

MgO Nanoparticles: Synthesis, Characterizations and Applications: A Short Review

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Abstract:

This current review provides a comprehensive overview of magnesium oxide (MgO) nanoparticles, focusing on their synthesis, characterization, and diverse applications. MgO nanoparticles have attracted considerable research interest owing to their remarkable physicochemical properties, such as high surface area, excellent thermal stability, strong ionic bonding, and chemical inertness. Various synthesis methods including sol–gel, co-precipitation, hydrothermal, and combustion techniques are discussed, emphasizing how processing parameters affect the size, morphology, and crystallinity of the resulting nanoparticles. Characterization techniques such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and UV–Visible spectroscopy are reviewed to understand the structural, morphological, and optical behavior of MgO nanoparticles. The review further highlights their wide range of applications in catalysis, gas sensing, environmental remediation, antibacterial treatments, and biomedical systems, driven by their non-toxic, biocompatible, and highly reactive nature. The study concludes by emphasizing the relationship between synthesis routes, material characteristics, and performance, suggesting pathways for the future design of MgO nanostructures with enhanced functionality for technological and environmental advancements.

Keywords: MgO nanoparticles, synthesis methods, photocatalysis, gas sensing, biomedical applications.

1. Introduction

Magnesium oxide (MgO) nanoparticles have emerged as one of the most versatile and extensively studied classes of inorganic nanomaterials owing to their exceptional physicochemical characteristics, environmental friendliness, and multifunctional properties. Over the past two decades, significant attention has been directed toward MgO nanomaterials due to their wide availability, low cost, chemical stability, biocompatibility, and rich surface chemistry, making them suitable for a diverse range of industrial, environmental, and biomedical applications (Sahooli et al., 2012; Umar et al., 2015). At the nanoscale, MgO displays distinct physical and chemical behaviors compared to its bulk counterpart, including a high specific surface area, abundant surface defects (such as oxygen vacancies and low-coordination sites), a tunable bandgap, and a strong basic surface character. These unique nanoscale effects contribute to MgO's excellent catalytic, adsorptive, and antimicrobial activities, positioning it as a promising material for next-generation technologies in catalysis, energy storage, pollutant degradation, and biomedical applications (Tian et al., 2020; Jena et al., 2021). The attractive properties of MgO nanoparticles are fundamentally rooted in their ionic rock-salt crystalline lattice, composed of Mg^{2+} and

O²⁻ ions arranged in a face-centered cubic (FCC) structure. The high lattice energy and strong ionic bonding impart mechanical robustness, thermal stability, and basicity, while the high proportion of surface atoms and edges at the nanoscale modifies the electronic structure and enhances chemical reactivity (Zhou et al., 2019). These surface oxygen vacancies and defect sites play a crucial role in dictating the optical and catalytic behavior of MgO, enabling selective adsorption of reactant molecules and facilitating electron transfer processes (Gonçalves et al., 2019). The ability to tailor the size, morphology, and porosity of MgO nanoparticles through controlled synthesis conditions offers a practical route to optimize performance for specific applications ranging from high-surface-area porous structures for adsorption and catalysis to monodisperse crystalline forms for optical and dielectric devices (Sharma et al., 2017).

A central focus in MgO nanoparticle research lies in the diversity of synthesis methods, which significantly affect particle characteristics such as size, crystallinity, and surface properties. Physical or “top-down” techniques, including ball milling and thermal evaporation, can produce MgO nanostructures but often result in broad particle size distributions and require high energy input (Jung et al., 2013). The bottom-up chemical synthesis approaches includes sol–gel, co-precipitation, hydrothermal, solvothermal, solution combustion, and precipitation methods offer better control over nucleation and growth processes. These techniques allow researchers to fine-tune parameters like precursor concentration, solvent type, pH, reaction temperature, and calcination conditions to yield nanoparticles with controlled size, morphology, and surface area (Ali et al., 2018; Elahi et al., 2021). The sol–gel methods typically yield uniform and fine-grained MgO nanoparticles, while hydrothermal methods can produce well-crystallized nanorods or nanoplates under relatively mild conditions.

