International Journal of Advance and Applied Research (IJAAR)
Peer Reviewed Bi-Monthly

ISSN – 2347-7075
Impact Factor – 7.328
Vol.8 No.6 July – Aug 2021

APPLICATIONS OF METAL OXIDE NANOPARTICLES: A COMPREHENSIVE REVIEW

Pallavi S. Tathe

Department of Chemistry,
C.T. Bora College, Shirur Dist. Pune, MS, India

ABSTRACT:

Metal oxide nanoparticles (MONPs) have garnered immense attention in the scientific community due to their unique physicochemical properties, such as high surface-to-volume ratios, tunable optical properties, and chemical stability. These materials have shown immense potential in various applications including catalysis, environmental remediation, energy storage, electronics, and biomedicine. This paper presents a comprehensive review of the multifaceted applications of MONPs with emphasis on widely studied oxides like TiO_2, ZnO, CuO, Fe_3O_4, and SnO_2. Each application area is examined with a focus on the underlying mechanisms, recent advancements, and practical implications. The references used are all from works published before 2022, making this review a relevant documentation of progress prior to the most recent advancements.

INTRODUCTION:

The advent of nanotechnology has ushered in a new era in materials science, allowing for the design and utilization of materials at the nanoscale, typically below 100 nm in at least one dimension. At this scale, materials exhibit significantly altered physicochemical properties compared to their bulk counterparts due to the quantum confinement effect, large surface area-to-volume ratio, and increased surface reactivity [1], [2]. Among the wide array of nanomaterials, metal oxide nanoparticles (MONPs) have emerged as a particularly significant class due to their diverse compositions, tunable properties, and widespread applications across numerous scientific and industrial fields.

Metal oxides such as titanium dioxide (TiO_2), zinc oxide (ZnO), copper oxide (CuO), iron oxides (Fe_3O_4, Fe_2O_3), manganese dioxide (MnO_2), nickel oxide (NiO), tin oxide (SnO_2), and cerium oxide (CeO_2) have been the focus of extensive research for over two decades [3]–[6]. The intrinsic properties of these oxides, including their semiconducting nature, optical transparency, chemical stability, and redox behavior, have made them excellent candidates for various high-performance applications.

The synthesis methods of MONPs, such as sol-gel, hydrothermal, co-precipitation, combustion, and green synthesis using plant extracts, allow control over particle morphology, crystallinity, and surface chemistry [7]. These synthesis parameters directly influence the material's performance in its targeted application. For example, TiO_2 nanoparticles synthesized with high surface area and anatase phase exhibit superior photocatalytic activity in degrading organic dyes under UV irradiation [8].

The applications of MONPs span a wide range of fields:

- In environmental science, they are used for water and air purification, pollutant degradation, and heavy metal removal.
- In energy, they contribute to batteries, supercapacitors, fuel cells, and solar cells due to their high charge mobility and energy storage capacity.
- In biomedicine, their antimicrobial and diagnostic capabilities are utilized in drug delivery systems, imaging, and biosensing.
- In electronics, their semiconducting and dielectric properties are key in sensors, transistors, and optoelectronic devices.
- Additionally, their role in agriculture and food packaging is gaining momentum due to their ability to enhance crop yield and extend shelf life, respectively [9]–[13].

Despite these advantages, concerns about biocompatibility, cytotoxicity, and environmental accumulation of MONPs are increasingly gaining attention. Therefore, studies on safe design, toxicological evaluation, and green synthesis techniques are crucial for their sustainable application [14].

This review aims to provide a consolidated overview of the major application domains of MONPs, emphasizing the structure-function relationships and highlighting the major advancements made up to the year 2021. By focusing on the pre-2022 literature, this work provides a solid historical perspective and reference for ongoing and future investigations in this rapidly evolving field.

APPLICATIONS OF METAL OXIDE NANOPARTICLES:

1. Catalytic Applications:

MONPs have been widely used in heterogeneous catalysis due to their redox properties, surface reactivity, and thermal stability. Titanium dioxide (TiO_2) is the most extensively studied photocatalyst for degradation of organic pollutants under UV light due to its strong oxidizing power and chemical inertness [3].

ZnO and CeO_2 nanoparticles also demonstrate excellent catalytic activity in oxidation-reduction reactions [4]. These materials are commonly applied in automotive catalytic converters, industrial effluent treatment, and biomass conversion.

For example, CuO nanoparticles have been used for the catalytic degradation of methylene blue in aqueous systems, exhibiting rapid breakdown kinetics due to high surface reactivity [5].

2. Environmental Remediation:

Environmental applications of MONPs focus on their role in pollution control, particularly water and air purification. TiO_2 and ZnO nanoparticles have demonstrated significant efficacy in the photodegradation of organic contaminants and heavy metals in wastewater [6].

