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REVIEW ARTICLE

# Green Synthesis and Biomedical and Environmental Remediation Applications of Phyto–Mediated Magnesium Oxide Nanoparticles

**Dimpal Chauhan[1], Shweta Kaushal[2,3], Kuldeep Kumar[2,3]***

**ABSTRACT:** Magnesium oxide nanoparticles (MgO NPs) have garnered significant attention due to their exceptional thermal stability, biocompatibility, and versatile applications in biomedicine and environmental remediation. Conventional synthesis methods often involve toxic chemicals, high energy consumption, and complex instrumentation, limiting their sustainability. In contrast, green synthesis—utilizing plant extracts, bacteria, fungi, or algae—offers an eco-friendly, cost-effective, and scalable alternative. This review comprehensively examines recent advancements in the biosynthesis of MgO NPs, emphasizing their dual role in environmental and biomedical applications. In environmental remediation, MgO NPs exhibit remarkable photocatalytic efficiency in degrading organic pollutants such as industrial dyes (e.g., methylene blue, rhodamine B) and heavy metal ions (e.g., $Pb^{2+}$, $Cr^{6+}$) from wastewater, owing to their high surface area and redox-active surfaces. Their antimicrobial and antioxidant properties further enhance their utility in water purification technologies. In biomedicine, biosynthesized MgO NPs demonstrate potent antimicrobial activity against drug-resistant pathogens, anticancer effects through reactive oxygen species (ROS)-mediated apoptosis, and antioxidant capabilities that mitigate oxidative stress. Additionally, their biocompatibility supports potential applications in drug delivery, bioimaging, and tissue engineering. This review critically evaluates the advantages of biogenic synthesis over conventional methods, addressing challenges such as reproducibility, scalability, and long-term environmental impact. By integrating interdisciplinary insights, we highlight future directions for optimizing green synthesis protocols and expanding the multifunctional applications of MgO NPs in sustainable technologies.

**Keywords:** Green synthesis, Magnesium oxide nanoparticles, Environmental remediation, Antimicrobial activity, Photocatalysis, Biomedical applications.

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## 1. INTRODUCTION

Nano-technology has appeared as a rapidly evolving field in science and technology, most predominantly in areas such as environment, biomedicine, and catalytic applications. This pertains the synthesis and functionalization of NPs, which possess unique characteristics such as nanoscale dimensions, diverse morphologies, and a high surface area/volume ratio. These features contribute to their enhanced magnetic, optical, electronic, and mechanical properties [1-4].

Conventionally, there has been a practice of synthesizing NPs by different physical and chemical procedures. Chemical methods often necessitate reducing agents, solvents, metal precursors, and stabilizers, whereas physical methods typically depend on high-energy equipment under extreme conditions [5-8]. These techniques can be energy-intensive, expensive, and environmentally hazardous. To overcome these limitations, green synthesis (biosynthesis) has gained importance as a substitute, rendering a more sustainable, economical, and eco-friendly approach for the

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production of NPs. This biogenic approach harnesses biological resources such as plant parts, algae, and microorganisms like bacteria, fungi, providing a safer and more accessible method for NP fabrication [9, 10].

Metal oxides (MO) are naturally abundant in the earth's crust. When these are scaled down to the nano-meter range, they are referred to as metal oxide nanoparticles (MO NPs). At this scale, they exhibit distinctive properties that significantly differ from their bulk forms [11,12]. Among various MO NPs, magnesium oxide (MgO) NPs have fascinated significant consideration owing to their outstanding biocompatibility, non-toxic nature, and remarkable stability under extreme conditions. MgO, an inorganic compound consisting of $Mg^{2+}$ and $O^{2-}$ ions, appears as a white, hygroscopic solid. In its bulk form, MgO features a cubic rock-salt crystal structure (Figure 1) and a wide bandgap of 7.8 eV. However, at the nanoscale, its physical and chemical properties become significantly enhanced due to changes in particle size and morphology, which are largely influenced by the synthesis method [13, 14]. MgO NPs can be prepared through top-down (physical) or bottom-up (chemical) approaches.

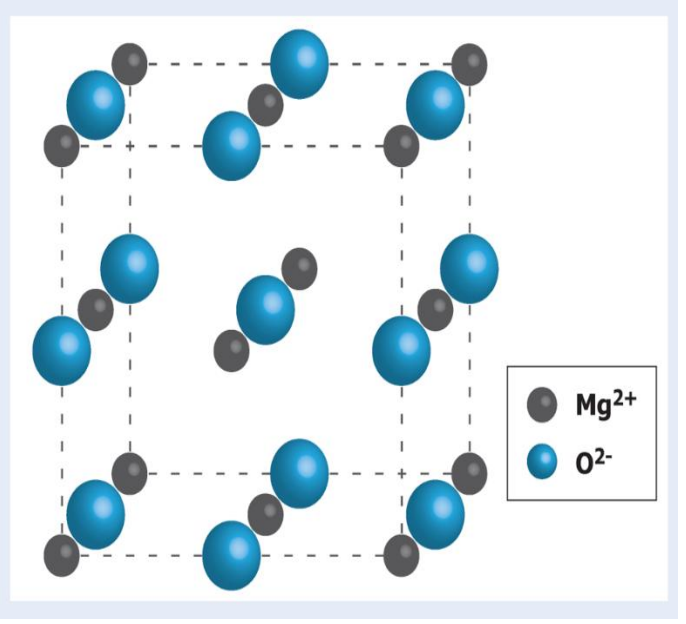


**Fig. 1.** Fce centred cubic structure of MgO. Reprinted with permission from ref. [19], Hornak, J., **2021**. Synthesis, properties, and selected technical applications of magnesium oxide nanoparticles: a review. *International Journal of Molecular Sciences*, *22*(23), p.12752. Copyright © MDPI.

As particle size decreases, surface effects such as lattice distortions and quantum confinement become more prominent. These effects introduce a greater number of surface defects—particularly oxygen vacancies and un-coordinated atoms, which in turn influence the optical, electronic, and catalytic behaviour of the NPs [14, 15]. Due to their high surface area and strong basicity provided by oxygen ions, MgO NPs exhibit superior catalytic performance and thermal stability, making them suitable for high-temperature applications. They have found applications such as, removal of organic pollutants, development of semiconductors and catalytic devices, as well as roles in ceramics, electronics, adsorbents, and refractory materials [16, 17]. Moreover, their environmentally benign nature further supports their use in sustainable catalytic systems [18, 19]. This review aims to offer an inclusive understanding of the role of green-synthesized MgO NPs in environmental remediation, emphasizing their advantages, challenges, and potential for sustainable environmental and biomedical applications.