In recent years, green or bio-inspired synthesis routes have gained prominence due to increasing environmental awareness and the demand for sustainable production. These methods utilize plant extracts, microorganisms, or natural polymers as reducing and stabilizing agents, offering eco-friendly, cost-effective, and biocompatible alternatives to conventional chemical synthesis (Ibrahim, 2015; Azizi et al., 2014). Phytochemical constituents in plant extracts such as flavonoids, terpenoids, and polyphenols act as capping agents, reducing magnesium precursors to MgO while preventing aggregation. The resulting nanoparticles often exhibit functionalized surfaces and enhanced biological compatibility, making them suitable for applications in antimicrobial coatings, biosensors, and drug delivery systems (Patil et al., 2019). The growing body of literature on these methods demonstrates the feasibility of tailoring synthesis routes to achieve specific performance characteristics aligned with environmental and biomedical requirements.

The MgO nanoparticles represent a highly adaptable class of nanomaterials with tunable physicochemical properties and a wide application spectrum. Understanding the interplay between synthesis parameters, structural features, and functional performance is key to advancing their practical applications. This review provides a detailed discussion on synthesis strategies, characterization methods, and emerging applications of MgO nanoparticles, highlighting current challenges and proposing pathways for sustainable development of MgO-based nanotechnologies.

2. Synthesis methods of MgO nanoparticles

The synthesis of MgO nanoparticles has been extensively explored through various physical, chemical, and biological methods, each influencing the structural, morphological, and functional properties of the resulting nanomaterials. Among these, chemical routes such as sol–gel, co-precipitation, hydrothermal, and combustion synthesis have been most widely employed due to their simplicity, cost-effectiveness, and ability to yield uniform and crystalline nanoparticles (Sahooli et al., 2012; Jena et al., 2021). The sol–gel method is one of the most commonly used techniques for producing highly pure and homogenous MgO nanoparticles. This process involves hydrolysis and condensation of magnesium precursors (such as magnesium nitrate, magnesium acetate, or magnesium methoxide) to form a sol, which subsequently transitions into a gel that, upon drying and calcination, yields MgO nanoparticles (Kumar et al., 2018). The sol–gel route offers fine control over particle size and morphology through parameters such as pH,

