

Antibiofilm Activity of MnO_2/MgO Nanocomposite Synthesized by Nonthermal Plasma

Niran K. Ali ^{a, }, Raghad S. Mohammed ^{a, }, and Jamoliddin Razzokov ^{b, }

^aDepartment of Physics, College of Science, Mustansiriyah University, Baghdad, Iraq

^bInstitute of Fundamental and Applied Research, National Research University TIIAME, Tashkent, Uzbekistan

CORRESPONDENCE

Raghad S. Mohammed
raghad.almaliki@uomustansiriyah.edu.iq

ARTICLE INFO

Received: May. 24, 2026

Revised: Aug. 27, 2026

Accepted: Sep. 04, 2026

Published: Sep. 30, 2026



© 2026 by the author(s).
Published by Mustansiriyah University. This article is an Open Access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

ABSTRACT: Background: Non-thermal plasma (NTP) is a partially ionized gas that generates reactive species at near-ambient temperatures without causing significant thermal effects. NTP devices have been developed through advances in plasma physics research. The reactive species produced by NTP can be used to synthesize biological nanomaterials and improve human health. **Objective:** This study presents the synthesis of a nanocomposite using a plasma jet technique for antibiofilm activity, a method considered environmentally friendly. **Methods:** The physical properties of the MnO_2/MgO nanocomposite were characterized using various analytical techniques. **Results:** Energy-dispersive X-ray (EDX) analysis confirmed the purity of the synthesized sample, detecting only Mn, Mg, and O elements corresponding to the nanocomposite. X-ray diffraction (XRD) analysis verified the crystal structure, revealing an average crystallite size of 64 nm composed of cubic and hexagonal phases. Fourier-transform infrared (FT-IR) spectroscopy confirmed the presence of active functional groups. Field emission scanning electron microscopy (FE-SEM) images showed an irregular, porous morphology with a sponge-like continuous surface formed by aggregated fine grains. The ultraviolet-visible (UV-Vis) absorption spectra showed that the MnO_2/MgO nanocomposite had an energy band gap of 4.7 eV and strong absorption at 222 nm. The nanocomposite exhibited high susceptibility to biofilm-forming *Pseudomonas aeruginosa* and *Staphylococcus aureus*. **Conclusions:** This research offers promising advancements in biosafety standards and may reduce the risk of nosocomial infections in hospital and industrial environments.

KEYWORDS: Antibiofilm; Biological application; Plasma jet; *Staphylococcus aureus*; *Pseudomonas aeruginosa*

INTRODUCTION

Nanoparticles exhibit distinct physical, chemical, and biological characteristics from bulk materials and, for this reason, a lot of effort has been given to their development in materials science and engineering [1]. Metal oxide nanocomposites are one of the nanomaterials that have gained much interest recently because of the wide range of sectors in which they could be used. Some of these sectors are biomedicine, catalysis, energy storage, and optoelectronics [2]. Metal oxide nanoparticles are inorganic materials at the nanoscale (<100 nm) with specific properties such as antibacterial activity, the ability to target a wide range of bacteria, high surface area that can interact with the cells, high stability even when subjected to extreme conditions, and the possibility of being tailored in terms of size, shape, surface properties, and chemical composition. These properties give a high potential for the development of nanoparticles as efficient antibacterial agents [3]. Reduction of metal ions in solutions is one of the several ways available for nanoparticles (NPs) production and is a potent method for the synthesis of NPs with different sizes, shapes, and compositions [4], [5]. One of the most investigated areas nowadays is nanotechnology, which has applications in different industries like biochemistry, electronics, optical sensing, medication delivery, antimicrobial coatings, energy storage, agriculture, cancer therapy, disease, and diagnosis [6]. These materials have many

desirable properties for many applications. However, it is still a problem to develop effective procedures to synthesize nanomaterials [7]. The most advanced techniques of NPs production are physical processes [8], photocatalysts [9], [10], biological methods [11].

In recent years, there has been an increasing interest in the synthesis of nanomaterials by plasma techniques, as an alternative method to the production of magnetic, metal, and metal oxide nanoparticles. This process may be performed in the ambient environment, using the active species produced in the interaction of plasma with water-based solutions [12], [13]. It has several benefits, such as being environmentally friendly, efficient, economical, and simple. Atmospheric pressure non-thermal plasma (NTP) produces a variety of reactive oxygen species (ROS), such as hydroxyl radicals ($\cdot\text{OH}$), atomic oxygen (O), singlet oxygen ($^1\text{O}_2$), ozone (O_3), hydrogen peroxide (H_2O_2), superoxide radicals ($\text{O}_2^{\cdot-}$), and other short-lived intermediates with oxidizing properties. The high redox potentials of these oxidants make them known as the major chemical oxidants that mediate the oxidation reactions at the plasma-liquid interface. These reactive species are able to reduce metal ions from their salt precursors, which helps to form stable colloidal nanoparticles [14], [15]. Inexpensive production processes, easy control, diversity of their architectures, unique structural properties and possibilities, and versatile applications in medical, engineering, and other industrial domains [6]. Nanoparticles have been widely used as antibiofilm agents to fight multidrug-resistant types of bacteria. Biofilms are collections of bacteria that are attached to surfaces and are composed of proteins, fibrin, and polysaccharides, rendering them proof against exogenous antibacterial agents. These biofilms protect the communities from environmental elements such as biocides, UV radiation, desiccation, temperature, and immunological factors. However, the number of antibiotics required to kill free-floating or isolated bacteria is often less than that required to kill bacterial biofilms, resulting in antibiotic resistance and continued spread of infection [16], [17], [18].

