JOURNAL OF SUSTAINABLE MATERIALS PROCESSING AND MANAGEMENT
e-ISSN: 2821-2843

Vol. 5 No. 2 (2025) 51-73
https://publisher.uthm.edu.my/ojs/index.php/jsmpm

JSMPM

A Review on Metal Oxide Nanoparticles: Bridging Chemical Synthesis Strategies to Emerging Applications

Pradhumansinh Kher[1], Gaurav Jadav[1], Sandhya Dodia[1], Bharat Kataria[2], J.H. Markna[2]*

[1] *School of Applied Sciences and Technology, Gujarat Technological University, Ahmedabad, 382424, INDIA*
[2] *Department of Nanoscience and Advanced Materials, Saurashtra University, Rajkot, 360005, INDIA*

*Corresponding Author: jaysukh28@gmail.com
DOI: https://doi.org/10.30880/jsmpm.2025.05.02.005

Article Info

Received: 22 July 2025
Accepted: 12 September 2025
Available online: 19 October 2025

Keywords

Metal oxide nanoparticles (MONPs), sol-gel synthesis, hydrothermal/solvothermal, thermal decomposition, microwave-assisted synthesis, electrochemical methods, catalysis, energy storage, gas sensing, biomedical applications, environmental remediation

Abstract

Metal oxide nanoparticles (MONPs) exhibit size-dependent properties that drive advances in catalysis, energy storage, sensing, remediation, and biomedicine. Chemical synthesis routes allow precise control over structure, composition, and crystallinity, typically yielding 5–100 nm particles. Sol-gel offers molecular-level mixing and uniformity; hydrothermal/solvothermal methods operate at 100–250 °C and 1–10 MPa; thermal decomposition yields highly crystalline oxides at 300–750 °C; and microwave-assisted synthesis achieves uniform nanoparticles within minutes. Unlike prior reviews that focus separately on methods or applications, this article uniquely bridges synthesis strategies with application-driven property requirements, mapping how reaction conditions govern morphology, defect states, and surface reactivity. Representative case studies highlight enhanced catalytic activity from high surface areas, improved Li-ion battery cycling stability, ppm-level gas sensing, pollutant degradation via photocatalysis, and targeted drug delivery using functionalized oxides. Finally, we critically assess challenges in scalability, reproducibility, and biocompatibility, and outline future directions in hybrid architectures and continuous-flow synthesis.

1. Introduction

Metal oxide nanoparticles (MONPs) have received a lot of interest for their unusual physicochemical features and wide range of applications in catalysis, sensing, energy storage, environmental remediation, and biomedicine. Their enormous surface area, customizable characteristics, and surface reactivity allow for personalized solutions for specific applications. Chemical synthesis methods, such as sol-gel [1], hydrothermal [2], solvothermal [3], and other chemical approaches, allow precise control over composition, size, morphology, and crystallinity. These techniques regulate nanoparticle properties by manipulating precursor concentrations, reaction kinetics, temperature, and surfactant use [4].

This review provides an extensive overview of the chemical processes used to synthesize MONPs, detailing the principles, advantages, and limitations of various methods. Representative examples of MONPs are provided, showcasing their versatile applications. Understanding these synthesis approaches will help researchers select appropriate methods to achieve desired nanoparticle characteristics for specific applications. MONPs have demonstrated exceptional performance across diverse fields, including catalysis [5], energy storage, sensing, environmental remediation, and biomedical applications [6]. Their high activity and selectivity have made them invaluable catalysts in chemical reactions, while their use in energy storage has improved battery performance and supercapacitor efficiency. In sensing applications, MONPs enable highly accurate detection of analytes, which has been instrumental in gas sensing, biosensing, and environmental monitoring.

Furthermore, MONPs have played a critical role in environmental remediation by removing pollutants and treating wastewater, and their utilization in biomedicine has revolutionized diagnosis and therapy as drug delivery systems, imaging agents, and theragnostic tools. Despite substantial progress in MONP synthesis and applications, challenges such as scalability, reproducibility, toxicity, safety, and integration into practical systems remain key issues requiring attention [7]. The future holds exciting opportunities for advancements, including the development of hybrid nanocomposites and multifunctional platforms that combine imaging, treatment, and sensing capabilities. By addressing these challenges and capitalizing on future perspectives, MONPs are expected to make substantial contributions to catalysis, energy storage, environmental protection, and biomedical sciences, offering transformative advancements across multiple industries.