## 2. BIOSYNTHESIS OF MgO NANOPARTICLES

Biosynthesis, is an innovative and sustainable method for producing NPs without the need for extreme reaction conditions such as high pressure, elevated temperatures, or excessive energy consumption. This eco-friendly approach eradicates the practice of toxic chemicals, thereby reducing waste generation and endorsing sustainable development. It utilizes non-toxic reagents derived from natural sources, such as plant-based material, micro-organisms or biomolecules (Figure 2) [13]. Moreover, these biologically derived molecules impart additional functionalities to the NPs, improving their catalytic, antimicrobial, and biomedical properties compared to their chemically synthesized counterparts [20].

### 2.1. Biosynthesis of MgO NPs from Microorganisms

Microbial growth can occur in both extracellular and intracellular environments, each facilitating the reduction of $Mg^{2+}$ ions into MgO NPs. In the extracellular synthesis pathway, enzymes secreted by microorganisms into the surrounding medium, acts as reducing and stabilizing mediators for metal salts, leading to NP formation. In contrast, the intracellular mechanism is more intricate, as it involves complex interactions within the cell, including uptake of metal ions and their subsequent transformation inside the cellular matrix due to the biochemical processes and internal composition of the microbial cells (Figure 3) [22].

Mohanasrinivasan et al. [23] adopted a microbial-mediated biogenic approach using *Lactobacillus* species (*L. plantarum* and *L. sporogenes*). The biomolecules from *Lactobacillus* not only reduce and stabilize the NPs but also modulate their biological properties, such as biocompatibility and anticancer activity. El-Sayyad et al. [24] presented one-pot green synthesis method for MgO NPs by means of melanin extracted from *Penicillium chrysogenum* in combination with gamma (γ) irradiation.

 

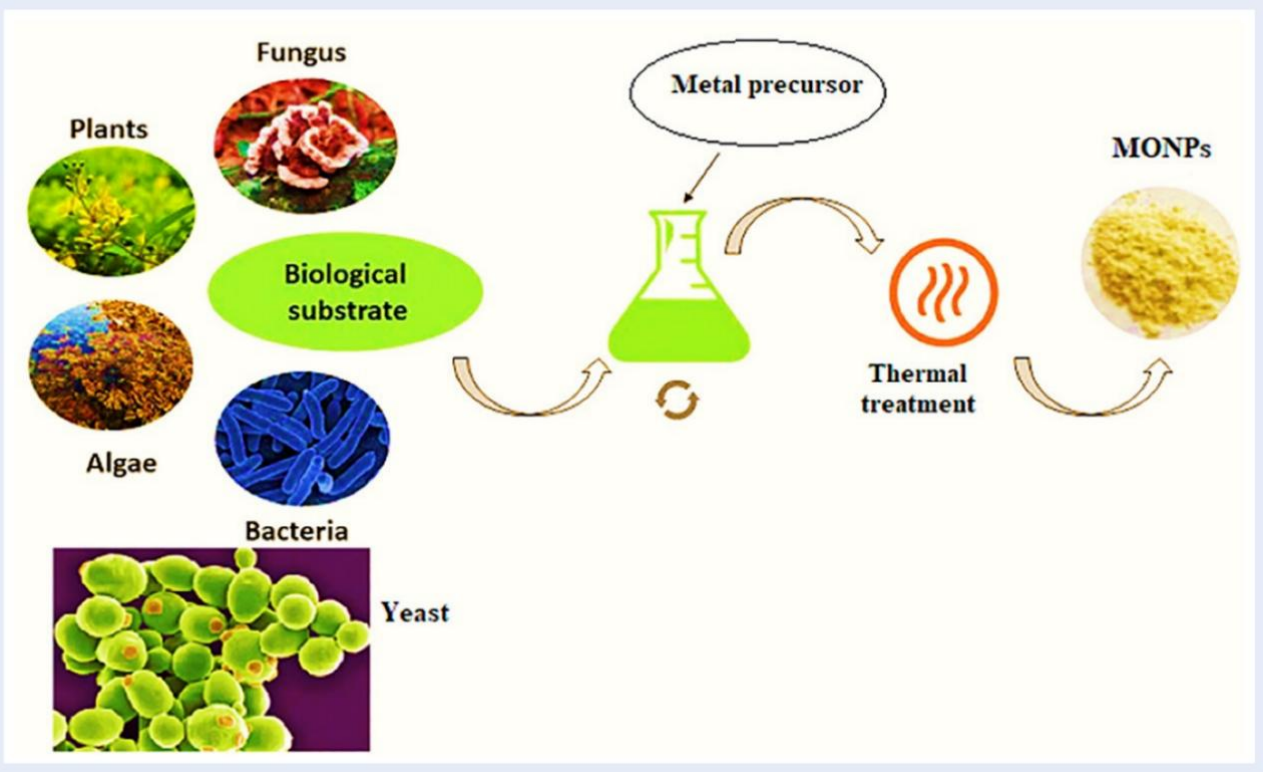


**Fig. 2.** Biosynthesis of metal oxide nanoparticles. Reprinted with permission from ref. [21], Ashour, M., Mansour, A.T., Abdelwahab, A.M. and Alprol, A.E., **2023**. Metal oxide nanoparticles' green synthesis by plants: prospects in phyto-and bioremediation and photocatalytic degradation of organic pollutants. *Processes*, *11*(12), p.3356. Copyright © MDPI.