aging time, and calcination temperature. Huang et al. (2019) reported that sol–gel-derived MgO nanoparticles exhibited uniform spherical morphology with average crystallite sizes ranging from 15 to 30 nm, depending on the calcination temperature. The sol–gel method ensures high purity and good dispersion, making it suitable for optical and catalytic applications (Tian et al., 2020). The co-precipitation method is another widely used bottom-up approach for synthesizing MgO nanoparticles, involving the precipitation of magnesium hydroxide [Mg(OH)₂] from aqueous solutions of magnesium salts (e.g., Mg(NO₃)₂ or MgCl₂) using alkali agents like NaOH or NH₄OH, followed by calcination to form MgO (Ali et al., 2018). This method offers several advantages, including low processing temperatures, high yield, and scalability. Sathishkumar et al. (2020) demonstrated that calcination temperature plays a crucial role in determining crystallinity and particle size; MgO nanoparticles synthesized at 500 °C showed smaller crystallites and higher surface areas than those calcined at 700 °C. The co-precipitation method's simplicity and reproducibility have made it a preferred technique for industrial-scale production of MgO nanoparticles used in catalysis and adsorption applications. The hydrothermal method utilizes high temperature and pressure in a sealed autoclave to promote controlled crystallization of MgO nanostructures from aqueous precursor solutions. This technique allows precise control of morphology such as nanorods, nanoplates, and nanocubes by adjusting parameters like temperature, pressure, solvent type, and mineralizer concentration (Elahi et al., 2021). Sharma et al. (2017) synthesized highly crystalline MgO nanorods via hydrothermal treatment at 180 °C, achieving excellent uniformity and defect control. The hydrothermal process is particularly advantageous for producing well-faceted and defect-free nanocrystals with high crystallinity, making them suitable for optical and dielectric applications. The solution combustion method involves an exothermic redox reaction between a magnesium salt (typically magnesium nitrate) and an organic fuel such as urea, glycine, or citric acid (Jung et al., 2013). The rapid combustion process generates high temperatures, leading to the formation of highly porous MgO nanoparticles within seconds. This method is energy-efficient and capable of producing large quantities of nanoparticles with high surface area and low agglomeration (Karthik et al., 2021). The parameters such as fuel-to-oxidizer ratio and ignition temperature significantly influence the final morphology and crystallinity. Sahooli et al. (2012) compared sol–gel and combustion-synthesized MgO nanoparticles and found that the latter exhibited higher surface areas and defect densities, beneficial for catalytic applications but less ideal for optical uniformity. In recent years, green or biological synthesis methods have gained increasing attention as eco-friendly alternatives to conventional chemical routes. These methods employ plant extracts, microorganisms, or natural polymers as both reducing and stabilizing agents to convert magnesium precursors into MgO nanoparticles under mild conditions (Ibrahim, 2015; Patil et al., 2019). The phytochemicals present in plant extracts such as polyphenols, terpenoids, and flavonoids facilitate the nucleation and stabilization of nanoparticles, reducing the need for toxic chemicals. Azizi et al. (2014) synthesized MgO nanoparticles using *Stevia rebaudiana* leaf extract, obtaining quasi-spherical nanoparticles with an average size of 20 nm and strong antibacterial activity. Similarly, Rajendran et al. (2020) reported that MgO nanoparticles produced through aloe vera extract exhibited high crystallinity, good dispersion, and excellent biocompatibility, making them suitable for biomedical and antimicrobial applications. The choice of synthesis method determines the physicochemical characteristics and potential applications of MgO nanoparticles. Sol–gel and hydrothermal techniques offer precise control over morphology and crystallinity; co-precipitation provides scalability and simplicity; combustion synthesis delivers rapid and porous structures; and green synthesis promotes environmental sustainability and biocompatibility. The growing diversity of synthesis strategies enables researchers to tailor MgO nanostructures for specific applications in catalysis, energy devices, and biomedical systems, thereby expanding the technological relevance of this versatile material (Tian et al., 2020; Alavi & Karimi, 2021). The different synthesis methods for MgO nanoparticles are display in Fig. 1.