Antibiofilm applications of metal oxide nanoparticles have demonstrated great potential, but there are still challenges to be overcome in finding environmentally friendly methods for nanoparticle synthesis that reduce the amount of harmful chemicals used and preserve the antibiofilm activity of the nanoparticles. Among the two materials, manganese oxide is known to possess high antimicrobial activity due to its redox property, and magnesium oxide is known for its biocompatibility, chemical stability, and antimicrobial property. A nanocomposite of these two metal oxides can be expected to display an enhanced antibiofilm effect due to synergistic effects. Moreover, non-thermal plasma at atmospheric pressure is a green synthesis strategy due to the absence of or use of dangerous chemical reducing agents. Hence, this study was designed to prepare a MnO_2/MgO nanocomposite by the plasma technology and assess the antibiofilm properties of such a material as the environment friendly one.

MATERIALS AND METHODS

Magnesium nitrate hexahydrate, an inorganic compound $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, was obtained from (Sigma-Aldrich, 3050 Spruce St, St. Louis, MO 63103, USA), and Manganese(II) chloride monohydrate, an inorganic compound with $\text{MnCl}_2 \cdot \text{H}_2\text{O}$, was obtained from (Alfa Aesar, 30 Burlington Street, Poughkeepsie, New York 12601, USA).

Setup of the Plasma Device

The schematic of the plasma jet system used to prepare the MnO_2/MgO nanocomposite is shown in Figure 1. The plasma jet setup was assisted by an AC high-voltage power supply of 4 kV operating at 20kHz and two stainless steel electrodes (cathode and anode). The cathode electrode was made into a hollow tube and served as the cathode for the gas to be introduced, and the anode electrode was dipped into a glass beaker of $\text{MnCl}_2 \cdot \text{H}_2\text{O}$ and $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ solution. A flowmeter-controlled Argon gas (99.99% purity) of 2 L/min was used for the discharge, and the experiment was repeated, taking the discharge nozzle to be 1 cm above the liquid surface and the plume length to be 2 cm.

Synthesis of MnO_2/MgO nanocomposite

For a 0.05 M concentration of the MnO_2/MgO nanocomposite, 0.256 g of magnesium nitrate hexahydrate ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) was dissolved in 20 mL of deionized water, and 0.162 g of manganese chloride monohydrate ($\text{MnCl}_2 \cdot \text{H}_2\text{O}$) was placed into 20 mL of deionized water separately. They were each stirred for 10 minutes, using a magnetic stir bar, to ensure complete dissolution, yielding aqueous solutions of manganese (II) chloride (MnCl_2) and magnesium nitrate ($\text{Mg}(\text{NO}_3)_2$). After this, 10 mL of each was then combined in the same container. Finally, the whole mixture was treated with plasma

for 20 minutes to start the reaction and manufacturing process. As soon as the plasma exposure began, we noticed that the color of the mixture started to change from light brown to dark brown, confirming that the nanoparticles had started forming successfully. The synthesized MnO_2/MgO nanocomposite suspension was then deposited on a clean glass substrate using the drop-casting method and dried on a hot plate before being subjected to the necessary characterization analyses.

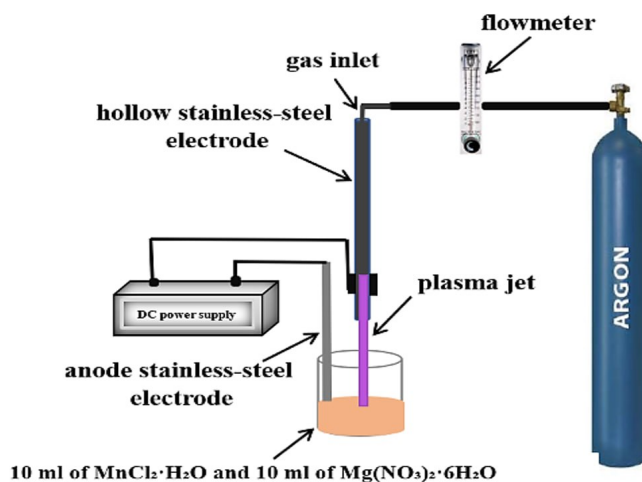


Figure 1. Plasma system setup for the synthesis of MnO_2/MgO nanocomposite

Characterizations of MnO_2/MgO Nanocomposite

The synthesized MnO_2/MgO nanocomposite was characterized using multiple auto analytical technique. The crystal structure of MnO_2/MgO nanocomposite was analyzed using X-ray diffraction (XRD), which was carried out by an X-ray diffraction spectrometer with a $\text{CuK}\alpha$ radiation source ($\lambda = 0.15418 \text{ nm}$) using the generator (PW, 1930) and goniometer (PW, 1820). A Fourier Transform Infrared (FTIR) spectrophotometer was used for FTIR spectroscopy. Transmittance data were collected in the spectral area of $4000\text{--}500 \text{ cm}^{-1}$ with a resolution of 4 cm^{-1} , and with 32 scans per spectrum, to get the best signal-to-noise and to reduce the weaknesses. Field emission scanning electron microscopy (FE-SEM) (Quanta 250-FEG) coupled with energy dispersive X-ray (EDS) analyzer was used to determine the surface topography and the elemental composition of the MnO_2/MgO nanocomposite, respectively, at 30 kV of energy dispersive analysis. Topographical characteristics of the surface were examined by atomic force microscopy, and roughness parameters were calculated. A UV-Vis-NIR Metertech dual-beam spectrometer was used to record the UV-vis absorption spectra of the samples in the $200\text{--}1200 \text{ nm}$ wavelength range.

Biological Procedure

1 Bacterial Isolates

Pathogenic bacteria such as *Staphylococcus aureus* (Gram-positive) and *Pseudomonas aeruginosa* (Gram-negative) were collected from the Department of Biology at Mustansiriyah University in Baghdad (Iraq). The bacteria had been obtained from clinical samples from different hospitals in Baghdad and confirmed by the VITEK2 system. *Staphylococcus aureus* (*S. aureus*) and *Pseudomonas aeruginosa* (*P. aeruginosa*) were chosen because they are both common biofilm-producing pathogens found in medical devices and healthcare-associated infections (HAIs). It is well established that these bacteria form persistent biofilms and have a higher degree of resistance to antimicrobial agents, thereby making them good model organisms to assess the antibiofilm activity of newly synthesized nanomaterials. The bacteria obtained were cultured on Mueller–Hinton agar (HiMedia, India) or in nutrient broth, and a 24-hour incubation at 37°C was used.