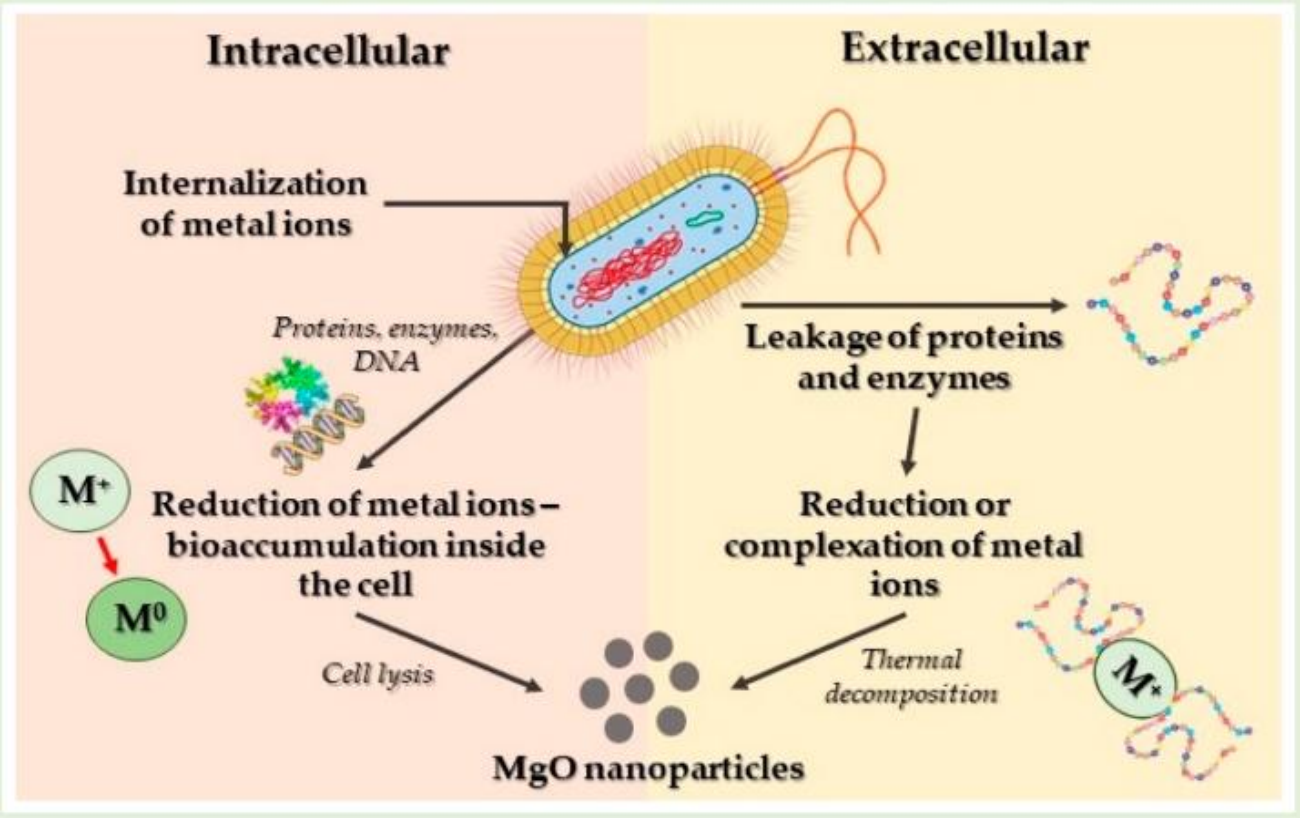


**Fig. 3.** Mechanism of synthesis of MgO NPs. Reprinted with permission from ref. [13], Gatou, M.A., Skylla, E., Dourou, P., Pippa, N., Gazouli, M., Lagopati, N. and Pavlatou, E.A., **2024**. Magnesium oxide (MgO) nanoparticles: synthetic strategies and biomedical applications. *Crystals*, *14*(3), p.215. Copyright © MDPI.

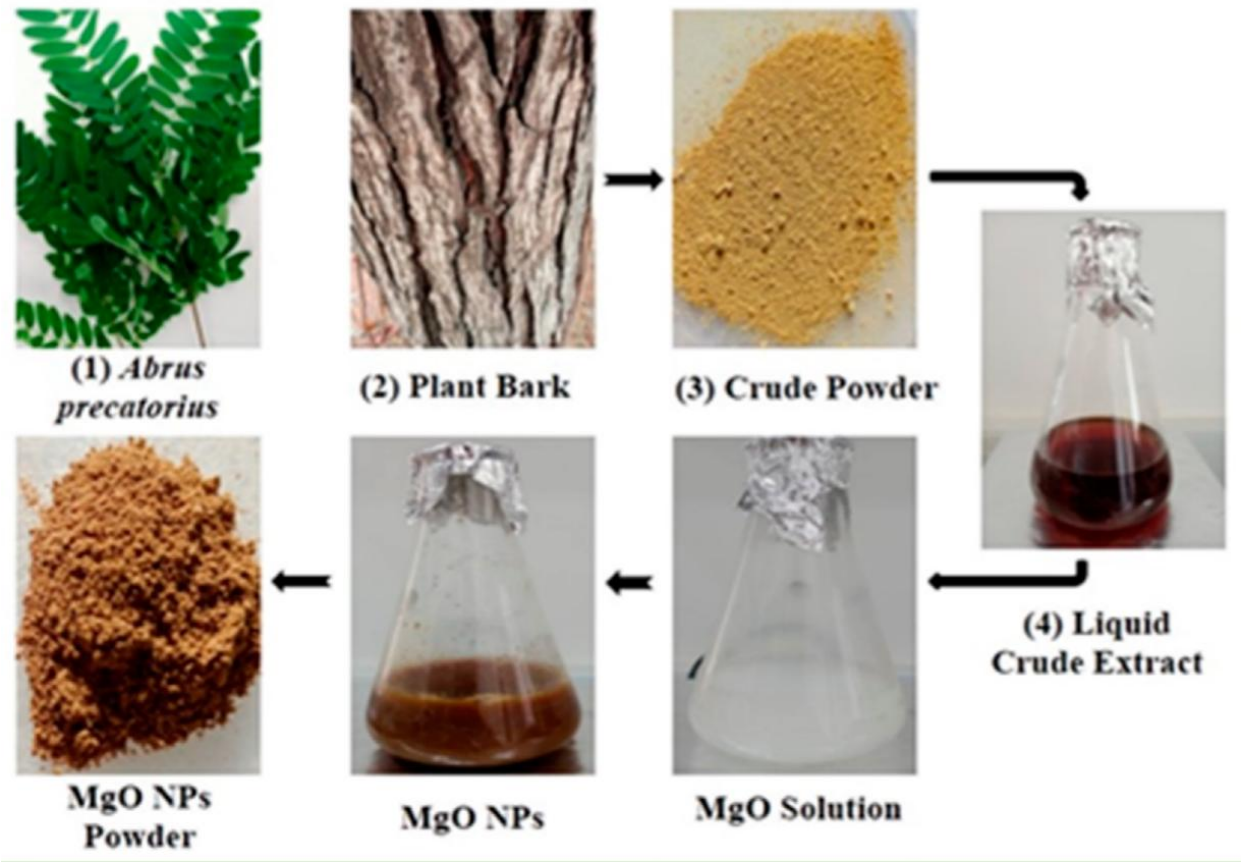


**Fig. 4.** Phyto-mediated synthesis of MgO NPs. Reprinted with permission from ref. [26], Ali, S., Sudha, K.G., Thirumalaivasan, N., Ahamed, M., Pandiaraj, S., Rajeswari, V.D., Vinayagam, Y., Thiruvengadam, M. and Govindasamy, R., **2023**. Green synthesis of magnesium oxide nanoparticles by using *Abrus precatorius* bark extract and their photocatalytic, antioxidant, antibacterial, and cytotoxicity activities. *Bioengineering*, *10*(3), p.302. Copyright © MDPI.