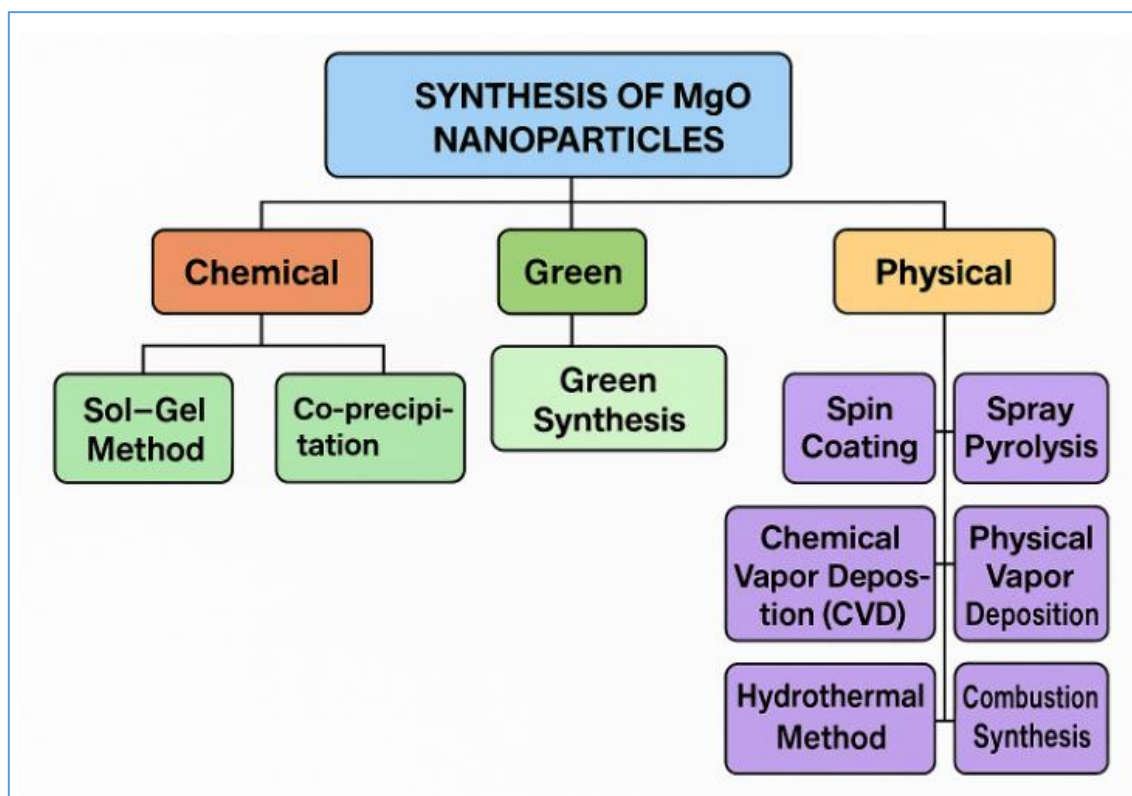


Fig. 1. Synthesis methods for MgO nanoparticles

3. Characterizations of MgO nanoparticles

Characterization of magnesium oxide nanoparticles is a crucial step in understanding their structure property relationships, which directly influence their physical, chemical, and functional behaviors in applications such as catalysis, adsorption, photocatalysis, and biomedicine. Since synthesis parameters such as precursor type, reaction temperature, pH, and calcination conditions can significantly affect the particle size, morphology, and surface properties, a comprehensive characterization is essential to confirm the successful formation of MgO and to correlate its structure with performance (Kumar et al., 2018; Jena et al., 2021). The primary goal of characterization is to determine the crystalline phase, morphology, particle size distribution, surface area, optical properties, and surface chemistry of the synthesized nanoparticles, ensuring reproducibility and quality control for specific applications. The different characterizations of MgO nanoparticles were investigated by research scholars are tabulated in Table 1.

Table 1: Characterization techniques of MgO nanoparticles and their reported findings.

Characterization Technique	Purpose / Information Obtained	Key Observations Reported by Researchers	References
X-Ray Diffraction (XRD)	Determines crystal structure, purity, and crystallite size.	Confirms cubic periclase structure of MgO with sharp peaks at $2\theta \approx 36.9^\circ$, 42.9° , 62.3° . Crystallite size (15–30 nm) increases with calcination temperature.	Kumar et al. (2018); Sathishkumar et al. (2020)

Scanning Electron Microscopy (SEM)	Examines surface morphology and agglomeration.	Reveals spherical and porous surface; morphology controlled by synthesis temperature and precursor type.	Sharma et al. (2017); Elahi et al. (2021)
Transmission Electron Microscopy (TEM)	Provides detailed internal structure and particle size distribution.	Shows well-dispersed nanoparticles with lattice fringes, confirming crystallinity of 10–20 nm MgO particles.	Elahi et al. (2021)
Fourier Transform Infrared Spectroscopy (FTIR)	Identifies surface functional groups and Mg–O bond vibrations.	Bands near 400–600 cm^{-1} indicate Mg–O stretching; bands near 3400 cm^{-1} and 1600 cm^{-1} show adsorbed hydroxyl and water molecules.	Ibrahim (2015); Rajendran et al. (2020)
UV–Visible Spectroscopy (UV–Vis)	Determines optical absorption and band gap energy.	Absorption in UV region (~200–250 nm) with bandgap 4.8–5.2 eV; redshift due to oxygen vacancies and size reduction.	Huang et al. (2019); Rajendran et al. (2020)
Brunauer–Emmett–Teller (BET) Analysis	Measures surface area and porosity.	High surface area (50–150 m^2/g) and mesoporous nature enhance adsorption and catalytic activity.	Sahooli et al. (2012); Karthik et al. (2021)
Photoluminescence (PL) Spectroscopy	Studies defect states and electron-hole recombination.	Emission peaks confirm presence of oxygen vacancies influencing photocatalytic efficiency.	Gonçalves et al. (2019)
X-Ray Photoelectron Spectroscopy (XPS)	Analyzes surface chemical composition and oxidation states.	Confirms Mg^{2+} and O^{2-} species; detects surface hydroxyl groups and oxygen vacancies.	Zhou et al. (2019); Tian et al. (2020)