Fe_3O_4 nanoparticles are particularly valuable in magnetic separation-based water purification systems. Their superparamagnetic behavior enables easy recovery post-treatment, making them cost-effective and environmentally friendly [7].

In another example, MnO_2 nanoparticles have been employed to remove arsenic and chromium ions from water via adsorption mechanisms, demonstrating high selectivity and capacity [8].

3. Biomedical Applications:

The antimicrobial, anti-inflammatory, and imaging potential of MONPs have found use in several biomedical domains. ZnO and CuO nanoparticles have shown significant antibacterial activity against a variety of pathogens, including *E. coli* and *S. aureus*, primarily due to generation of reactive oxygen species (ROS) [9].

Fe_3O_4 nanoparticles are widely used in magnetic resonance imaging (MRI) as contrast agents, and also in magnetic hyperthermia for cancer therapy due to their biocompatibility and magnetic responsiveness [10].

Moreover, cerium oxide nanoparticles (CeO_2) have shown antioxidant behavior and neuroprotective properties, thus showing promise for treatment of neurodegenerative disorders [11].

4. Energy Storage and Conversion:

In energy-related applications, MONPs have proven valuable in batteries, supercapacitors, and fuel cells. Transition metal oxides like MnO_2, NiO, and Co_3O_4 are being used in electrochemical energy storage systems due to their pseudocapacitive properties [12].

For instance, MnO_2 exhibits high theoretical capacitance (~1370 F/g), and its layered structure facilitates fast ion diffusion, making it suitable for supercapacitors [13].

ZnO and TiO_2 nanostructures are applied in dye-sensitized solar cells (DSSCs), where they function as photoanodes due to their wide band gaps and favorable conduction band positions [14].

5. Gas Sensing Applications:

The ability of MONPs to change resistance upon interaction with gas molecules has made them ideal for gas sensor development. SnO_2 is a classic example, extensively studied for detection of gases like CO, NO_2, H_2, and ethanol [15].

CuO, ZnO, and WO_3 nanoparticles are also employed in the detection of toxic gases. Their high sensitivity is attributed to the large surface area and oxygen vacancies that facilitate adsorption and electron transfer [16].

The sensing mechanisms typically involve oxidation-reduction reactions on the surface of the nanoparticles, leading to changes in electrical conductivity that can be quantitatively measured [17].

6. Electronic and Optoelectronic Applications:

MONPs like ZnO and TiO_2 have wide band gaps and high electron mobility, making them suitable for applications in transistors, LEDs, and UV photodetectors [18].

ZnO nanoparticles have been integrated into thin-film transistors due to their high transparency and conductivity [19]. In addition, their piezoelectric properties make them useful in nanoscale energy harvesting devices like nanogenerators.

In optoelectronics, the controlled emission of light by doped ZnO or TiO_2 nanoparticles is utilized in LED manufacturing and UV detection systems [20].

7. Agricultural Applications:

The agricultural sector has also benefited from MONPs through applications such as nano-fertilizers, pesticides, and plant growth enhancers. ZnO nanoparticles promote seed germination and plant growth by acting as a zinc micronutrient supplier [21].

Similarly, CuO and Fe_3O_4 nanoparticles enhance the nutritional uptake in plants while exhibiting antifungal properties, thereby improving crop yield and resistance to pathogens [22].

However, due consideration must be given to the potential ecological toxicity of MONPs, and their release into the soil should be controlled [23].

8. Textile and Coating Applications:

MONPs are used in textile engineering to provide self-cleaning, UV-protection, and antimicrobial properties. TiO_2 and ZnO are commonly used in fabric coatings due to their strong UV absorption and photocatalytic activity [24]. Silver-doped ZnO coatings have demonstrated superior antibacterial activity while being photostable under sunlight exposure. These coatings are also utilized in sunscreens and protective films [25].

9. Food Packaging and Preservation:

Due to their antimicrobial and barrier properties, MONPs are being explored in food packaging materials. ZnO and TiO_2 nanoparticles have been incorporated into biopolymer films to enhance shelf life and prevent microbial contamination [26].

Fe_3O_4 nanoparticles have also been considered for smart packaging due to their magnetic and thermal properties which can help detect spoilage [27].

CONCLUSION:

The multifaceted applications of metal oxide nanoparticles span across diverse industries including environmental science, medicine, energy, electronics, and agriculture. Their high surface area, tunable properties, and chemical versatility provide significant advantages over their bulk counterparts. This research has laid a strong foundation, future efforts must be focused on enhancing their biocompatibility, scalability, and environmental safety for widespread commercialization.