2 Antibiofilm Activity of MnO_2/MgO Nanocomposite

The microdilution broth method in a 96-well microtiter plate was used for the estimation of the antibiofilm activity of the MnO_2/MgO nanocomposite. MnO_2/MgO nanocomposite was added into

the wells with 100 μL , in a 1:2 serial dilution, and 100 μL from the last well was discarded. For each bacterial species, 2 μL of an overnight culture of each was added to the wells of a microtiter plate to be allowed to grow. Negative control wells were set up with LB broth alone, grown overnight at 37 °C, and used as a background control for the optical density value. On the next day, the absorbance was determined by an EMax microplate ELISA reader Molecular Devices with optical density (OD) measurement at 600 nm. Antibiofilm activity was also evaluated by using resazurin. This test was repeated twice. Inhibition of biofilm formation was calculated as a percentage by the following equation [19]:

$$\text{Biofilm inhibition}\% = \frac{\text{Control OD} - \text{Treated OD}}{\text{Control OD}} \times 100\% \quad (1)$$

RESULTS AND DISCUSSION

XRD Analysis

The crystal structure and phase purity of the MnO_2/MgO nanocomposite prepared by plasma jet technology at atmospheric pressure were determined using X-ray diffraction (XRD) analysis. Diffraction angles (2θ) were compared with those from literature values of the JCPDS data cards for the nanocomposite. The XRD pattern of the MnO_2/MgO nanocomposite is shown in Figure 2, and it contains seven diffraction peaks in the range 10° to 80° .

Five of the peaks were determined to be in the nanostructured form of the compound manganese dioxide, at 2θ angles of 15.58° , 24.6° , 32.6° , 36.8° , and 42.2° . These peaks are very close to the crystal planes denoted by the Miller indices (110), (221), (103), (211), and (420). With the help of comparison of these results with those of the traditional crystal model (JCPDS card no. 00-035-0821), it is concluded that the crystallographic structure of the prepared sample was a cubic crystal system, which is good evidence for the formation of MnO_2 nanoparticles with the desired crystal structure.

On the other hand, peaks can be seen at 23.8° , 36.9° , and 42.2° , which correspond to (002), (111), and (200) of the cubic structure for MgO (periclase) as given in the reference (JCPDS card no. 45-0946). To avoid possible partial overlaps of peaks of a multiphase system, the overall diffraction pattern was matched against the standard diffraction pattern from the ICDD database in order to identify the phases.

The XRD pattern does not show any other peaks associated with secondary phases for the MnO_2/MgO nanocomposite, which confirms the purity of the synthesized sample. Furthermore, the diffraction angle change in the MnO_2/MgO nanocomposite from the standard data suggests a change in the unique peaks of the MnO_2/MgO nanocomposite.

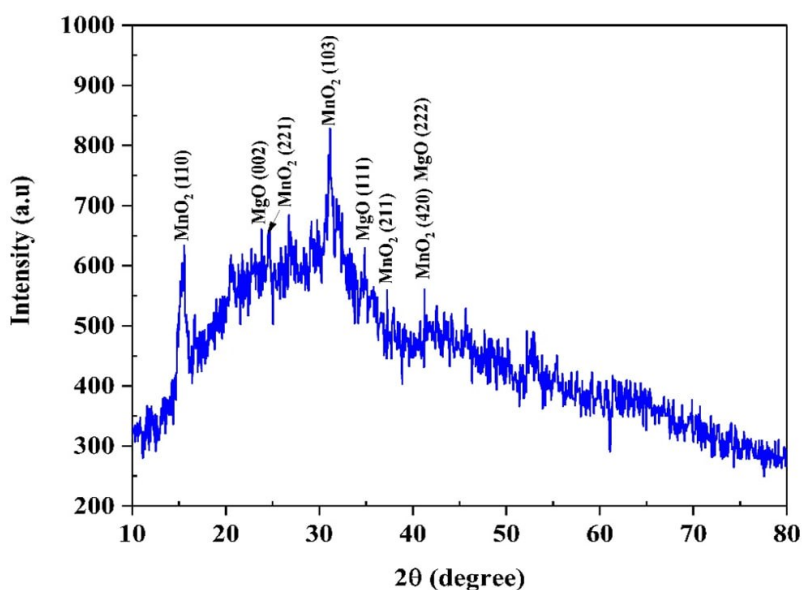


Figure 2. XRD pattern of MnO_2/MgO nanocomposite

The crystallite sizes of the MnO₂/MgO nanocomposite were calculated using the Debye–Scherrer equation, which is given by Eq. (2) [20], [21]:

$$D = \frac{k\lambda}{\beta \cos(\theta)} \quad (2)$$

The FWHM of the peaks at the diffracting angle from the Bragg angle position is denoted as β . The crystallite size is D, with an X-ray wavelength of $\lambda = 1.540 \text{ \AA}$ and Scherrer's constant of $k = 0.9$. The average crystallite size of the MnO₂/MgO nanocomposite was 64 nanometers, as listed in Table 1.

Table 1. Crystal structure parameters for MnO₂/MgO nanocomposite

Sample	Diffraction angle (degrees)	FWHM (nm)	Crystallite size (nm)
MnO ₂	15.58	0.08	100.1
	24.6	0.1	81.5
	32.6	0.12	69.1
	36.8	0.09	93.2
	42.3	0.03	284.6
MgO	23.7	0.1	81.4
	34.8	0.085	98.2
	42.3	0.03	284.6
Average crystallite size			64

EDS Analysis

Using energy-dispersive X-ray (EDX) analysis, the chemical constitution of the MnO₂/MgO NCs produced by plasma jet. The EDS spectra, shown in Figure 3, indicate the existence of main peaks related to the elements Mn, Mg, and O in the MnO₂/MgO nanocomposite. The weight percent of magnesium (Mg) is 31.25%, and the atomic percent is 26.92%. The percentage of manganese (Mn) by weight is 18.21%, and by atomic percentage is 6.94%. By atomic numbers, oxygen (O) is the most abundant element, with 66.14% of the atoms, or a weight percentage of 50.53%. The EDS analysis confirmed that the composition of the MnO₂/MgO nanocomposite was pure, without the presence of any extraneous impurity components. The XRD results confirmed the results found in the present study, where only the phases of MnO₂ and MgO were detected, and no secondary phases were observed. The XRD and EDX analyses show that the plasma jet method is a suitable technique for the synthesis of the MnO₂/MgO nanocomposite.