Energy Dispersive X-ray Spectroscopy (EDS)	Determines elemental composition.	Shows characteristic Mg and O peaks confirming purity of MgO nanoparticles.	Jena et al. (2021)
Thermogravimetric Analysis (TGA)	Assesses thermal stability and decomposition behavior.	Stable MgO phase formation above 400 °C with minimal weight loss.	Alavi & Karimi (2021)

The need for characterization of MgO nanoparticles lies not only in confirming phase and morphology but also in establishing the relationship between synthesis conditions, surface properties, and functional behavior. MgO nanoparticles' performance in catalysis, sensing, or biomedicine is largely governed by surface chemistry and defect structure, multi-technique characterization ensures that the synthesized material meets the desired application requirements (Tian et al., 2020; Alavi & Karimi, 2021). In biomedical applications, surface characterization helps confirm biocompatibility and absence of harmful contaminants, while in gas sensing, it identifies active surface sites responsible for adsorption. The different characterization techniques for MgO nanoparticles are shown in Fig. 2.

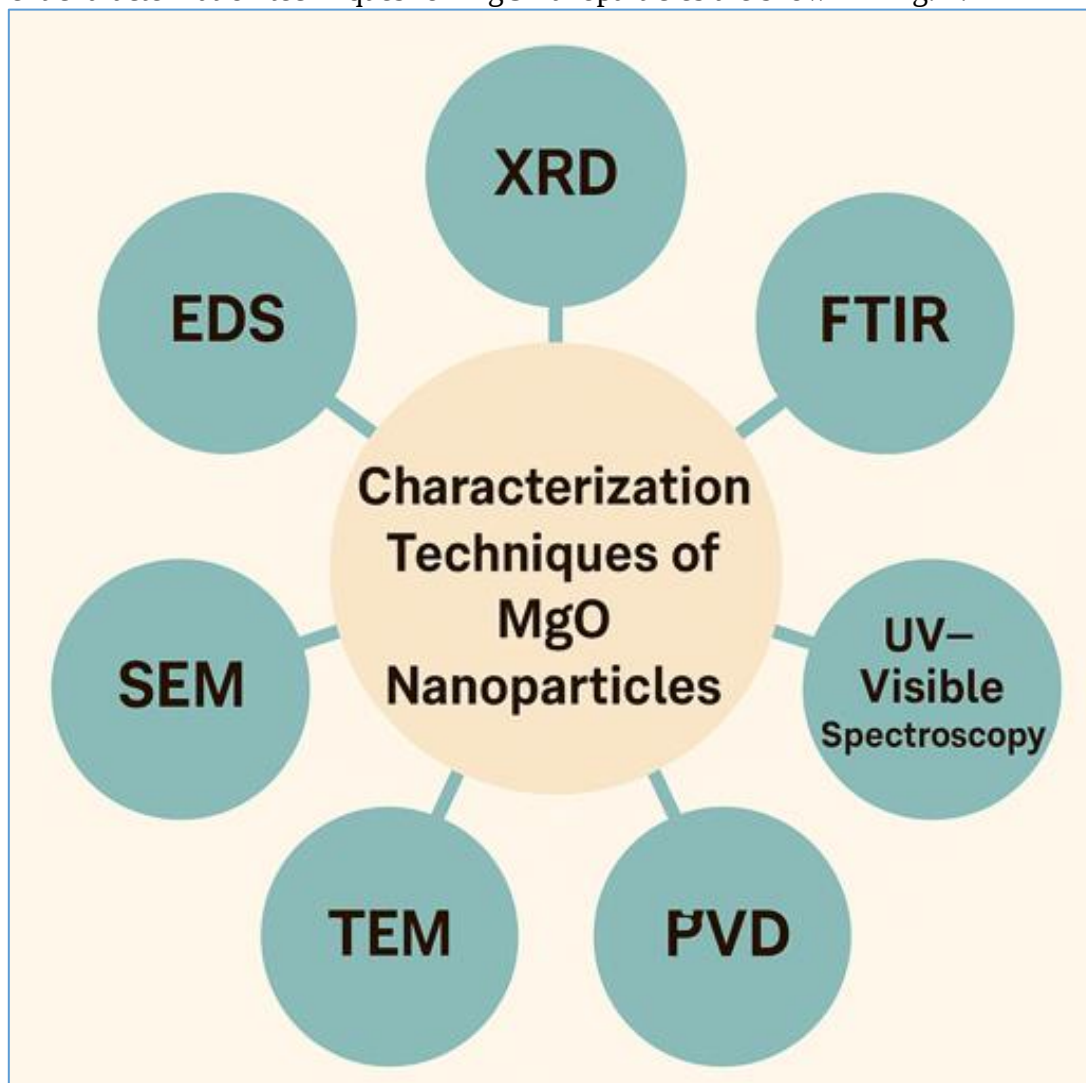


Fig. 2. Characterization techniques for MgO nanoparticles

Characterization plays a crucial role in understanding the structure property relationships of MgO nanoparticles. X-ray diffraction (XRD) is routinely employed to confirm the cubic crystal phase and estimate crystallite size using the Scherrer equation (Kumar et al., 2018). Microscopic techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed insights into the particle morphology, size distribution, and degree of agglomeration. The Brunauer–Emmett–Teller (BET) surface area analysis is essential to determine porosity and surface area, key parameters influencing catalytic and adsorption efficiencies (Sathishkumar et al., 2020). Spectroscopic techniques further enrich structural understanding: Fourier-transform infrared spectroscopy (FTIR) identifies surface functional groups and vibrational modes of Mg–O bonds; UV–Visible spectroscopy reveals optical absorption features and bandgap values; photoluminescence (PL) and X-ray photoelectron spectroscopy (XPS) offer insights into surface