Mn doped MgO nanoparticle, (d) Graph of dielectric constant vs. Frequency of 0.5 wt% Mn doped MgO nanoparticle, (e) Graph of dielectric constant vs. Frequency of 1.0 wt% Mn doped MgO nanoparticle, (f) Graph of dielectric constant vs. Frequency of 1.5 wt% Mn doped MgO nanoparticle

Figure 3(a), 3(b) and 3(c) shows that for different concentration of Mn doped MgO nanoparticles, the dielectric permittivity ϵ increases at a fixed temperature as frequency (f) decreases. The dielectric constant's real part shows a sharp increase at low frequencies, pointing to significant dispersion driven by charge diffusion between electrodes. This low-frequency behavior is also connected to the freezing of electric dipoles via a relaxation process, which causes polarization to decrease with changes in the applied field. The material's inhomogeneous nature further restricts charge carrier movement in conductive areas. To understand these phenomena comprehensively, we investigated the total AC conductivity of the synthesized Mn-doped MgO nanoparticles. This study spanned a frequency range of 20 Hz to 1

MHz and a temperature range from room temperature to 523 K. From the measured data it is observed that at lower frequency region the conductivity is almost independent of frequency but at higher frequency region conductivity increases with frequency, so it is frequency dependent. From Jonscher's power law variation, total conductivity (σ') can be written as [24,25].

$$\sigma'(f) = \sigma_{dc} + \sigma_{ac}(f) = \sigma_{dc} + \gamma f^n \quad (2)$$

where $0 < n < 1$. Here σ_{dc} , γ and n are the dc conductivity, temperature-dependent constant, and power-law exponent ($n \leq 1$). The changes of total conductivity (σ') at different temperatures with frequency for the different doped samples by Figure 3(a) - (c).

We can calculate the value of σ_{dc} and n at different temperatures by fitting equation (2). The changing frequency exponent with variation of temperature for each sample shown in the inset of the figures. The varying exponent 'n' can be attributed to a significant electron-phonon interaction and a narrow conduction band [28]. Notably, 'n' may initially decrease with rising temperature before subsequently increasing, a behaviour consistent with the overlapping large polaron tunneling model [29]. Correlated Barrier Hopping model (CBH) [30] is responsible for the hopping of charges over the barrier and it is also significant to explain the conduction process. Frequency exponent 'n' can be represented by

$$n = 1 - \frac{6k_B T}{[W_H - k_B T \ln(\frac{1}{\omega \tau_0})]} \quad (3)$$

The parameters τ_0 and W_H represent the relaxation time and effective barrier height,

respectively. Notably, the frequency exponent variation 'n' is independent of frequency [31], when value of the parameter $W_H/k_B T$, is very large. In the figure, points represent theoretical data, while a solid line shows the theoretical best fit. The best fitted value of W_H and τ_0 for 0.5 wt %, 1.0 wt% and 1.5 wt% Mn doped MgO nanoparticles are respectively (1.07 eV and 6.04×10^{-13} s), (1.18 eV and 6.09×10^{-13} s)

3.2. Antibacterial characterization

Figure 4(a) and 4(b) shows the TEM image of cell structure of *E.coli* and *Bacillus sp.* without any treatment of 0.5 wt %, 1.0 wt% and 1.5 wt% Mn doped MgO and Figure 4(c)-(d) represent the TEM image of *E.coli* and *Bacillus sp.* after treatment of Mn doped MgO nanoparticles on it. A distinct disruption of cell wall for pathogen strain after the treatment of different concentration of Mn doped MgO nanoparticle is observed.

Table 1. Zone sizes in agar cup media: Inclusive of bore / well /cup diameter 9 mm