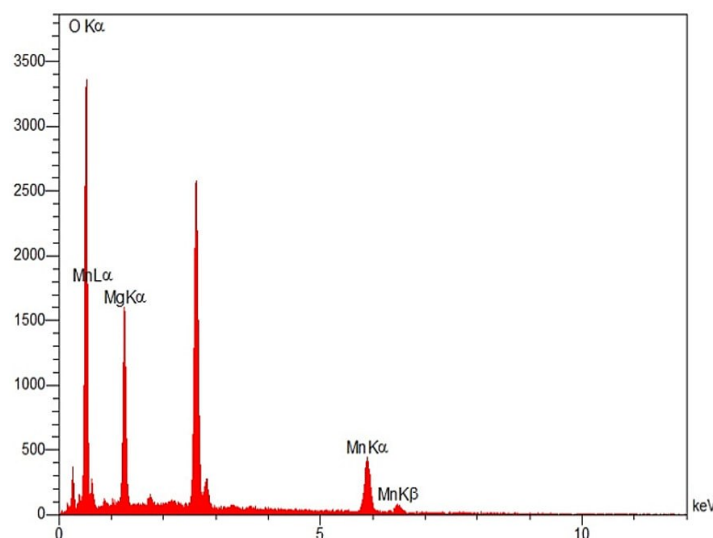


Figure 3. EDX analysis of the MnO₂/MgO nanocomposite

FTIR Analysis

FTIR analysis of the MnO_2/MgO nanocomposite, as shown in Figure 4, depicts several characteristic absorption bands, which indicate the successful formation of the material. The broadband around 3435 cm^{-1} is attributed to the stretching vibration of surface hydroxyl ($-\text{OH}$) groups and adsorbed water molecules. The presence of aliphatic C-H bond stretching vibrations is seen in the weak features at 2923 and 2851 cm^{-1} , which are indicative of the presence of residual organic species. The low absorption at 2168 cm^{-1} could be due to the presence of CO- or $\text{C}\equiv\text{C}/\text{C}\equiv\text{N-}$ type species that are adsorbed. The strong band at 1628 cm^{-1} is attributed to the bending of adsorbed water (H-O-H). The bands at 1380 and 1113 cm^{-1} are assigned to carbonate species and to C-O/M-O-C vibrations, respectively. Finally, the absorption band at 620 cm^{-1} confirms the successful formation of the MnO_2/MgO nanocomposite and is attributed to the vibrations of the metal-oxygen bond (Mn-O and Mg-O).

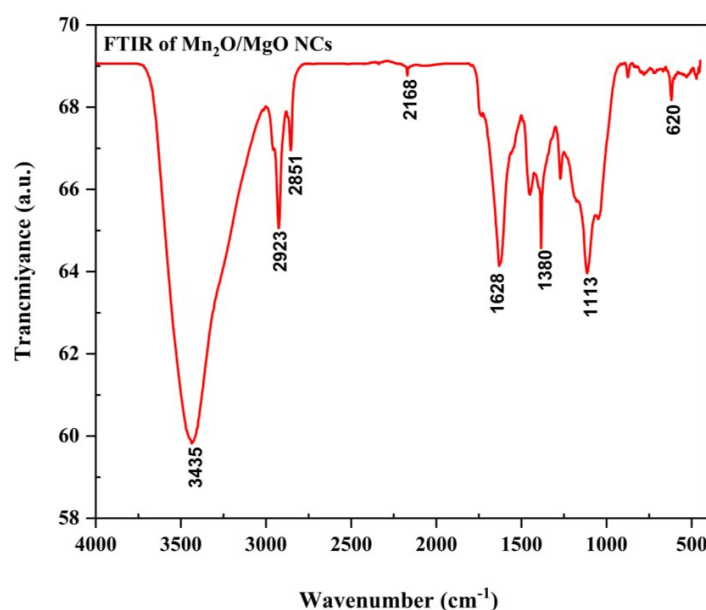


Figure 4. FTIR spectra of MnO_2/MgO nanocomposite

FE-SEM Analysis

The FE-SEM micrograph of the synthesized MnO_2/MgO nanocomposite shows a heterogeneous surface morphology in the form of densely agglomerated particles with irregular shapes and sizes, as shown in Figure 5. The particles seem to be linked together and to create dense clusters in which the interparticle voids are numerous and randomly distributed in the microstructure. This phenomenon of agglomeration is typically seen in nanomaterials of metal oxides due to their high surface energy and larger surface interaction between particles. Additionally, the micrograph suggests some rough surface texture with open voids and inter-particle aggregates, indicating a morphology resembling a porous material.

UV Analysis

The light-absorbing capability of the MnO_2/MgO nanocomposite was analyzed with the help of ultraviolet-visible (UV-Vis) spectroscopy. From the data we obtained, we were able to determine the two most important properties of the material, namely its absorption coefficient and bandgap energy. As shown in Figure 6, the UV-Vis absorption spectrum of the plasma-assisted synthesized MnO_2/MgO nanocomposite shows the presence of a high absorption range with a maximum at 222 nm , which corresponds to intense electronic excitation in the ultraviolet region. The absorption is mostly attributed to charge transfer transitions between oxygen $2p$ and manganese $3d$ orbitals in MnO_2 [22], with the magnesium contribution mostly to the UV region, due to the wide band gap of MgO . The rapid drop in absorbance at longer wavelengths and the almost no absorbance in the visible

region further show the broad band gap of the composite. The observed absorption behavior is in line with the successful synthesis of MnO₂/MgO nanocomposite and in accordance with the reported optical behavior of MnO₂- and MgO-based nanomaterials.