defects and oxidation states (Huang et al., 2019). For catalytic and gas sensing studies, temperature-programmed desorption (TPD), in-situ diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), and temperature-programmed reduction (TPR) techniques provide valuable information on adsorption sites, reaction intermediates, and surface reactivity. This multi-faceted approach ensures the rational design and optimization of MgO nanostructures for targeted applications in environmental, catalytic, and biomedical domains.

4. Applications of MgO nanoparticles

The applications of MgO nanoparticles have diversified across multiple technological domains. In environmental remediation, MgO serves as a photocatalyst and adsorbent for pollutant degradation and dye removal, often in composite form with materials like TiO₂, ZnO, or graphene to enhance photocatalytic performance (Karthik et al., 2021). The combination of high surface basicity, strong adsorption capability, and defect-mediated charge transfer facilitates efficient degradation of organic dyes and toxic compounds. MgO nanoparticles have also demonstrated remarkable antimicrobial and antifungal activities. Studies attribute this to multiple mechanisms, including the generation of reactive oxygen species (ROS), direct particle–cell membrane interactions, and localized pH alterations that disrupt microbial integrity (Nair et al., 2018). These characteristics have spurred research into MgO-based antimicrobial coatings, wound dressings, and packaging materials. In the field of gas sensing, MgO's strong basicity and selective adsorption of acidic gases such as CO₂, SO₂, and H₂S make it suitable for resistive and capacitive gas sensor applications. Doping with other metal oxides (e.g., SnO₂, ZnO, Fe₂O₃) or forming composites can improve sensitivity, selectivity, and stability (Wagh et al., 2019). Furthermore, MgO finds utility in polymer nanocomposites for enhancing mechanical strength, thermal resistance, and flame retardancy, as well as in biomedical applications such as drug delivery, bone regeneration, and bioactive implants owing to its biodegradability and biocompatibility (Rajendran et al., 2020). The few applications of MgO nanoparticles are shown in Fig. 3.