The melanin pigment acted as reducing cum stabilizing agent, while γ-rays facilitated the growth and nucleation of NP. Fouda et al. [25] synthesized MgO NPs utilizing the algal extracts of marine brown alga *Cystoseira crinita*. The algal extract is rich in phytochemicals such as flavonoids, terpenoids, polyphenols, and polysaccharides, which reduces the $Mg^{2+}$ ions and leading to stabilization of the NPs.

### 2.2. Biosynthesis of MgO NPs from Extracts of Plant Parts

Plants serve as another biocompatible and sustainable natural resource for biosynthesis of NPs, as they contain a variety of phytochemicals in them. Although the exact mechanism remains uncertain, it is commonly recommended that plant-derived phytochemicals function jointly as reducing, capping, and stabilizing agents in NP formation. Antioxidant-rich molecules such as methylxanthines, saponins, and phenolics play a crucial role in neutralizing free radicals, reactive oxygen species (ROS) scavenging, and capping and chelation of metal ions. Moreover, bioactive compounds regulate their size and prevent agglomeration by stabilizing the particles thus facilitating the transformation of metal salts into stable NPs [17, 22]. Several key aspects, such as plant extract, temperature, pH, and precursor concentration, influence the characteristics of the synthesized NPs [8].

In biosynthesis of MgO NPs, to the salt of $Mg^{2+}$ ions, commonly nitrate, chloride, or acetate, the biological extract is introduced under controlled conditions of optimized pH, temperature, and stirring rates. The $Mg^{2+}$ ions are reduced by phytochemicals, initiating nucleation of the NPs. To enhance the reaction, the pH is often adjusted using NaOH, which leads to the formation of $Mg(OH)_2$ as a key intermediate. This mixture is incubated for a set duration to allow complete reduction and stabilization, followed by centrifugation to isolate the precipitate. The final step involves calcination at high temperatures (typically 300–800°C), converting $Mg(OH)_2$ into crystalline MgO nanoparticles [20]. Figure 4 depicts the synthesis of MgO NPs from the bark extract of *Abrus precatorius* plant.

Barzegar et al. [27], synthesized MgO NPs using *Caccinia macranthera* extract. The synthesis process involves the sol-gel technique, where the extract of *Caccinia macranthera* served as reducing agent. The phytochemicals present in extract facilitated the reduction of $Mg^{2+}$ ions. FTIR

 

spectroscopy confirmed the role of functional groups in the synthesis of MgO NPs.

Younis et al. [28], utilized *Rosa floribunda charisma* extract to biosynthesize MgO NPs. The bioactive compounds present in *Rosa floribunda charisma* extract, contain polyphenols, flavonoids, and other phytochemicals, facilitating the conversion of $Mg^{2+}$ precursors into stable MgO NPs. The NPs exhibited potent antioxidant, antiaging, and antibiofilm activities, making them highly promising for biomedical, pharmaceutical, and skincare applications. They had strong free radical scavenging ability, enzyme inhibition properties, and significant biofilm inhibition against pathogens.

## 3. ENVIRONMENTAL REMEDIATION APPLICATIONS

High surface area, enhanced reactivity, and selective interaction capabilities enables MgO NPS, in degrading organic dyes. A study by Ramakrishna et al. [29] demonstrated a green approach for the fabrication of MgO NPs using fruit extracts from watermelon, Aloe vera, and Jamun as natural fuels. SEM analysis revealed a porous morphology, which is beneficial for catalytic and electrochemical applications. Additionally, DRS measurements showed an energy band gap ($E_g$) of 4.8–4.9 eV, indicating the material's suitability for photocatalytic and electronic applications. The photocatalytic study demonstrated that MgO NPs synthesized using Jamun extract exhibited the highest photocatalytic efficiency (84%) in degrading Direct Green (DG) dye under UV light irradiation.

A study by Tahir et al. [30] produced MgO NPs using *Manilkara zapota* as a bioingredient. The incorporation of activated carbon (AC) with MgO NPs through solution evaporation technique resulted in an efficient AC/MgO photocatalyst. SEM, FTIR, XRD, UV-DRS, and XPS characterizations established the successful incorporation of MgO NPs into the AC matrix, leading to improved movement of electrons, reduced $E_g$, and enhanced photocatalytic action. The AC/MgO photocatalyst resulted in 99% degradation of Rhodamine-B (Rh-B) dye under solar light. They attributed this to the synergistic consequence of AC acting as catalytic support as well as adsorbent, while MgO acting primarily as photocatalyst. Moreover, the AC/MgO nanocomposite displayed strong antibacterial activity towards both gram-positive (*E. coli-745*) and gram-negative (*S. aureus-9779*) bacteria. Figure 5 illustrates the mechanism of photocatalytic degradation of organic dyes and anti-bacterial activity by MgO NPs.

Muhaymin et al. [32] demonstrated in their study synthesis of MgO NPs using *Hyphaene thebaica* (gingerbread tree) fruit extract. The photocatalytic performance of MgO NPs was evaluated for methylene blue (MB) dye degradation under visible light illumination, where an impressive 98% degradation efficiency was achieved within 110 minutes using 1 g/L of MgO nano-catalyst.