Name of pathogens↓	Diameter of inhabitation zone						
	Concentration of 0.5 wt% Mn doped MgO nanoparticle↓						
	0 µg/ml	1.5 µg/ml	2.5µg/ ml	3.5µg / ml	4.5µg / ml	5.5µg / ml	6.5µg / ml
<i>E.coli</i>	9 mm	9 mm	9mm	14.5 mm	16 mm	16.5 mm	17 mm
<i>Bacillus sp.</i>	9 mm	9 mm	9mm	15 mm	16 mm	16.5 mm	17.5 mm
Name of pathogens↓	Concentration of 1.0 wt% Mn doped MgO nanoparticle↓						
	0 µg/ml	1.5 µg/ml	2.5µg/ ml	3.5µg / ml	4.5µg / ml	5.5µg / ml	6.5µg / ml
<i>E.coli</i>	9 mm	9 mm	9 mm	15 mm	16.5 mm	17 mm	18 mm
<i>Bacillus sp.</i>	9 mm	9 mm	9 mm	15 mm	16.5 mm	17.5 mm	18 mm
Name of pathogens↓	Concentration of 1.5 wt% Mn doped MgO nanoparticle↓						
	0 µg/ml	1.5 µg/ml	2.5µg/ ml	3.5µg / ml	4.5µg / ml	5.5µg / ml	6.5µg / ml
<i>E.coli</i>	9 mm	9 mm	9 mm	14 mm	16 mm	17 mm	17.5 mm
<i>Bacillus sp.</i>	9 mm	9 mm	9 mm	15 mm	16 mm	17 mm	17.5 mm

After treatment of 0.5 wt% ,1.0 wt% and 1.5 wt% Mn doped MgO nanoparticles, it is observed that different morphological changes can be seen in both the pathogens. The overall shapes of both the pathogens are found to be changed for different concentration of Mn doped MgO nanoparticle in comparison to the untreated samples. The result of agar-cup method shows that there are no changes

in the cup size of 0.5 wt%, 1.0 wt% and 1.5 wt% Mn doped MgO nanoparticles up to a concentration of 1.5 µg/ml for the treatment of *E.coli* and *Bacillus sp.* The zone sizes in agar cup medium has been reported in table 1, from which it is shown that the killing effect is relatively more pronounced in case of *Bacillus sp.* than the *E.coli*.

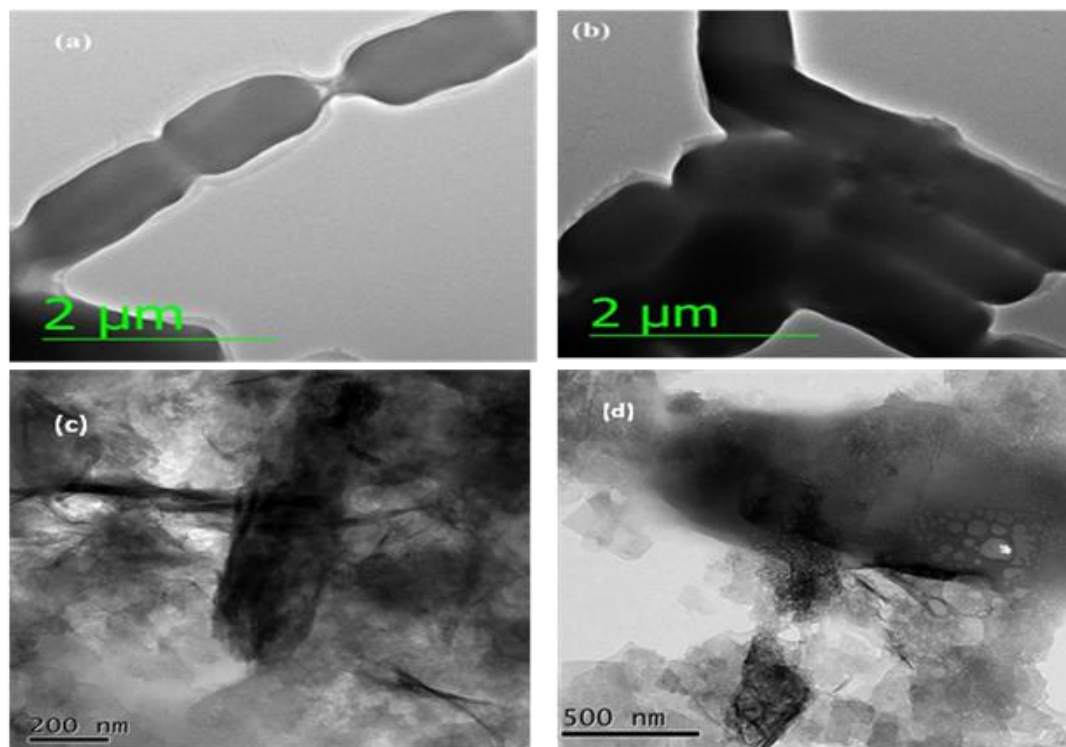


Figure 4. (a) TEM images of cell structure of untreated *E. coli*, (b) TEM images of cell structure of untreated *Bacillus sp.*, (c) TEM images of cell structure of *E. coli* after the treatment with 1.5 wt% Mn doped MgO nanoparticle, (d) TEM images of cell structure of *Bacillus sp.* after the treatment with 1.5 wt% Mn doped MgO nanoparticle