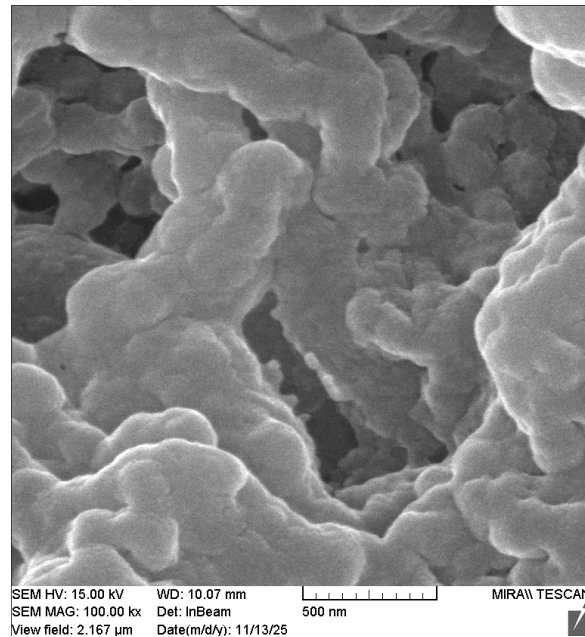


Figure 5. FE-SEM image of MnO₂/MgO nanocomposite

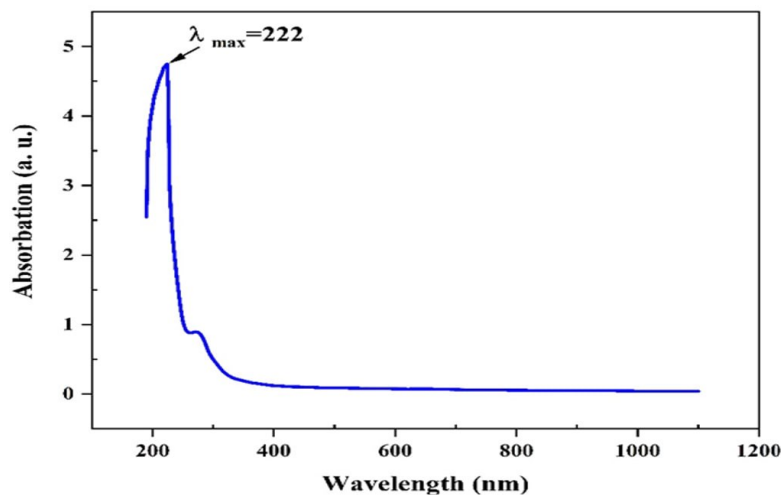


Figure 6. Optical absorption spectra of MnO₂/MgO nanocomposite

The absorbance spectra were used to visually determine the absorption coefficients of the MnO₂/MgO nanocomposite by following the equation from Tauc's [3]:

$$(\alpha h\nu)^r = A(h\nu - E_g) \quad (3)$$

where h is the Planck constant, α is the absorption coefficient, ν is the input photon frequency, A is a constant with a value of 0.9, E_g is the optical energy gap, and r is a parameter that depends on the kind of transition ($r = 2$ for permitted direct transitions). A traditional technique for figuring out the bandgap is to plot photon energy ($h\nu$) versus $(\alpha h\nu)^2$, extending the linear segment to the axis intercept, as shown in Figure 7. The MnO₂/MgO nanocomposite has a bandgap energy (E_g) of 4.7 eV.

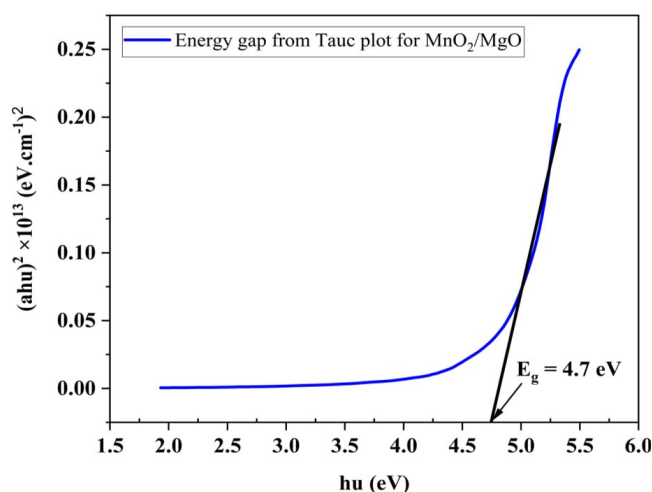


Figure 7. Optical bandgap energy from Tauc's plot of MnO₂/MgO nanocomposite

The obtained value is higher than the typical values reported for pure MnO₂, whose optical band gap is in the range of about 1.3–2.5 eV, depending on the crystallographic phase and the method of preparation of the oxide [23]. In comparison, the optical band gap of bulk MgO is about 7.8 eV [24]. Hence, the measured band gap of the MnO₂/MgO nanocomposite is found between those of its constituents, thus confirming the formation of a heterostructured composite and not a physical mixture. The increasing optical band gap can be explained by the introduction of the wide-bandgap MgO phase, which changes the electronic band structure of the composite. Furthermore, the transition energy of the optical transition depends on the size of the nanoscale crystallites, the electronic interaction between MnO₂ and MgO at the interfaces, and the electronic states related to the defects. The intermediate band gap values are also reported for MgO-based nanostructured composites, in which, by adding MgO, a larger gap is created as compared to narrow band gap transition metal oxides and a lower band gap than the intrinsic band gap of bulk MgO, as surface defects and local energy levels are present in the composites [25].