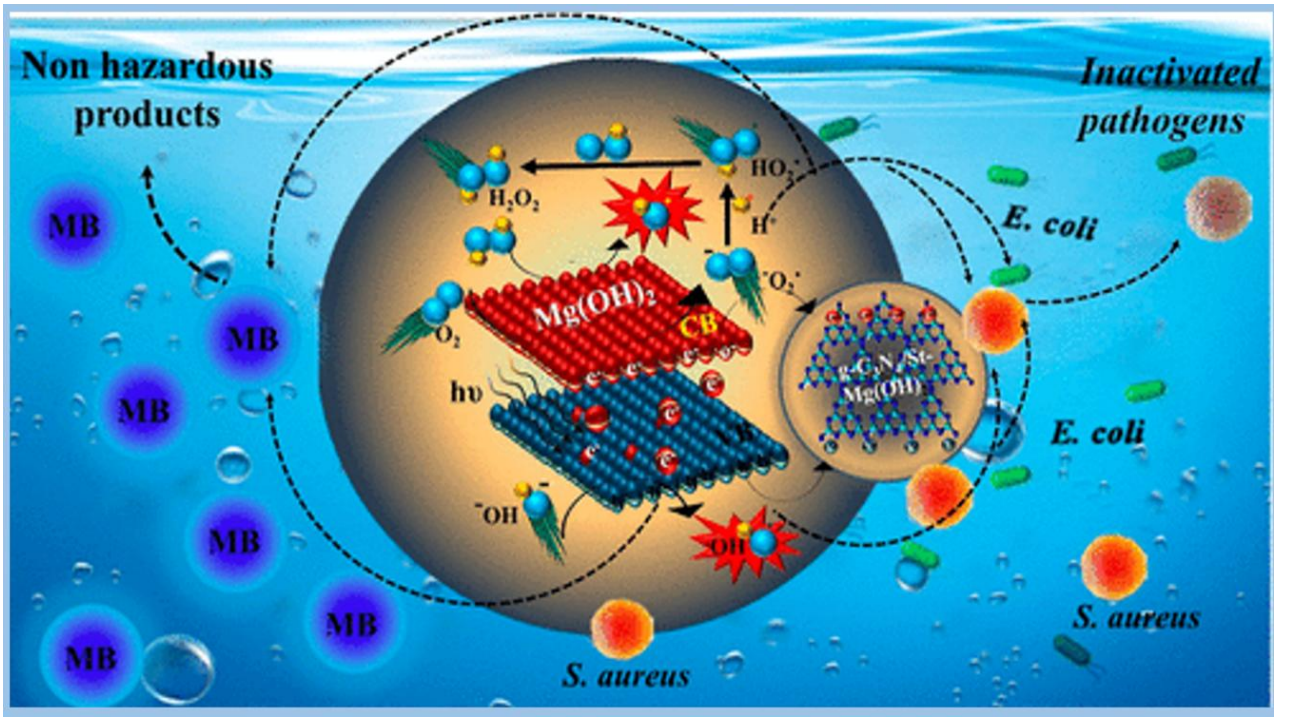


**Fig. 5.** Photocatalytic degradation and antibacterial activity of MgO NPs. Reprinted with permission from ref. [31], Ikram, M., Jamal, F., Haider, A., Dilpazir, S., Shujah, T., Naz, M., Imran, M., Ul-Hamid, A., Shahzadi, I., Ullah, H. and Nabgan, W., **2022**. Efficient photocatalytic dye degradation and bacterial inactivation by graphitic carbon nitride and starch-doped magnesium hydroxide nanostructures. *ACS Omega*, *7*(44), pp.39998-40008. Copyright © American Chemical Society.

Gatou et al. [33] synthesized MgO NPs employing precipitation technique and evaluated photocatalytic degradation of rhodamine B (RhB) and rhodamine 6G (Rh6G) dyes under UV and visible light. The photocatalytic experiments demonstrated remarkable dye degradation efficiency, particularly for RhB, with: 100% degradation under UV and 83.23% degradation under visible light. Whereas, for Rh6G, MgO showed: 92.62% degradation under UV light and 38.71% degradation under visible light. Additionally, the reusability of MgO NPs was successfully tested across five consecutive photocatalytic cycles, maintaining high degradation efficiency, particularly for RhB.

Musayeib et al. [34] biogenically synthesized MgO NPs using citron waste peel extract (CP-MgO). Different characterizations confirmed the polyhedral morphology of CP-MgO NPs with slight agglomeration. The resulted CP-MgO NPs were evaluated for the degradation of acid orange 8 (AO-8) dye under UV light. They displayed over 94% degradation efficiency in a short duration, comparable to standard MgO powder. Additionally, CP-MgO NPs exhibited strong antibacterial properties, showing the highest inhibition against *E. coli* (20.72 mm) and *S. aureus* (19.52 mm). Their anticancer potential was also significant, with an IC50 value of 15.3 µg/mL towards HepG2 cancer cells, inducing oxidative stress, apoptosis, and cell membrane damage.

Asha et al. [35] in their study successfully synthesized MgO NPs using Tulsi (holy basil) leaf extract via a solution combustion method. The structural and morphological analyses confirmed a crystallite size of approximately 52 nm, with a clumped, puffy, and porous morphology, contributing to its high surface area and catalytic efficiency. Degradation experiments performed on Fast Blue (FB) and Fast Orange (FO) dyes under UV light revealed high degradation efficiencies of 80.5% and 80.35%, respectively, within 90 minutes. The semiconductor behaviour of MgO NPs, with an $E_g$ of 4.31 eV, played a crucial role in promoting charge transfer and generating ROS for efficient dye degradation.

Khan et al. [36] synthesized MgO NPs using leaf extract of *Dalbergia sissoo*, optimizing reaction parameters to control the $E_g$ values. The photocatalytic potential of MgO-NPs was demonstrated through the degradation of MB dye, with the most effective NPs exhibiting an $E_g$ value of 4.1758 eV. Kumar et al. [37] MgO NPs using tea extract. These NPs displayed efficient photocatalytic degradation of Victoria Blue dye under UV light illumination, achieving an impressive 88% degradation within 90 minutes. Fouda et al. [38] biosynthesised MgO NPs using *Aspergillus niger* strain F1. When these NPs are examined for their photocatalytic efficiencies, they displayed sunlight-assisted catalytic degradation with remarkably high decolorization efficiencies-92.8% for textile and 97.5% for tannery effluents-within 180 minutes at an optimal MgO-NP concentration of 1.0 mg $mL^{-1}$.

Srivastava et al. [39] synthesised of MgO nanoflowers (NFs) using bio-compatible acacia gum via chemical precipitation. The MgO NFs exhibited outstanding adsorptive properties, particularly in the elimination of heavy metal ions, $Co^{2+}$, $Cd^{2+}$, $Zn^{2+}$, $Cu^{2+}$, $Mn^{2+}$, $Pb^{2+}$, and $Ni^{2+}$, from synthetic wastewater, demonstrating their broad-spectrum applicability for water purification. Sierra-Fernandez et al. [40] have explored the use of MgO NPs in preserving calcareous stone monuments. Mustapha et al. [41] biosynthesised MgO- rice husk ash (MgO-RHA) nanocomposite for the effective removal of $Cr^{6+}$ and $Pb^{2+}$ ions from wastewater of mines. The incorporation of green-synthesized MgO NPs, derived using *Moringa oleifera* leaf extract, into the porous structure of rice husk ash significantly enhanced the composite's surface area and functional reactivity, as confirmed by BET and morphological analyses. The MgO-RHA composite exhibited a superior surface area (102.71 $m^2/g$), surpassing that of individual RHA or MgO, thereby offering more active sites for contaminant interaction. The adsorption experiments revealed remarkably high removal efficiencies, achieving up to 96.02% for $Pb^{2+}$ and 79.20% for $Cr^{6+}$. Their findings suggested that the adsorption mechanism was chemically driven (chemisorption), endothermic, and spontaneous, which are the hallmarks of a catalytically active adsorbent.