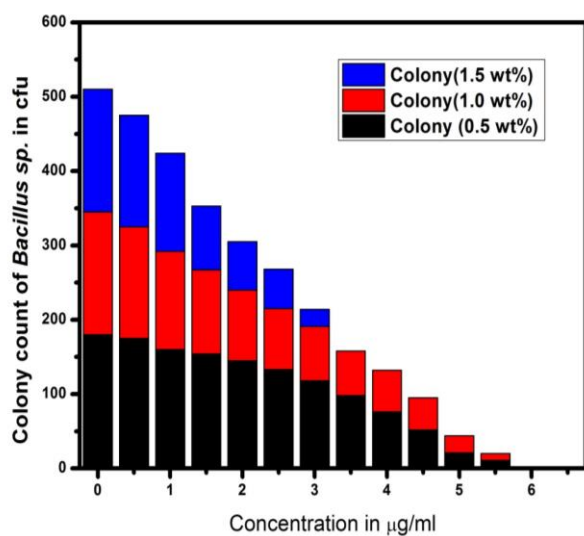


Figure 5. (a) Plot of number of colonies *E. coli* with respect to the concentration of 0.5 wt% Mn doped MgO nanoparticles to calculate MIC, (b) Plot of number of colonies *E. coli* with respect to the concentration of 1.0 wt% Mn doped MgO nanoparticles to calculate MIC, (c) Plot of number of colonies *E. coli* with respect to the concentration of 1.5 wt% Mn Doped MgO nanoparticles to calculate MIC

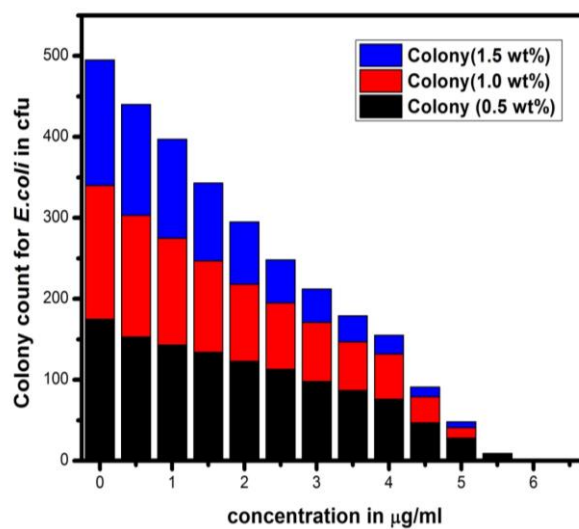


Figure 6. (a) Plot of number of colonies *Bacillus sp.* with respect to the concentration of 0.5 wt% Mn doped MgO nanoparticles to calculate MIC, (b) Plot of number of colonies *Bacillus sp.* with respect to the concentration of 1.0 wt% Mn doped MgO nanoparticles to calculate MIC, (c) Plot of number of colonies *Bacillus sp.* with respect to the concentration of 1.5 wt% Mn doped MgO nanoparticles to calculate MIC

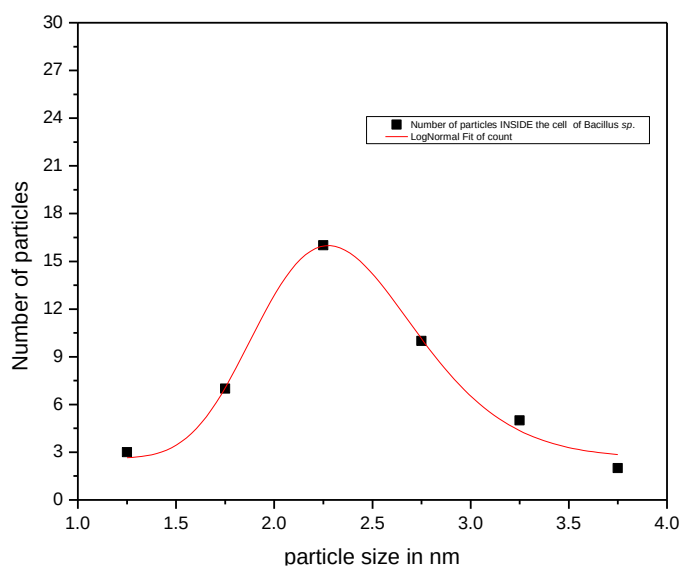


Figure 7 (a)