Recent reviews on metal oxide nanoparticles (MONPs) have provided valuable insights, yet most concentrate on either synthesis strategies or application domains individually. For instance, Yin et al. [8] emphasize microwave-assisted and solution-combustion approaches with a focus on synthetic efficiency, while Radulescu et al. [9] highlight eco-friendly and biomedical aspects of green-synthesized MONPs. More recently, Belew and Assege [10] reviewed solvothermal synthesis with attention to morphology control and application challenges. These contributions are important, yet they largely treat synthesis and applications as distinct discussions. In contrast, the present review aims to bridge this gap by systematically linking chemical synthesis parameters—such as temperature, pressure, reaction time, and precursor chemistry—to nanoparticle morphology, defect chemistry, and performance in catalysis, energy storage, sensing, environmental remediation, and biomedicine. By integrating synthesis principles with application-oriented case studies, this article provides a distinct framework for guiding the rational design and deployment of MONPs.

2. Chemical Synthesis Methods

The Chemical synthesis procedures are crucial for determining the properties of metal oxide nanoparticles (MONPs), which affect their performance in a variety of applications. Key techniques include the sol-gel process, hydrothermal and solvothermal treatments, thermal decomposition, electrochemical synthesis, and microwave-assisted synthesis as seen in Fig. 1. The sol-gel approach [11] provides great purity and uniformity, while hydrothermal and solvothermal treatments [12] provide precise control over particle size, morphology, and enhanced crystallinity. Thermal decomposition [13] offers a straightforward approach to obtaining nanoparticles with controlled sizes and shapes. Electrochemical synthesis [14] is valued for its simplicity and ability to produce high-quality nanoparticles. Microwave-assisted synthesis [15] significantly reduces reaction times and enhances particle uniformity. Each method manipulates precursor concentrations, reaction kinetics, temperature, and surfactants to tailor MONPs for specific applications in catalysis, energy storage, sensing, environmental remediation, and biomedicine [16]. This review explores these synthesis techniques, highlighting their principles, advantages, and limitations, which are essential for advancing MONP research and broadening its practical applications.

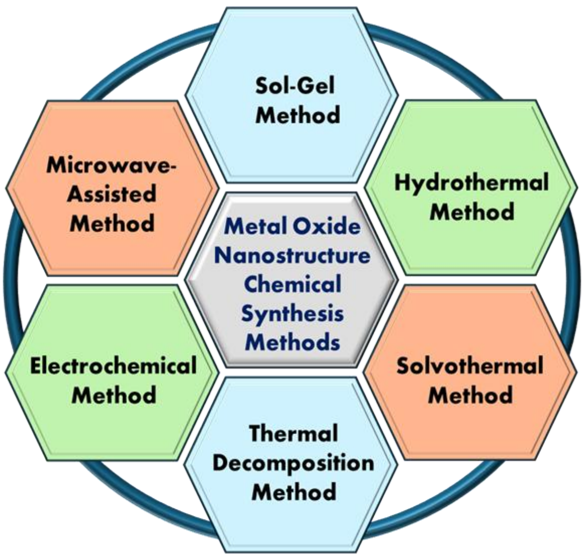

Fig. 1 *Schematic overview of major chemical synthesis methods for MONPs, including sol–gel, hydrothermal/solvothermal, thermal decomposition, electrochemical, and microwave-assisted routes*

2.1 Sol-Gel Process

2.1.1 Principle and Mechanism

The sol-gel procedure is a flexible approach for the synthesis of metal oxide nanoparticles (MONPs), involving the initial mixing of metal alkoxides with a solvent and a hydrolyzing agent. During hydrolysis, the metal-oxygen bonds in the precursor compounds are cleaved, releasing hydroxyl groups. These metal hydroxides subsequently undergo condensation reactions, where the hydroxyl groups react to form metal-oxygen-metal linkages [17]. This condensation leads to the formation of a gel network. To obtain nanoparticles, the gel undergoes aging or drying, followed by calcination at elevated temperatures. The aging process ensures the complete removal of solvent and water molecules while drying removes residual moisture. Calcination involves heating the gel at high temperatures, causing the precursor compounds to decompose and crystallize, forming MONPs [18].