## 4. BIOMEDICAL APPLICATIONS

Bacterial infections pose a growing global health concern, primarily due to the advent of pathogens that have developed resistance to multiple antibiotics. MgO NPs have demonstrated considerable antibacterial activity [3]. The antibacterial properties of MgO NPs likely result from a combination of ROS-induced oxidative stress, membrane disruption, and electrostatic interactions, with surface area playing a significant role in enhancing their effectiveness. Electrostatic interactions between positively charged MgO NPs and negatively charged bacterial membranes may contribute to their antibacterial activity (Figure 6) [42].

A study by He et al. [43], demonstrated that MgO NPs, averaging 20 nm in size, exhibit strong antibacterial activity against major foodborne pathogens such as *Campylobacter jejuni*, *Escherichia coli* O157:H7, and *Salmonella Enteritidis*. SEM and qPCR data confirmed significant structural damage and increased membrane permeability upon treatment. Low levels of $H_2O_2$ produced by the NPs still induced strong expression of oxidative stress-related genes like *KatA* in *C. jejuni*, indicating a biological response to ROS. The physical contact between NPs and bacterial membranes plays a key role in initiating cell damage. Their study further confirmed that MgO NPs exert their antibacterial effect primarily by physically disrupting bacterial membranes, inducing oxidative stress, and increasing membrane permeability, leading to cell leakage and death. Figure 7 shows the SEM images were captured for *C. jejuni*, *E. coli* O157:H7, and *S. Enteritidis* to evaluate morphological changes following treatment. Bacterial cells were exposed to 2 mg/mL of MgO NPs for 8 hours (right side), while control samples (left side) were incubated under identical conditions without the addition of nanoparticles.

 

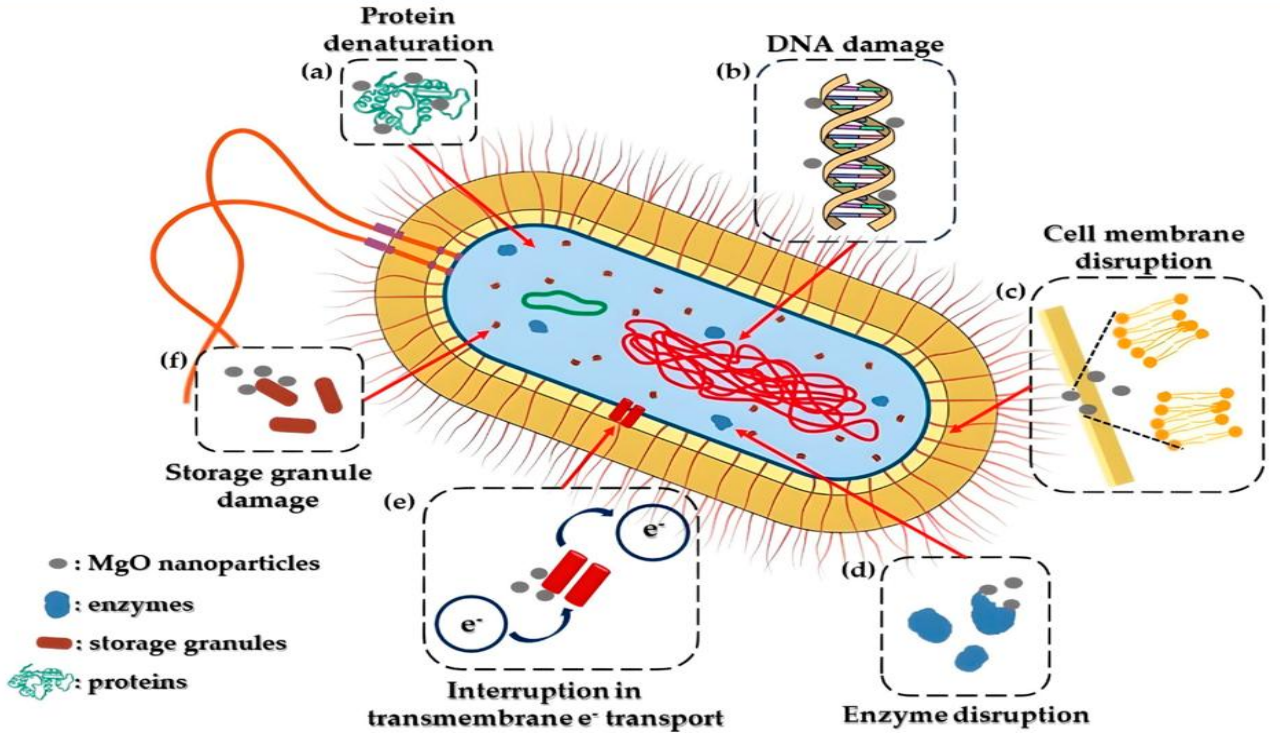


**Fig. 6.** Antibacterial action of MgO NPs. Reprinted with permission from ref. [13], Gatou, M.A., Skylla, E., Dourou, P., Pippa, N., Gazouli, M., Lagopati, N. and Pavlatou, E.A., **2024**. Magnesium oxide (MgO) nanoparticles: synthetic strategies and biomedical applications. *Crystals*, *14*(3), p.215. Copyright © MDPI.