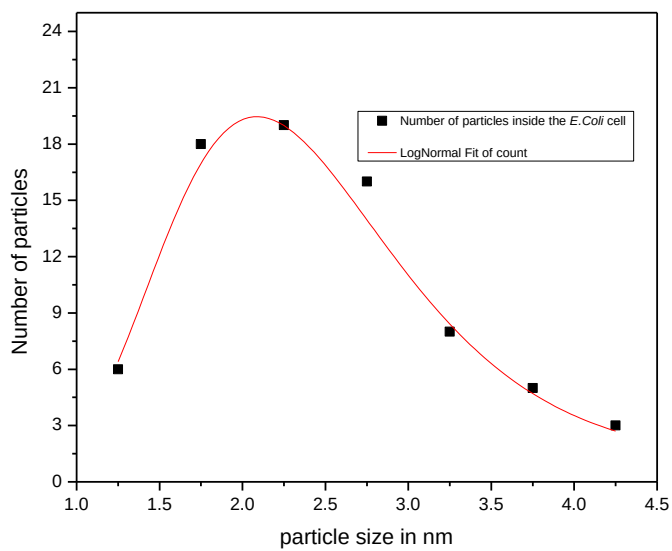


Figure 7(b)

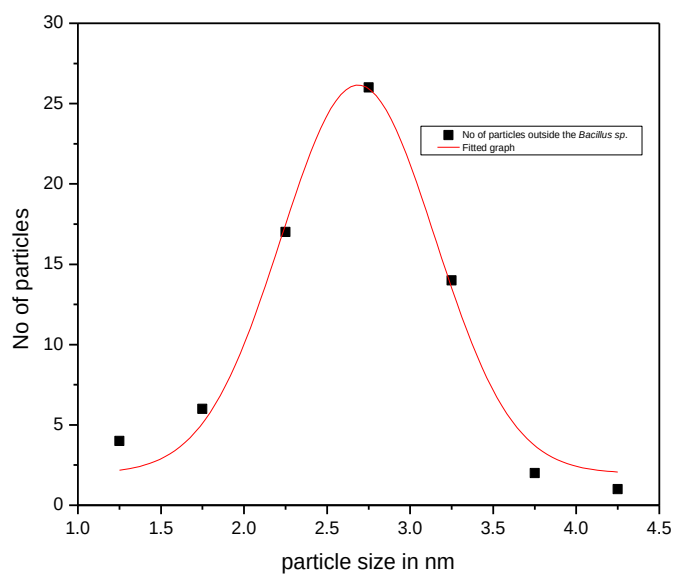


Figure 7(c)

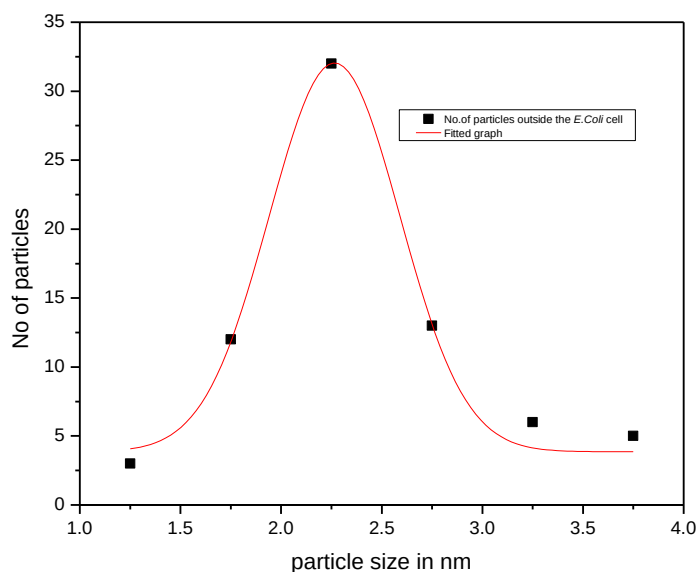


Figure 7(d)

Figure 7. (a) Plot of log normal distribution of number of particles inside the cell of *Bacillus sp.* treated with Mn doped MgO nanoparticles, (b) Plot of log normal distribution of number of particles outside the cell of *Bacillus sp.* treated with Mn doped MgO nanoparticles, (c) Plot of log normal distribution of number of particles inside the cell of *E. coli* treated with Mn doped MgO nanoparticles, (d) Plot of log normal distribution of number of particles outside the cell of *E. coli* treated with Mn doped MgO nanoparticles