Antibiofilm Activity of MnO₂/MgO Nanocomposite

According to Table 2, the results showed that the MnO₂/MgO nanocomposite was successful in stopping the development of biofilm. Nevertheless, it successfully combated both Gram-positive and Gram-negative bacteria, including *S. aureus* and *P. aeruginosa*. The comprehensive findings demonstrated a somewhat stronger response from gram-negative bacteria, with *P. aeruginosa*'s biofilm production being decreased by about 65%. The MnO₂/MgO nanocomposite demonstrated a clear efficacy in decreasing biofilm formation against *S. aureus* with an inhibition rate of 50%, indicating its dual effectiveness; nevertheless, the findings for Gram-positive bacteria were satisfactory since their reaction to the chemical was not weak.

Table 2. Efficacy of the MnO₂/MgO nanocomposite in inhibiting biofilm

Bacterial isolates	Average inhibition rate (%)
<i>P. aeruginosa</i>	65 ± 0.25
<i>S. aureus</i>	50 ± 0.31

By organizing themselves into microbial communities, biofilms help bacteria defend against antibiotics and survive. The bacteria produce a protective polymer coating that acts as a robust chemical and physical barrier to prevent the effects of antimicrobial agents and shield the body's germs from them. permeating. Specifically, an antibacterial agent finds it difficult to reach the bottom of the biofilm due to the physical barrier formed by the polymers [26]. Because of the low oxygen levels and steady pH, the environment is perfect for bacteria to enter metabolic hibernation. The conventional antibiotics are far less effective in this state and are difficult to get rid of. When bacteria are at their most active and going through mitosis, the majority of these drugs function best; when they come into contact with dormant bacterial cells in their biofilms, they have no effect at all [27]. Dormant cells

pose a major obstacle to successful therapeutic intervention since they stop vital functions and go into a quiescent biological state, making them difficult to penetrate. Despite outward signs of effective treatment completion, this confers exceptional resistance to even the most powerful antibiotics, increasing the risk of patient relapse and infection recurrence [28]. Because they enable microorganisms to proliferate on natural tissues, surgically implanted devices, and medical components like catheters and prosthetic joints, biofilms are strongly linked to persistent infections. In individuals with the condition, for instance, they may develop internal complications that result in persistent respiratory infections [29].

The size of the accessible pores and the existence of a network of aqueous channels have a significant impact on how nanoparticles spread within the biological membrane [30]. Three primary processes explain the antibacterial properties of nanoparticles. The first is the breakdown of the cell wall structure as a result of the nanoparticle surface's electrostatic attraction or repulsion to the wall's constituent parts. The second is the microbial cell's development of oxidative stress, which results in the production of very reactive oxygen species that harm essential cellular components. The capacity of nanoparticles to interfere with essential cellular processes, the metal ions they release, impair protein function, and harm intracellular components, is the third primary mechanism of their antibacterial action [31]. Additionally, negatively charged bacteria have been shown to adhere to metal oxide nanoparticles more firmly. They attribute this increased binding to these nanoparticles' positively charged surfaces [32]. The structural and optical properties of the synthesized MnO_2/MgO nanocomposite can be correlated with the observed antibiofilm activity. The XRD results confirmed the successful synthesis of crystalline domains, as a crystalline nanocomposite with an average crystallite size of 64 nm was found. The FE-SEM images showed that there were rough and irregularly shaped agglomerated nanoparticles and interconnected voids between the aggregates. As agglomeration of the primary particles prevented the accurate determination of the primary particle size, these morphological features might still represent available surface-active sites for interaction with the bacterial cells and the extracellular polymeric substance (EPS) matrix. Moreover, the large optical band gap (4.7 eV) from the UV-Vis spectroscopy study implies the electronic properties of the MnO_2/MgO nanocomposite. The synergistic results of crystallinity, surface morphology, and electronic properties could be beneficial for increasing interactions between the nanocomposite and the bacterial biofilms, contributing to the inhibition of biofilm formation against both *P. aeruginosa* and *S. aureus*.

CONCLUSION

A nanocomposite of manganese dioxide and magnesium oxide (MnO_2/MgO) was synthesized using plasma technology, an eco-friendly method. The material's structural stability was confirmed by diffraction patterns exhibiting distinct, sharp peaks, indicating that the hybrid compound phases were pure and well-crystallized. X-ray EDS further supported these findings by verifying elemental purity and ideal chemical composition ratios, which ensure the compound's stability. FTIR analysis identified the functional groups, confirming the presence of active compounds. FE-SEM revealed the aggregate's sponge-like porous structure. With an energy band gap of approximately 4.7 eV, the nanocomposite qualifies as a semiconductor and holds potential for advanced electronic applications. Regarding the biological aspect of the study, tests demonstrated the material's effectiveness in inhibiting biofilm formation. This research offers numerous opportunities to enhance biosafety standards and reduce the risk of nosocomial infections in industrial and hospital environments.

SUPPLEMENTARY MATERIAL

None.

AUTHOR CONTRIBUTIONS

Niran K. Ali: Data curation, Investigation, Methodology and Writing – original draft. Raghad S. Mohammed: Methodology, Formal analysis, Supervision, Writing, reviewing, and editing. Jamoliddin Razzokov: Conceptualization, Investigation, Validation, and Writing – review & editing.

FUNDING

This research received no external funding.

DATA AVAILABILITY STATEMENT

Data are available from the authors upon reasonable request.

ACKNOWLEDGMENTS

The authors express their sincere gratitude to department of biology, college of science, Mustansiriyah University, for its support and assistance in completing this work.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DECLARATION OF GENERATIVE AI USE

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to improve the language. After using this tool, the authors thoroughly reviewed and revised the generated content, taking full responsibility for the accuracy and integrity of the final manuscript.