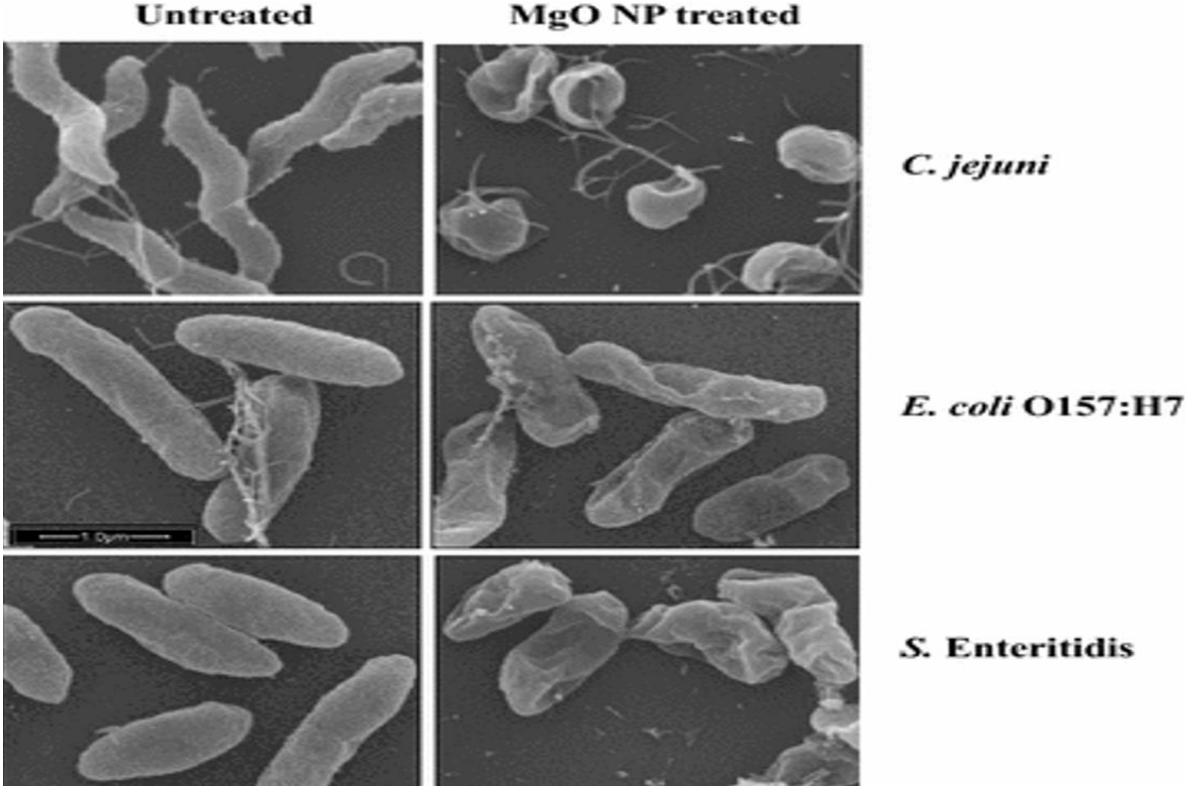


**Fig. 7**. SEM images of *C. jejuni*, *E. coli* O157:H7, and *S. enteritidis*. Reprinted with permission from ref. [43], He, Y., Ingudam, S., Reed, S., Gehring, A., Strobaugh, T.P. and Irwin, P., **2016**. Study on the mechanism of antibacterial action of magnesium oxide nanoparticles against foodborne pathogens. *Journal of Nanobiotechnology*, *14*, pp.1-9. Copyright © Springer-Nature.

Pavithra et al. [44] reported the biosynthesis of MgO nanosheets using *Achyranthes aspera*. The antibacterial and antifungal activities of these nanosheets were thoroughly evaluated. Their findings revealed that the biosynthesized MgO nanosheets exhibited notable antimicrobial efficacy against both bacterial and fungal strains, showing comparable or enhanced activity when measured against ciprofloxacin, which was used as the positive control. A study by Abinaya and Kavitha [42] demonstrated that MgO NPs exhibited strong bactericidal activity against *Enterococcus faecalis*, *Staphylococcus aureus*, *Escherichia coli* and *Klebsiella pneumoniae*. Moreover, these NPs exhibited great potential against larvae of *Aedes aegypti* and *Aedes albopictus*. Suba et al. [45] synthesized MgO NPs using *Lactococcus spp.* isolated from cow's milk. These MgO NPs exhibited strong cytotoxicity towards colon cancer cells (HT-29), with significant results in MTT and NRU assays, indicating their dual potential as both antimicrobial and anticancer agents. A study by Khan et al. [46] demonstrated strong anticancer efficacy of biogenic MgO NPs against breast cancer cells. Tabrez et al. [47], synthesized MgO NPs using pumpkin seed extract as biological source. These NPs hold substantial anticarcinogenic effect against the ovarian teratocarcinoma cell line.

Nowadays, MgO NPs doped with some transition metal ions are also gaining noteworthy consideration because of their improved properties and extensive applications**.** This process involves the deliberate incorporation of small amounts of transition metal atoms into the crystal lattice of MgO to modify its properties. It occurs by structural and electronic modifications that significantly improve their functionality. These doped NPs display enhanced antimicrobic, photocatalytic, and adsorption potential as compared to pure MgO NPs. This mainly occurs due to modified surface charge, more ROS generation, and increased number of defects [48].

Panchal et al. [49] biosynthesized Ag-doped MgO nanocomposites (Ag/MgO-NCs) using *Aloe vera* extract. These Ag/MgO-NCs resulted in 90.18% degradation of MB and 80.67% degradation of phenol within 120 minutes under sunlight. They attributed the enhanced photocatalytic performance to the synergistic effect of Ag doping. Chauhan et al. [50] synthesized (Co, Cu, and Zn) doped MgO NPs utilizing the leaf extract of mint plant. Their results showed that Co- and Cu-doped MgO NPs exhibited significantly enhanced photocatalytic activity as compared to undoped counterparts. They attributed this to reduced $E_g$ owing to doping resulting in improved light absorption and catalytic efficiency. Begum et al. [51] green synthesised MgO NPs and Ag-doped MgO nanocomposites (MgO–Ag NCs) using *Eucalyptus globulus* leaf extract. The incorporation of silver not only reduced the $E_g$ significantly, enabling better absorption in the visible range, but also resulted in near-complete degradation of hazardous dyes such as Malachite Green and Congo Red. They attributed this superior photocatalytic efficacy to the improved charge separation and enhanced surface reactivity facilitated by Ag doping. The applications of biosynthesized MgO NPs have been summarized in Table 1.

## 5. FUTURE DIRECTIONS

The field of biosynthesized magnesium oxide nanoparticles (MgO NPs) holds immense potential, yet several key areas require further exploration to fully harness their capabilities in environmental and biomedical applications. One critical direction involves deepening the understanding of the biochemical mechanisms governing the green synthesis of MgO NPs. While plant extracts and microbial metabolites are known to act as reducing and stabilizing agents, the precise roles of specific phytochemicals—such as flavonoids, polyphenols, and terpenoids—in nucleation and growth remain unclear. Advanced spectroscopic and computational studies could elucidate these interactions, enabling precise control over particle size, morphology, and crystallinity. Standardizing synthesis protocols across different biological sources is equally essential to ensure reproducibility and scalability for industrial adoption.