The MIC levels of *E. coli* and *Bacillus sp.* are shown in the Figure 5(a)-(c) and 6(a)-(c). The result is inconsistent with the agar-cup method showing an MIC of 1.75 $\mu\text{g/ml}$ in case of *Bacillus sp.* and that of 2.75 $\mu\text{g/ml}$ for *E. coli*. Thus *Bacillus sp.* seems to be more sensitive than *E. coli* as far as the antibacterial activity of Mn doped MgO nanoparticles is concerned. The particle sizes inside and outside the cell of both the bacteria is almost similar. Log normal distribution of number of particles with particle size (inside the cell and outside the cell) for *Bacillus sp.* and *E. coli* treated with 1.5 wt% Mn doped MgO is shown in Figure 7(a)-(d).

4. DISCUSSION

TEM analysis confirmed the entry of Mn-doped MgO nanoparticles into microbial cells, showing their direct impact on cell walls. The antibacterial mechanism of these nanoparticles is primarily linked to their chemical properties. Studies suggest this activity stems from two main factors: The release of toxic metal ions and The generation of intracellular reactive oxygen species (ROS) within the microbes. Furthermore, the ferromagnetism observed in Mn-doped MgO nanoparticles, a distinct property compared to bulk MgO's diamagnetic ordering [32] plays a crucial role. This ferromagnetism promotes the formation of oxygen vacancies on the nanocrystal surface [33-35], which are then adsorbed onto the bacterial cell

surface [36]. Ultimately, the antimicrobial action of any substance, including these nanoparticles, is surmised to involve the disruption of the bacterial cell membrane, leading to altered membrane characteristics, changes in permeability, and the breakdown of respiratory functions, which causes cell death [34, 37]. Superoxide radicals are very sensitive species. These radicals induce their effect by breaking of the carbonyl group of the peptide cross-linkages of the cell wall peptidoglycan. In the study we understand that gram positive bacteria shows more antibacterial activity in comparison with gram negative bacteria due to the existence of extra one barrier in the membrane where superoxide radicals cannot diffuse easily. Another important parameter for exhibit good antibacterial activity for the Mn doped MgO nanoparticles is particle size. Moreover, different factors which is related with death of bacterial cell by this nanocomposite could be associated to its structure, size and surface properties of the composite since smaller particles with larger surface area shows more antibacterial activity with respect to larger nanoparticles [38, 39].

Increased surface area leads to a greater number of reactive groups on particle surfaces. Bacterial cell shape is regulated by proteins such as FtsZ, MerB, and crescentin. Specifically, MreB protein plays a crucial role in cell wall remodeling. Depolymerization of MreB can cause *E. coli* cells to

transition from a rod shape to a spherical shape. When treated with Mn-doped MgO nanoparticles, the Minimum Inhibitory Concentration (MIC) for *E. coli* was 2.75 µg/ml, while for *Bacillus* sp. it was 1.75 µg/ml. In contrast, using undoped MgO nanoparticles resulted in higher MICs: 3.75 µg/ml for *E. coli* and 3.0 µg/ml for *Bacillus* sp. [36]. Therefore Mn doped MgO exhibits more antibacterial activity instead of MgO nanoparticles towards the bacterial pathogens.

5. CONCLUSION

From our work we find that Mn doped MgO nanoparticles exhibit more antibacterial activity in comparison with MgO nanoparticles. The concentration required for checking antibacterial phenomenon using Mn doped MgO nanoparticle is less instead of MgO nanoparticles. From the study of electrical properties of different concentration of Mn doped MgO nanoparticles, we have found that at fixed temperature for the different concentration of Mn doped MgO nanoparticles dielectric permittivity of the sample increases as the frequency decreases. For the sample of different concentration of Mn doped MgO nanoparticles the value of frequency dependent constant (ϵ'') decreases as the temperature increases and relaxation time is $\sim 10^{-13}$ sec.

Acknowledgements

This work has been accomplished under the supervision of Asansol Engineering College, and Botany Department of B.B. College, Asansol. The author considers the principal assistance accepted from the above organizations.