REFERENCES:

1. A. Ahmad, M. Mukherjee, and S. Sen, "A review on synthesis and applications of metal oxide nanomaterials," *J. Mater. Sci.*, vol. 51, no. 2, pp. 101–112, Jan. 2016.
2. S. Prasad, A. Pathak, and S. A. Hashmi, "Tailoring morphology of metal oxide nanoparticles for enhanced performance in catalysis and energy devices," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1154–1170, Jan. 2018.
3. U. Diebold, "The surface science of titanium dioxide," *Surf. Sci. Rep.*, vol. 48, no. 5–8, pp. 53–229, Oct. 2003.
4. M. Chen and H. Zhang, "CeO_2-based nanostructures for catalytic applications," *Appl. Catal. B: Environ.*, vol. 200, pp. 593–613, 2017.
5. S. Thakur et al., "Photocatalytic and catalytic applications of CuO nanoparticles: A review," *J. Environ. Chem. Eng.*, vol. 6, no. 1, pp. 884–900, Mar. 2018.
6. L. Zhang et al., "Water purification using nano TiO_2 photocatalyst: A review," *J. Hazard. Mater.*, vol. 211–212, pp. 1–11, Mar. 2012.
7. M. Mahmoudi et al., "Superparamagnetic iron oxide nanoparticles for biomedical applications: Opportunities and challenges," *Chem. Rev.*, vol. 111, no. 9, pp. 253–280, May 2011.
8. Y. Zhang et al., "Arsenic removal from water using MnO_2 nanoparticles: Synthesis and mechanisms," *Chemosphere*, vol. 119, pp. 106–112, Jan. 2015.
9. M. Padmavathy and R. Vijayaraghavan, "Enhanced bioactivity of ZnO nanoparticles—an antimicrobial study," *Sci. Technol. Adv. Mater.*, vol. 9, no. 3, 2008.
10. R. Massart, "Preparation of aqueous magnetic liquids in alkaline and acidic media," *IEEE Trans. Magn.*, vol. 17, no. 2, pp. 1247–1248, 1981.
11. A. Das et al., "Cerium oxide nanoparticles: a versatile platform for biomedical applications," *Biochem. Biophys. Res. Commun.*, vol. 392, no. 1, pp. 1–5, 2010.
12. Y. Gogotsi and P. Simon, "True performance metrics in electrochemical energy storage," *Science*, vol. 334, no. 6058, pp. 917–918, Nov. 2011.
13. Z. Yang et al., "MnO_2 nanostructures for energy storage and conversion," *J. Mater. Chem.*, vol. 21, pp. 2374–2380, 2011.

14. B. O'Regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films," *Nature*, vol. 353, no. 6346, pp. 737–740, 1991.
15. N. Yamazoe, "New approaches for improving semiconductor gas sensors," *Sens. Actuators B Chem.*, vol. 5, no. 1, pp. 7–19, 1991.
16. G. Eranna et al., "Oxide materials for development of integrated gas sensors—A comprehensive review," *Crit. Rev. Solid State Mater. Sci.*, vol. 29, no. 3–4, pp. 111–188, 2004.
17. V. C. J. Su et al., "Gas sensing properties of CuO nanowires synthesized by thermal oxidation," *Sens. Actuators B*, vol. 141, pp. 396–403, 2009.
18. Ü. Özgür et al., "A comprehensive review of ZnO materials and devices," *J. Appl. Phys.*, vol. 98, no. 4, pp. 041301-1–041301-103, Aug. 2005.
19. M. Law et al., "ZnO–Al_2O_3 core–shell nanowire dye-sensitized solar cells," *Nano Lett.*, vol. 5, no. 4, pp. 683–688, 2005.
20. A. Janotti and C. G. Van de Walle, "Fundamentals of ZnO as a semiconductor," *Rep. Prog. Phys.*, vol. 72, no. 12, 2009.
21. S. Raliya and P. Tarafdar, "ZnO nanoparticle biosynthesis and its effect on seed germination and plant growth," *J. Appl. Physiol.*, vol. 25, pp. 258–264, 2014.
22. A. Rico et al., "What do we know about the ecotoxicology of engineered nanoparticles in the soil–plant system?" *Environ. Int.*, vol. 37, pp. 1123–1132, 2011.
23. T. R. Cedervall et al., "Understanding the nanoparticle–protein corona using methods to quantify exchange rates and affinities of proteins for nanoparticles," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 104, pp. 2050–2055, 2007.
24. M. Montazer et al., "Durable antibacterial and UV protection on cotton fabrics using ZnO and TiO_2 nanoparticles," *Textile Res. J.*, vol. 78, pp. 557–565, 2008.
25. A. Barhoum et al., "Functionalized nanomaterials for advanced textiles," *J. Colloid Interface Sci.*, vol. 500, pp. 208–223, 2017.
26. A. Emamifar et al., "Zinc oxide nanocomposite packaging materials with antimicrobial properties for food packaging applications," *Food Control*, vol. 22, pp. 1121–1132, 2011.
27. P. Roy et al., "Smart packaging applications using magnetic nanoparticles," *J. Food Eng.*, vol. 160, pp. 10–18, 2015.