Another promising avenue lies in optimizing the functional performance of MgO NPs through doping and hybrid nanocomposite formation. Transition metal doping (e.g., Ag, Cu, Co) has shown enhanced photocatalytic and antimicrobial properties, but systematic studies comparing different dopants and their concentrations are needed to establish structure-activity relationships. Similarly, integrating MgO NPs with carbon-based materials (e.g., graphene oxide, activated carbon) or polymers could improve stability, recyclability, and selectivity in environmental applications. For instance, designing MgO-based nanocomposites for targeted pollutant removal or sustained drug delivery could bridge gaps in current technologies.

In environmental remediation, future research should focus on real-world applicability, such as pilot-scale testing of MgO NPs in industrial wastewater treatment or soil decontamination. Long-term ecological impact assessments are also vital to evaluate potential toxicity to aquatic and terrestrial ecosystems. Developing regeneration techniques for spent MgO NPs—such as thermal or chemical reactivation—could enhance their economic viability and sustainability. Additionally, exploring their role in emerging areas like air purification (e.g., photocatalytic degradation of volatile organic compounds) or renewable energy (e.g., photocatalytic hydrogen production) could broaden their environmental utility.

In biomedicine, the therapeutic potential of MgO NPs warrants further validation through in vivo studies to assess pharmacokinetics, biodistribution, and biocompatibility. Their antimicrobial and anticancer mechanisms, particularly in combination with conventional therapies, need deeper investigation to optimize dosing and minimize off-target effects. Functionalizing MgO NPs with targeting ligands (e.g., antibodies, peptides) could enhance their specificity for cancer cells or pathogenic bacteria, reducing side effects.

 

**Table 1.** Biosynthesis of MgO Nanoparticles and their applications

| Plant extract/ stabilizing agent | Particle size | Characterizations | Activity | Ref. |
|---|---|---|---|---|
| Leaf extracts of *Mangifera indica*, *Azadirachta indica* and *Carica papaya* | 10.25–27.08 nm | PXRD, FTIR, SEM | Antibacterial activity against *E. coli*, *S. aureus*, and *P. aeruginosa* | [52] |
| Tea leaves extract of *Camellia sinensis* | 65 ± 5 nm | XRD, FTIR, SEM | Upto 97% photocatalytic degradation of methylene blue | [53] |
| Leaf extract of *Tinospora Cordifolia* | 7.08 ± 4.70 nm | UV-Vis, XRD, FTIR, BET | Antidiabetic and antioxidant | [54] |
| Leaf extract of *Azadirachta indica* | 90–100 nm | FTIR, UV-Vis, XRD, SEM | Up to 92% degradation of Reactive Red 195 dye | [55] |
| Metabolites of *Rhizopus oryaze* (fungal strain) | 20.38 ± 9.9 nm | XRD, XPS, FTIR, TEM, SEM, DLS | Antimicrobial and mosquitocidal activities and 95.6 % decolorization of tannery effluents | [56] |
| Bark extract of *Abrus precatorius* L. | -- | XRD, FTIR, SEM, TEM, and UV-visible | Antibacterial and anticancer activity | [26] |
| *Aloe vera*, *Echeveria elegans*, *Sansevieria trifasciata*, and *Sedum morganianum* | 81-157 nm | XRD, EDX, DLS, UV-Vis, SEM | Up to 80% photocatalytic degradation of methyl orange | [57] |
| Aqueous extract of *Pterocarpus marsupium rox.b* | 15-20 nm | XRD, DLS, UV-Vis, FTIR, SEM, EDX | Antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* | [58] |
| *Vitis vinifera* | 50-200 nm | XRD, Raman, XPS, FESEM, FTIR, EDAX, HR-TEM | Antifungal, anti-inflammatory antibacterial, and anti-diabetic activities | [59] |
| Fruit extract of Jujube | 21.96 nm | UV–Vis, FTIR, XRD, SEM, EDX | Anti-yeast activity against *Saccharomyces cerevisiae* | [60] |
| Leaf extract of *Azadirachta indica* | 23 nm | UV–Vis, FTIR, XRD, SEM, TEM, TGA | Anti-cancer, anti-oxidant, anti-bacterial, anti-diabetic | [61] |
| Grain extract of *Oryza sativa* L. *indica* | 5-25 nm | XRD, SEM, TEM, FTIR | Anti-cancer, an excellent blood compatibility (low haemolytic activity) | [62] |

Moreover, their application in regenerative medicine—such as in bioactive coatings for implants or scaffolds for tissue engineering—remains underexplored. The interdisciplinary collaboration is essential to address scalability challenges. Innovations in continuous-flow synthesis, energy-efficient calcination methods, and waste-minimizing purification techniques could make large-scale production feasible. Concurrently, life-cycle assessments (LCAs) should be conducted to compare the environmental footprint of green synthesis with conventional methods, ensuring alignment with circular economy principles. By addressing these gaps, biosynthesized MgO NPs can transition from laboratory curiosities to transformative solutions for global sustainability and health challenges.

## 6. CONCLUSION

The biosynthesis of magnesium oxide nanoparticles (MgO NPs) represents a transformative approach in nanotechnology, merging sustainability with multifunctionality. This review underscores the pivotal role of plant- and microbe-mediated synthesis in producing MgO NPs with enhanced physicochemical properties, making them ideal for environmental and biomedical applications. In environmental remediation, MgO NPs exhibit exceptional efficiency in photocatalytic degradation of organic pollutants and adsorption of heavy metals, addressing critical challenges in wastewater treatment. Their ability to generate reactive oxygen species (ROS) under light irradiation facilitates the breakdown of complex dyes, while their high surface area enables effective heavy metal sequestration. In biomedicine, biosynthesized MgO NPs demonstrate broad-spectrum antimicrobial activity, combating multidrug-resistant pathogens through membrane disruption and oxidative stress. Their anticancer potential, particularly in inducing apoptosis in cancer cells, positions them as promising candidates for nanotherapeutics. Furthermore, their antioxidant properties and biocompatibility open avenues for applications in drug delivery, wound healing, and diagnostic imaging. Despite these advancements, challenges remain in standardizing synthesis protocols to ensure reproducibility and scalability. Variations in biological sources, reaction conditions, and post-synthesis treatments can influence nanoparticle properties, necessitating optimized methodologies. Additionally, long-term ecological and toxicological studies are imperative to assess the environmental impact of MgO NPs.

## DECLARATIONS

### Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

### Funding

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### Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

### Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

### Authors' contributions

All authors contributed equally to this work.

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