6. REFERENCES

- [1] S. P. Bharti, E. Singh, U. Kumar, Synthesis and characterization of nickel doped tin oxide nanoparticles by hydrothermal method, *Nanosci. Nanotech. Res.*, 2017, 4 (3), 115–119. <https://doi.org/10.12691/nnr-4-3-5>
- [2] R.S. Raveendra, P.A. Prashanth, B. Daruka Prasad, S. Chandra Nayaka, G.P. Suresha, B.M. Nagabhushana, H. Nagabhushana, N.P. Bhagya, Synthesis, characterization and antibacterial activity of zinc ferrite nanopowder, *Int. Jour. of Sci. Res.*, 2013, 1 (4), 543–547. <https://doi.org/10.15373/22778179/APR2013/182>
- [3] F.H. Soares Jr., A.V.B. Pinheiro, Marco Antonio Morales Torres, Joao Maria Soares, Novel one-pot preparation of CoFe₂O₄-Ag nanocrystalline powders, *J. Material Letters*, 113, 2013, 67–70. <https://doi.org/10.1016/j.matlet.2013.09.071>
- [4] Genchi, G.G. Marino, A.; Tapeinos, C.; Ciofani, G. Smart Materials Meet Multifunctional Biomedical Devices: Current and Prospective Implications for Nanomedicine. *Front. Bioeng. Biotechnol.* 5, 2017, 80. <https://doi.org/10.3389/fbioe.2017.00080>
- [5] Patra, J.K. Das, G. Fraceto, L.F. Campos, E.V.R. Rodriguez-Torres, M.d.P.; Acosta-Torres, L.S.; Diaz-Torres, L.A.; Grillo, R.; Swamy, M.K.; Sharma, S.; et al. Nano based drug delivery systems: Recent developments and future prospects. *J. Nanobiotechnol.* 16, 2018, 71. <https://doi.org/10.1186/s12951-018-0392-8>
- [6] Huh, A.; Kwon, Y.J. "Nanoantibiotics": A new Paradigm for Treating Infectious Diseases Using Nanomaterials in the Antibiotics Resistant Era. *J. Control. Release Soc.* 2011, 156, 128–145. <https://doi.org/10.1016/j.jconrel.2011.07.002>
- [7] Lee, N.-Y.; Ko, W.-C.; Hsueh, P.-R. Nanoparticles in the Treatment of Infections Caused by Multidrug-Resistant Organisms. *Front. Pharmacol.* 10, 2019, 1153. <https://doi.org/10.3389/fphar.2019.01153>
- [8] Aghebati-Maleki, A.; Dolati, S.; Ahmadi, M.; Baghbanzadeh, A.; Asadi, M.; Fotouhi, A.; Yousefi, M.; Aghebati-Maleki, L. Nanoparticles and cancer therapy: Perspectives for application of nanoparticles in the treatment of cancers. *J. Cell. Physiol.* 235, 2020, 1962–1972. <https://doi.org/10.1002/jcp.29126>
- [9] Nune, S.K.; Gunda, P.; Thallapally, P.K.; Lin, Y.-Y.; Laird Forrest, M.; Berkland, C.J. Nanoparticles for biomedical imaging. *Expert Opin. Drug Deliv.* 6, 2009, 1175–1194. <https://doi.org/10.1517/17425240903228031>
- [10] Wolfbeis, O.S. An overview of nanoparticles commonly used in fluorescent bioimaging. *Chem. Soc. Rev.* 44, 2015, 4743–4768. <https://doi.org/10.1039/c4cs00392f>
- [11] Boschi, F.; De Sanctis, F. Overview of the optical properties of fluorescent nanoparticles for optical imaging. *Eur. J. Histochem. EJH* 61, 2017, 2830. <https://doi.org/10.4081/ejh.2017.2830>
- [12] Varna, M.; Xuan, H.V.; Fort, E. Gold nanoparticles in cardiovascular imaging. *Wires Nanomed. Nanobiotechnol.* 10, 2018, 1470. <https://doi.org/10.1002/wnan.1470>
- [13] Kumar, V.V., Anthony, S.P., Antimicrobial studies of metal and metal oxide nanoparticles. In *Surface Chemistry of Nanobiomaterials*; Grumezescu, A.M., Ed.; William Andrew Publishing: Norwich, UK, 2016; 265–300. <https://doi.org/10.1016/B978-0-323-42861-3.00008-1>
- [14] K. Karthik, S. Dhanuskodi, C. Gobinath, S. Prabukumar, S. Sivaramakrishnan, Fabrication of MgO nanostructures and its efficient photocatalytic, antibacterial and anticancer performance, 190, 2019, 8–20. <https://doi.org/10.1016/j.ijbiomac.2018.11.166>
- [15] Xiaojia He, Hueng, Huey-min Hwang, The current application of nanotechnology in food and agriculture, 27, 2019, 1–21. <https://doi.org/10.1080/10643389.2018.1538888>
- [16] Laurenti, M.; Cauda, V. Porous Zinc Oxide Thin Films: Synthesis Approaches and Applications. *Coatings* 2018, 8, 67. <https://doi.org/10.3390/coatings8020067>
- [17] Znaidi, L. Sol-gel-deposited ZnO thin films: A review. *Mater. Sci. Eng. B* 2010, 174, 18–30.