REFERENCES

- [1] C. Huang, X. Chen, Z. Xue, and T. Wang, "Effect of structure: A new insight into nanoparticle assemblies from inanimate to animate," *Science Advances*, vol. 6, no. 20, Art no. eaba1321, 2020, doi: [10.1126/sciadv.aba1321](https://doi.org/10.1126/sciadv.aba1321).
- [2] W. R. Talib, A. Sudhakaran, A. Sudhakaran, and R. S. Mohammed, "Potential biological and optoelectronic applications of AgO:ZnO nanocomposite synthesized by green approach," *The European Physical Journal Plus*, vol. 139, no. 12, Art no. 1118, 2024, doi: [10.1140/epjp/s13360-024-05920-7](https://doi.org/10.1140/epjp/s13360-024-05920-7).
- [3] N.-Y. Lee, W.-C. Ko, and P.-R. Hsueh, "Nanoparticles in the treatment of infections caused by multidrug-resistant organisms," *Frontiers in Pharmacology*, vol. 10, Art no. 1153, Oct. 2019, doi: [10.3389/fphar.2019.01153](https://doi.org/10.3389/fphar.2019.01153).
- [4] F. Rezaei, P. Vanraes, A. Nikiforov, R. Morent, and N. De Geyter, "Applications of plasma-liquid systems: A review," *Materials*, vol. 12, no. 17, Art no. 2751, 2019, doi: [10.3390/ma12172751](https://doi.org/10.3390/ma12172751).
- [5] O. Rac-Rumijowska, J. Macioszczyk, T. Matusiak, L. Golonka, and H. Teterycz, "Plasma jets fabricated in low-temperature cofired ceramics for gold nanoparticles synthesis," *Materials*, vol. 13, no. 14, Art no. 3191, 2020, doi: [10.3390/ma13143191](https://doi.org/10.3390/ma13143191).
- [6] R. S. Mohammed and M. F. Al-Marjani, "Plasma-solution interaction as green pathway to synthesize novel hybrid nanoparticles for medical sterilization (catheter sterilization)," *The European Physical Journal Plus*, vol. 140, no. 2, Art no. 156, 2025, doi: [10.1140/epjp/s13360-025-06105-6](https://doi.org/10.1140/epjp/s13360-025-06105-6).
- [7] Y. He, S. Ingudam, S. Reed, A. Gehring, T. P. Strobaugh, and P. Irwin, "Study on the mechanism of antibacterial action of magnesium oxide nanoparticles against foodborne pathogens," *Journal of Nanobiotechnology*, vol. 14, no. 1, Art no. 54, 2016, doi: [10.1186/s12951-016-0202-0](https://doi.org/10.1186/s12951-016-0202-0).
- [8] I. Ijaz, E. Gilani, A. Nazir, and A. Bukhari, "Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles," *Green Chemistry Letters and Reviews*, vol. 13, no. 3, pp. 223–245, 2020, doi: [10.1080/17518253.2020.1802517](https://doi.org/10.1080/17518253.2020.1802517).
- [9] J. L. Zuo, S. Yang, Y. Li, C. Tan, Z. Xia, S. Yuan, S. Yu, and J. Li, "Preparation and photoelectrocatalytic performance study of Au-RGO/TiO₂ NTs photoelectrode," *Macromolecular Research*, vol. 30, no. 11, pp. 783–790, 2022, doi: [10.1007/s13233-022-0083-2](https://doi.org/10.1007/s13233-022-0083-2).
- [10] J. Li, J. Xu, M. Xu, T. Guan, Z. Xia, L. Jiang, C. Tan, and J. Zuo, "Synthesis of ZnTiO₃/tourmaline/Ni foam catalyst and enhanced photocatalytic performance," *Arabian Journal of Chemistry*, vol. 16, no. 1, Art no. 104436, 2023, doi: [10.1016/j.arabjc.2022.104436](https://doi.org/10.1016/j.arabjc.2022.104436).
- [11] C. Pandit, A. Roy, S. Ghotekar, A. Khusro, M. N. Islam, T. B. Emran, S. E. Lam, M. U. Khandaker, and D. A. Bradley, "Biological agents for synthesis of nanoparticles and their applications," *Journal of King Saud University - Science*, vol. 34, no. 3, Art no. 101869, 2022, doi: [10.1016/j.jksus.2022.101869](https://doi.org/10.1016/j.jksus.2022.101869).
- [12] Q. Chen, J. Li, and Y. Li, "A review of plasma-liquid interactions for nanomaterial synthesis," *Journal of Physics D: Applied Physics*, vol. 48, no. 42, Art no. 424005, 2015, doi: [10.1088/0022-3727/48/42/424005](https://doi.org/10.1088/0022-3727/48/42/424005).
- [13] L. Chandana, P. Ghosal, T. Shashidhar, and C. Subrahmanyam, "Enhanced photocatalytic and antibacterial activity of plasma-reduced silver nanoparticles," *RSC Advances*, vol. 8, no. 44, pp. 24 827–24 835, 2018, doi: [10.1039/c8ra03961e](https://doi.org/10.1039/c8ra03961e).