The controlled synthesis of zirconia nanoparticles for catalytic applications using the sol-gel technique has been demonstrated, demonstrating the impacts of various reaction variables, including precursor concentration, solvent composition, particle size, morphology, reaction temperature, and crystallinity [19]. The study indicated that precise control over the final properties of zirconia nanoparticles is achievable by adjusting these factors [20]. Another example is the creation of alumina (Al2O3) nanoparticles using the sol-gel process. Researchers have created and analyzed alumina nanoparticles, emphasizing the importance of a catalyst for hydrolysis to facilitate the formation of well-dispersed, uniform nanoparticles [21]. Aging, drying, and calcination steps are crucial for producing crystalline alumina nanoparticles with controlled shapes and enhanced properties. For the purpose of producing crystalline alumina nanoparticles with a regulated shape and improved features, aging, drying, and calcination operations were required. Other MONPs synthesized using the sol-gel process include iron oxide (Fe3O4) [22], tin oxide (SnO2) [23], and zinc oxide (ZnO) [24]. Each of these nanoparticles requires specific precursor materials, solvent compositions, hydrolyzing agents, and subsequent aging, drying, and calcination steps. The sol-gel technique enables fine control over particle size and shape, resulting in improved characteristics and performance adapted to specific applications [25].

2.1.2 Advantages and Limitations

The sol–gel method offers important advantages such as high product homogeneity, chemical purity, and the possibility of tailoring surface functionality through dopant or ligand incorporation [26]. These features make it attractive for designing MONPs with properties suited to catalytic, optical, or biomedical applications. However, the method also has limitations. It requires stringent control of reaction parameters such as pH, temperature, and reaction time, which complicates scalability [27]. In addition, the precursors, particularly metal alkoxides, are relatively expensive, and the multi-step process (hydrolysis, gelation, drying, and calcination) often leads to longer synthesis times compared to other chemical routes [27]. Nevertheless, refinements in sol–gel protocols have enabled the preparation of novel nanomaterials with specialized functionalities, reinforcing its role as a versatile synthesis strategy [28]. Representative sol–gel conditions for common MONPs are summarized in Table 1.

Table 1 *Representative sol–gel syntheses of metal-oxide nanoparticles (MONPs): typical precursors, media, processing, and size ranges*

Metal Oxide	Precursors	Solvent	Hydrolyzing agent/catalyst	Aging & Drying	Calcination (°C)	References
ZrO_2	Zirconium alkoxides	Alcohol / H_2O	Acid or base	Aging, oven drying	400–700	[26]
Al_2O_3	Aluminum alkoxides/nitrates	EtOH / H_2O	Acid or base	Aging, drying	500–800	[28]
Fe_2O_3 (γ/α)	$Fe(NO_3)_3·9H_2O$, $FeCl_3$	H_2O / EtOH	NH_4OH (base)	12–24 h aging, drying	400–600	[29]
SnO_2	$SnCl_4·5H_2O$	H_2O or EtOH/H_2O	NH_4OH / bio-extract	Aging, drying	350–550	[30]
ZnO	$Zn(CH_3COO)_2·2H_2O$	EtOH (+ H_2O)	NaOH (base)	Aging, drying	400–550	[31]

Abbreviations: EtOH = ethanol; H_2O = deionized water; NH_4OH = ammonium hydroxide. Values indicate typical ranges reported in the cited studies.

2.2 Hydrothermal and Solvothermal Treatments

2.2.1 Principle and Mechanism

Metal oxide nanoparticles (MONPs) are frequently synthesized using hydrothermal and solvothermal techniques. These approaches use the high temperature along with high-pressure settings to help nanoparticles develop. In the hydrothermal approach, a precursor solution is sealed in a pressure vessel and heated above its boiling point, facilitating the dissolution, nucleation, and development of nanoparticles under controlled circumstances (see Table 2 for representative examples) [32]. Solvothermal synthesis is similar but utilizes organic solvents as the reaction medium [3]. Detailed analysis of hydrothermal synthesis-produced materials, including oxides [33], hydroxides [34], sulphides [35], nitrides [36], and organic-inorganic hybrids [37]. The precise control over reaction parameters in these methods allows for the tailored synthesis of MONPs with specific properties for diverse applications [38].