- <https://doi.org/10.1016/j.mseb.2010.07.001>
- [18] Bagga, S.; Akhtar, J.; Mishra, S. Synthesis and applications of ZnO nanowire: A review. *AIP Conf. Proc.* 2018, 1989, 020004. <https://doi.org/10.1063/1.5047680>
- [19] Cauda, V.; Pugliese, D.; Garino, N.; Sacco, A.; Bianco, S.; Bella, F.; Lamberti, A.; Gerbaldi, C. Multi-functional energy conversion and storage electrodes using flower-like Zinc oxide nanostructures. *Energy* 2014, 65, 639–646. <https://doi.org/10.1016/j.energy.2013.12.051>
- [20] Yi, G.-C.; Wang, C.; Park, W.I. ZnO nanorods: Synthesis, characterization and applications. *Semicond. Sci. Technol.* 2005, 20, S22–S34. <https://doi.org/10.1088/0268-1242/20/4/003>
- [21] Li, Y.B.; Bando, Y.; Sato, T.; Kurashima, K. ZnO nanobelts grown on Si substrate. *Appl. Phys. Lett.* 2002, 81, 144–146. <https://doi.org/10.1063/1.1485122>
- [22] Garino, N.; Limongi, T.; Dumontel, B.; Canta, M.; Racca, L.; Laurenti, M.; Castellino, M.; Casu, A.; Falqui, A.; Cauda, V. A Microwave-Assisted Synthesis of Zinc Oxide Nanocrystals Finely Tuned for Biological Applications. *Nanomaterials* 2019, 9, 212. <https://doi.org/10.3390/nano9020212>
- [23] Phokha S., Klinkaewnarong J., Hunpratub S., Boonserm K., Swatsitang E., Maensiri S. Ferromagnetism in Fe doped MgO nanoparticles, *Journal of material Science: materials in Electronics*, 27, 33-39 (2016). <https://doi.org/10.1007/s10854-015-3730-x>
- [24] M. Mirsaneh, E. Furman, J. V. Ryan, M. T. Lanagan, C. G. Pantano, "Frequency dependent electrical measurements of amorphous GeSbSe chalcogenide thin films", *Applied physics letters*, 96, 112907 (2010). <https://doi.org/10.1063/1.3360226>
- [25] N.Chakchouk, K.Karoui, N.Drissi, A.Fjomni, A. Ben Rhaïem (2024) An Investigation Of Structural, Thermal, And Electrical Conductivity Properties For Understanding Transport Mechanisms Of Cu₂O₄ And A-Cu₂O₄ Compounds, *RSC Adv.* 14(1), 46–58, <https://doi.org/10.1039/d3ra07453f>
- [26] M. Pollak, On frequency dependence of conductivity in amorphous solids, *Philos. Mag.* 23 (1991) 519–542. <https://doi.org/10.1080/14786437108216397>
- [27] A.Ghosh (1990) Transport properties of vanadium germinate glassy semiconductor, *Phys. Rev. B*, 42 5665–5676. <https://doi.org/10.1103/PhysRevB.42.5665>
- [28] A. Duran, E. Verdin, R. Escamilla, F. Morales, R. Escudero, *Materials Chem. And Phys.* 133 (2012) 1011–1017. <https://doi.org/10.1016/j.matchemphys.2012.01.096>
- [29] Pravin Kumar Singh, S.K. Sharma, S.K. Tripathi, D.K. Dwivedi, "Study of dielectric relaxation and thermally activated a.c. conduction in multi component Ge₁₀–xSe₆₀Te₃₀ In_x (0 ≤ x ≤ 6) chalcogenide glasses using CBH model", *Results in Physics*, 12(2019), 223–236. <https://doi.org/10.1016/j.rinp.2018.11.082>
- [30] D. M. Habashy, H. E. Atyia, H. I. Lebda, "Exploring conduction mechanisms in chalcogenide thin films: an experimental and soft computing approach with ANN and GP techniques", *The European Physical Journal Plus*, 138, (2023), 798. <https://doi.org/10.1140/epjp/s13360-023-04403-8>
- [31] Ghosh M, Barman A, De S.K and Chatterjee S., "Transport properties of HCl doped polyaniline and polyaniline–methyl cellulose dispersion", 1998 *J. Appl. Phys* 84 806. <https://doi.org/10.1063/1.368141>
- [32] G. Sharma, P. Jeevanandam, Synthesis of MgO supported Co₃O₄ nanoparticles by a novel thermal decomposition approach and studies on their magnetic properties" *Microporous Mesoporous Mater.* 165, 55 (2013). <https://doi.org/10.1016/j.micromeso.2012.07.037>
- [33] S.Azzaza, M.El-Hilo, S.Narayanan, J.J.Vijaya, N.Mamouni, A.Benyoussef, A. El Kenz, M. Bououdina, "Tuning optical bandgap of crystalline MgO by MeV Co ion beam induced defects", *Mater. Chem. Phys.* 143, 1500 (2014). <https://doi.org/10.1016/j.micromeso.2012.07.034>
- [34] ChN Rao, U.T. Nakate, R.J. Choudhary, S.N. Kale, "Approaches to synthesize MgO nanostructures for diverse applications", *Appl. Phys. Lett.* 103, 151107 (2013). <https://doi.org/10.1016/j.heliyon.2020.e04882>
- [35] B. Choudhury, A. Choudhury, *Mater. Res. Express* 1, 025026 (2014). <https://doi.org/10.1088/2053-1591/1/2/025026>
- [36] J.Maji, S.Basu, S.Pandey, "Synthesis and evaluation of antibacterial properties of MgO nanoparticles", *Bull. Mater Sci*, 43, 0025 (2019), <https://doi.org/10.1007/s12034-019-1963-5>
- [37] K. Ramanujam and M. Sundarajan, "Antibacterial effects of biosynthesized MgO nanoparticles using ethanolic fruit extract of *Embllica officinalis*", *Journal of Photochemistry and Photobiology B: Biology*, vol. 141, 296–300, 2014. <https://doi.org/10.1016/j.jphotobiol.2014.09.011>
- [38] Y. H Leung, A. Ng, X. Xu et al., "Mechanisms of antibacterial activity of MgO: non-ROS mediated toxicity of MgO nanoparticle towards *Escherichia coli*", *Small*, 10 ; 6, pp. 1171–1183, 2014. <https://doi.org/10.1002/sml.201302735>
- [39] K. R. Raghupathi, R. T. Koodali, and A. C. Manna, "Size dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles," *Langmuir*, 27; 7, 4020–4028, 2011. <https://doi.org/10.1021/la104825u>