- [14] N. K. Kaushik, N. Kaushik, N. N. Linh, B. Ghimire, A. Pengkit, J. Sornsakdanuphap, S.-J. Lee, and E. H. Choi, "Plasma and nanomaterials: Fabrication and biomedical applications," *Nanomaterials*, vol. 9, no. 1, Art no. 98, 2019, doi: [10.3390/nano9010098](https://doi.org/10.3390/nano9010098).
- [15] J. Horák, A. Nikiforov, F. Krčma, M. Březina, Z. Kozáková, L. Dostál, M. Kalina, and L. Kalina, "Synthesis of Ag and Cu nanoparticles by plasma discharge in inorganic salt solutions," *Nanotechnology Reviews*, vol. 12, no. 1, Art no. 20220549, 2023, doi: [10.1515/ntrev-2022-0549](https://doi.org/10.1515/ntrev-2022-0549).
- [16] L. M. Mahlaule-Glory, Z. Mbita, M. M. Mathipa, Z. N. Tetana, and N. C. Hintsho-Mbita, "Biological therapeutics of AgO nanoparticles against pathogenic bacteria and A549 lung cancer cells," *Materials Research Express*, vol. 6, no. 10, Art no. 105402, 2019, doi: [10.1088/2053-1591/ab36e3](https://doi.org/10.1088/2053-1591/ab36e3).
- [17] L. K. Vestby, T. Grønseth, R. Simm, and L. L. Nesse, "Bacterial biofilm and its role in the pathogenesis of disease," *Antibiotics*, vol. 9, no. 2, Art no. 59, 2020, doi: [10.3390/antibiotics9020059](https://doi.org/10.3390/antibiotics9020059).
- [18] R. M. Donlan, "Biofilms and device-associated infections," *Emerging Infectious Diseases*, vol. 7, no. 2, pp. 277–281, 2001, doi: [10.3201/eid0702.010226](https://doi.org/10.3201/eid0702.010226).
- [19] J. A. S. Salman, M. F. H. AL-Kadhemy, and S. A. Madhloom, "Preparation of titanium dioxide nanoparticles and polyvinyl pyrrolidone polymer films as antibacterial, antibiofilm against pathogenic bacteria on different surfaces," *Malaysian Journal of Science*, vol. 36, no. 3, pp. 132–144, 2017, doi: [10.22452/mjs.vol36no3.1](https://doi.org/10.22452/mjs.vol36no3.1).
- [20] T. N. Abdulsada, A. M. Rheima, and S. H. Al-Al-Rubae'i, "Sustainable new biosynthesis of zero valence gold nanoparticles via healthy *Alchemilla vulgaris* L. extract as capping agent," *Case Studies in Chemical and Environmental Engineering*, vol. 10, Art no. 100888, Dec. 2024, doi: [10.1016/j.cscee.2024.100888](https://doi.org/10.1016/j.cscee.2024.100888).
- [21] N. D. Hayif, H. A. Hadi, and I. H. Hashim, "Enhancement of performance Au/PSi/n-Si/Ag heterojunction photodetector by non-thermal plasma jet: Design and impact of plasma voltage," *Silicon*, vol. 17, no. 3, pp. 531–554, 2025, doi: [10.1007/s12633-024-03208-0](https://doi.org/10.1007/s12633-024-03208-0).
- [22] S. Devaraj and N. Munichandraiah, "Effect of crystallographic structure of MnO₂ on its electrochemical capacitance properties," *The Journal of Physical Chemistry C*, vol. 112, no. 11, pp. 4406–4417, 2008, doi: [10.1021/jp7108785](https://doi.org/10.1021/jp7108785).
- [23] A. M. Toufiq, F. Wang, Q.-a. Javed, Q. Li, and Y. Li, "Hydrothermal synthesis of MnO₂ nanowires: Structural characterizations, optical and magnetic properties," *Applied Physics A*, vol. 116, no. 3, pp. 1127–1132, 2013, doi: [10.1007/s00339-013-8195-0](https://doi.org/10.1007/s00339-013-8195-0).
- [24] R. Hazarika and B. Kalita, "Effect of oxygen vacancy defects on electronic and optical properties of MgO monolayers: First principles study," *Materials Science and Engineering: B*, vol. 286, Art no. 115974, Dec. 2022, doi: [10.1016/j.mseb.2022.115974](https://doi.org/10.1016/j.mseb.2022.115974).
- [25] A. C. Mohan, A. Athira, B. P. Nair, G. Sivasubramanian, K. M. Sreekanth, G. Anoop, S. P. Sree, and K. M. Sreedhar, "Multifaceted properties of Ni and Zn codoped MgO nanoparticles," *Scientific Reports*, vol. 14, no. 1, Art no. 32067, 2024, doi: [10.1038/s41598-024-83779-5](https://doi.org/10.1038/s41598-024-83779-5).
- [26] R. M. Pinto, F. A. Soares, S. Reis, C. Nunes, and P. Van Dijck, "Innovative strategies toward the disassembly of the EPS matrix in bacterial biofilms," *Frontiers in Microbiology*, vol. 11, Art no. 952, May 2020, doi: [10.3389/fmicb.2020.00952](https://doi.org/10.3389/fmicb.2020.00952).
- [27] N. Parvin, S. W. Joo, and T. K. Mandal, "Nanomaterial-Based strategies to combat antibiotic resistance: Mechanisms and applications," *Antibiotics*, vol. 14, no. 2, Art no. 207, 2025, doi: [10.3390/antibiotics14020207](https://doi.org/10.3390/antibiotics14020207).
- [28] M. Huemer, S. Mairpady Shambat, S. D. Brugger, and A. S. Zinkernagel, "Antibiotic resistance and persistence-implications for human health and treatment perspectives," *The EMBO Reports*, vol. 21, no. 12, Art no. EMBR2020-51034, 2020, doi: [10.15252/embr.202051034](https://doi.org/10.15252/embr.202051034).
- [29] O. Ciofu, T. Tolker-Nielsen, P. Ø. Jensen, H. Wang, and N. Høiby, "Antimicrobial resistance, respiratory tract infections and role of biofilms in lung infections in cystic fibrosis patients," *Advanced Drug Delivery Reviews*, vol. 85, pp. 7–23, May 2015, doi: [10.1016/j.addr.2014.11.017](https://doi.org/10.1016/j.addr.2014.11.017).
- [30] P. S. Stewart, "Diffusion in biofilms," *Journal of Bacteriology*, vol. 185, no. 5, pp. 1485–1491, 2003, doi: [10.1128/jb.185.5.1485-1491.2003](https://doi.org/10.1128/jb.185.5.1485-1491.2003).
- [31] M. A. Kohanski, D. J. Dwyer, B. Hayete, C. A. Lawrence, and J. J. Collins, "A common mechanism of cellular death induced by bactericidal antibiotics," *Cell*, vol. 130, no. 5, pp. 797–810, 2007, doi: [10.1016/j.cell.2007.06.049](https://doi.org/10.1016/j.cell.2007.06.049).
- [32] E. N. Taylor and T. J. Webster, "The use of superparamagnetic nanoparticles for prosthetic biofilm prevention," *International Journal of Nanomedicine*, vol. 4, pp. 145–152, Aug. 2009, doi: [10.2147/ijn.s5976](https://doi.org/10.2147/ijn.s5976).