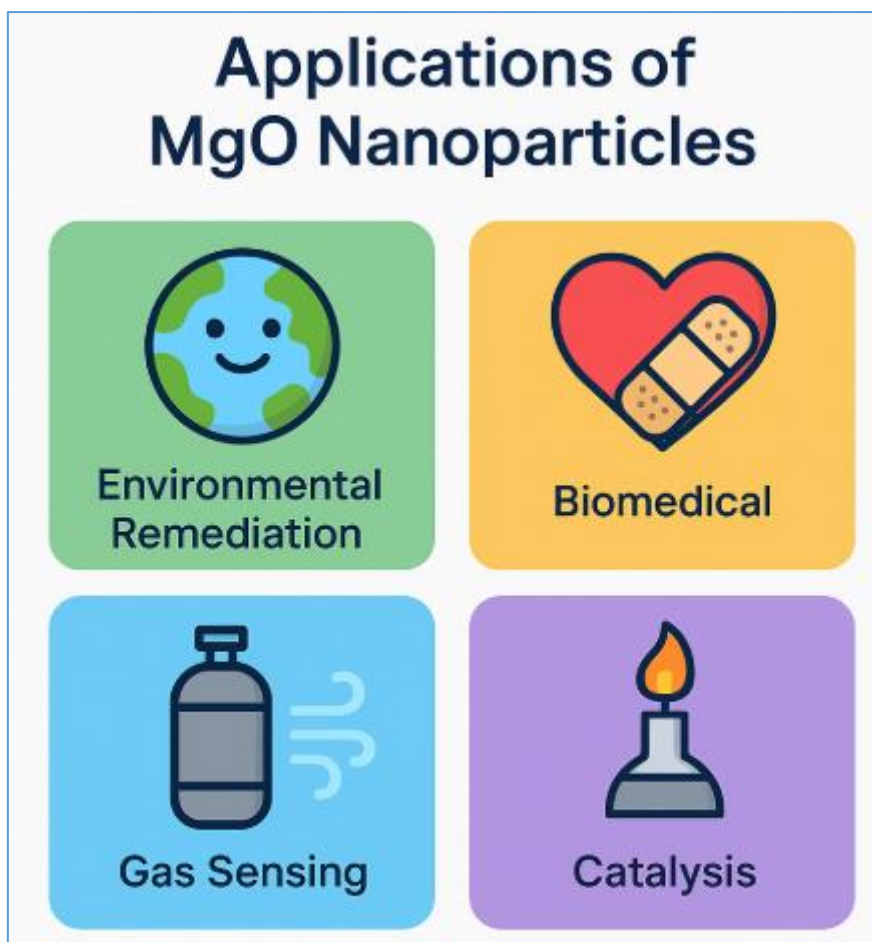


Fig. 3. Applications of MgO nanoparticles

MgO nanoparticles exhibit wide-ranging applications due to their unique physicochemical properties, such as high surface area, strong basicity, thermal stability, and biocompatibility. These characteristics make MgO a multifunctional nanomaterial for environmental, biomedical, catalytic, and electronic applications (Tian et al., 2020; Rajendran et al., 2020). One of the major applications of MgO nanoparticles lies in environmental remediation and photocatalysis. MgO has been explored for the degradation of organic pollutants, dyes, and toxic chemicals from wastewater due to its high adsorption capacity and basic surface nature (Karthik et al., 2021). For instance, Sahoo et al. (2012) synthesized porous MgO nanoparticles via combustion synthesis and demonstrated their effective performance in removing methylene blue dye. MgO often acts as a photocatalyst or a catalyst support material for other oxides such as TiO₂ and ZnO, enhancing charge separation and photocatalytic efficiency (Tian et al., 2020). The presence of surface oxygen vacancies and defects further improves adsorption and reaction rates by facilitating electron transfer processes. In the biomedical field, MgO nanoparticles have shown remarkable antibacterial, antifungal, and anticancer properties due to their ability to generate reactive oxygen species (ROS), induce cell membrane disruption, and alter intracellular pH (Ibrahim, 2015; Alavi & Karimi, 2021). Nair et al. (2018) demonstrated that MgO nanoparticles effectively inhibit *E. coli* and *S. aureus* growth through ROS-mediated oxidative stress and membrane damage. Similarly, Azizi et al. (2014) used plant-extract-mediated MgO nanoparticles and observed excellent antibacterial efficacy against pathogenic strains, highlighting their potential for medical coatings, wound dressings, and antimicrobial packaging materials. In addition, the non-toxic and biodegradable nature of MgO makes it suitable for drug delivery systems, bone tissue engineering, and bioactive implants (Rajendran et al., 2020). MgO nanocomposites incorporated into polymer scaffolds improve biocompatibility and mechanical strength, making them promising materials for orthopedic and dental applications.