IZVOD

ISTRAŽIVANJE Mn-DOPIRANIH MgO NANOČESTICA: MEKI HEMIJSKI PUT DO POBOLJŠANE ELEKTRIČNE I ANTIBAKTERIJSKE FUNKCIONALNOSTI

Mn-dopirane MgO nanočestice (kristalna veličina 8 nm) sintetizovane su korišćenjem jednostavne meke hemijske metode. Njihova antibakterijska aktivnost protiv gram-pozitivnih i gram-negativnih patogena procenjena je korišćenjem MIC, živog brojanja i testova u agar šoljicama. AC provodljivost i dielektrična svojstva merena su na različitim temperaturama, a mehanizam transporta naelektrisanja ispitan je korišćenjem CBH modela. Transmisiona elektronska mikroskopija (TEM) otkrila je poremećaj ćelijskog zida kod patogena tretiranih Mn-dopiranim MgO nanočesticama. Antibakterijska aktivnost se povećavala sa koncentracijom nanočestica. Ovi nanomaterijali pokazuju obećanje kao antibakterijski agensi za medicinske primene, u očekivanju uspešnih in vivo ispitivanja.

Ključne reči: MgO dopiran Mn, nanočestica, antibakterijska aktivnost, superoksidni radikal, sol-gel mehanizam, poremećaj ćelijskog zida.

Naučni rad

Rad primljen: 06.12.2025.

Rad korigovan: 24.04.2026.

Rad prihvaćen: 26.04.2026.

Joyshree Maji 0000-0001-6633-9080

© 2026 Authors. Published by Engineering Society for Corrosion. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>)