MgO nanoparticles are also utilized in gas sensing applications, particularly for detecting acidic gases such as CO₂, SO₂, and H₂S. The strong basicity and high reactivity of MgO surfaces enable selective adsorption of these gases (Wagh et al., 2019). Doping MgO with other metal oxides like SnO₂ or ZnO improves sensitivity and reduces operating temperatures, offering stable and reproducible gas sensor performance. The high surface area and defect density of MgO make it suitable for integration in photoactivated gas sensors, enhancing their response to environmental pollutants. In the field of catalysis, MgO nanoparticles act as solid base catalysts for various organic transformations such as transesterification, aldol condensation, and CO₂ fixation (Sharma et al., 2017). Their high basicity and surface defect sites provide active centers for catalytic reactions. For instance, Gonçalves et al. (2019) showed that defect-engineered MgO nanoparticles exhibited superior performance in photocatalytic oxidation reactions compared to bulk MgO. MgO also serves as a catalyst support, stabilizing active metal particles and improving the overall catalytic efficiency and durability (Tian et al., 2020).

In polymer nanocomposites, MgO nanoparticles are used to enhance the mechanical, thermal, and flame-retardant properties of polymers. The incorporation of MgO nanoparticles into polymer matrices improves tensile strength, dielectric stability, and barrier properties due to strong interfacial interactions (Jena et al., 2021). MgO-based composites are also employed in coatings, ceramics, and refractory materials because of their excellent thermal resistance and stability. MgO nanoparticles find applications in energy storage and conversion systems, such as in solid oxide fuel cells (SOFCs), as dielectric materials in capacitors, and as additives to improve the thermal stability of electrodes. Their wide bandgap and high dielectric constant make them useful in insulating and optical coating applications (Huang et al., 2019). The versatility of MgO nanoparticles across multiple domains arises from their tunable structural, optical, and surface properties. By tailoring particle size, morphology, and surface defects through synthesis control, researchers can optimize MgO nanostructures for targeted applications, ranging from environmental cleanup and catalysis to biomedical and sensing technologies (Tian et al., 2020; Rajendran et al., 2020).

5. Future Perspectives of MgO Nanoparticles

The future of MgO nanoparticles research focuses on developing eco-friendly, scalable, and high-performance nanomaterials for applications in energy, environment, and healthcare. Emphasis will be placed on green synthesis routes using plant extracts and bio-reducing agents to enhance sustainability and biocompatibility. Advanced surface modification and defect engineering will enable better control over optical, catalytic, and sensing properties. MgO-based hybrid nanocomposites with materials like graphene and TiO₂ are expected to show improved photocatalytic and gas sensing performance. In biomedicine, MgO's non-toxic and antibacterial nature makes it suitable for drug delivery, wound healing, and tissue engineering. Future research will also address toxicity, stability, and large-scale production challenges, ensuring safe and efficient use in real-world applications.

6. Conclusions

Magnesium oxide nanoparticles represent a highly versatile and promising class of nanomaterials due to their exceptional physicochemical properties, including high surface area, strong basicity, chemical stability, and biocompatibility. This review highlights that various synthesis methods such as sol-gel, co-precipitation, hydrothermal, combustion, and green synthesis enable precise control over particle size, morphology, and surface chemistry, which directly influence their functional behavior. Comprehensive characterization through techniques like XRD, SEM, TEM, FTIR, UV-Vis, BET, and XPS provides crucial insights into the structural, optical, and surface properties that determine performance in different applications. MgO nanoparticles have demonstrated significant potential in diverse fields including environmental remediation, catalysis, antibacterial and biomedical systems, polymer nanocomposites, and gas sensing. However, challenges remain in achieving large-scale, energy-efficient, and environmentally sustainable synthesis while maintaining uniformity and stability. Future work should focus on eco-friendly production, defect engineering, and hybridization with other materials to enhance multifunctional

performance. The MgO nanoparticles hold tremendous potential for advancing sustainable technologies in environmental, energy, and biomedical sectors, marking them as an important material for next-generation nanoscience and engineering applications.

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