Table 2 *Representative examples of MONPs synthesized using hydrothermal and solvothermal treatments*

Metal Oxide	Precursors	Solvent	Temperature / Pressure	Time	Morphology / Particle Size	References
ZnO	Zn acetate	H_2O / EtOH	160–200 °C, autogenous	12–24 h	Nanoflakes, ~40–50 nm	[39]
CeO_2	$Ce(NO_3)_3$	Ethanol	180–200 °C, autogenous	12 h	Spherical, ~10–20 nm	[40]
TiO_2 (rutile)	TBOT	HCl/H_2O	150 °C	12 h	Globosa-like nanorods (~250 nm × 2.1 μm)	[41]
SiO_2 (mesoporous MSNs	TEOS	EtOH / H_2O + catalyst	180 °C, autogenous	24 h	Mesoporous spheres (MSNs)/ ~50–200 nm	[42]

Abbreviations: EtOH = ethanol; TEOS = tetraethyl orthosilicate; MSNs= mesoporous silica nanoparticle; TBOT = titanium butoxide.

2.2.2 Advantages and Limitations

Hydrothermal and solvothermal methods offer several advantages. Firstly, they make it possible to create extremely crystalline nanoparticles that have precise command over their size, shape, and surface characteristics [43]. The high temperatures and pressures aid in the dissolution of precursors and the creation of thermodynamically stable crystalline phases [44]. Additionally, these methods allow for the incorporation of dopants or the formation of composite nanoparticles [45]. Moreover, the relatively fast reaction kinetics of hydrothermal and solvothermal methods result in shorter synthesis times compared to other techniques. However, these methods also have limitations. One significant limitation is the requirement for specialized equipment capable of withstanding high temperatures and pressures [46]. The cost and complexity of such equipment can hinder their widespread use. Additionally, controlling the growth and nucleation processes can be challenging, potentially leading to a diverse size distribution of nanoparticles. Furthermore, the selection of solvents and precursors is constrained by the high temperatures and pressures, as some chemicals may decompose or react unfavorably under such conditions.

2.3 Thermal Decomposition Method

2.3.1 Principle and Mechanism

The thermal decomposition method is widely used to produce metal oxide nanoparticles (MONPs). This approach involves the decomposition of precursor compounds at elevated temperatures, leading to the formation of nanoparticles. Typically, the precursor materials are organic compounds such as metal carboxylates, metal alkoxides, or metal acetylacetonates [47]. Upon heating, these compounds undergo thermal decomposition, releasing volatile by-products and resulting in the formation of MONPs. This method offers the advantage of producing nanoparticles with controlled size and morphology, as the decomposition conditions can be precisely regulated. Also, thermal decomposition can yield highly crystalline nanoparticles due to the high temperatures. The choice of precursor materials and decomposition conditions significantly influence the properties of the resulting nanoparticles, making this method versatile for synthesizing various types of MONPs for applications in catalysis, energy storage, sensing, and biomedicine [8,46-47]. As seen in Table 3, various examples of metal oxide nanoparticles synthesized through the thermal decomposition method are presented, showcasing the versatility of this approach in controlling nanoparticle properties.

Table 3 *Representative examples of MONPs synthesized using the thermal decomposition method*

Metal Oxide	Precursors	Reaction Temperature	References
Iron Oxide (Fe_3O_4)	Iron carboxylates	300-500°C	[48]
Cobalt Oxide	Co $(NH_3)_5(H_2O)]$ $(NO_3)_3$	300-500°C	[49]
Copper Oxide (CuO)	Copper (II) Sulphate	750°C	[50]
Zinc Oxide (ZnO)	Zinc acetate Dehydrate	550°C	[51]

2.3.2 Advantages and Limitations

The thermal decomposition approach is a simple and efficient technique for synthesizing metal oxide nanoparticles (MONPs), Providing control over size and morphology by modifying parameters such as precursor concentration and temperature. It avoids solvent use, reducing contamination risks. However, limitations include the possibility of unwanted by-products, inconsistent size distribution, and challenges with scaling up due to difficulties in maintaining uniform heating. These factors can affect the final nanoparticle quality, necessitating careful optimization of reaction conditions to ensure desired properties are achieved [50-51].

2.4 Electrochemical Synthesis

2.4.1 Principle and Mechanism

Electrochemical synthesis is a versatile technique for producing metal oxide nanoparticles (MONPs) using electrochemical cells. The process involves applying an electric potential to induce redox reactions of metal ions in solution, leading to nanoparticle formation. Techniques like electrodeposition [52], anodization [53], and electrochemical precipitation [54] are commonly used for MONP synthesis. This approach enables control over particle size, composition, and morphology by altering parameters including applied potential, electrolyte concentration, and timing of reaction making it significant for applications in catalysis, sensing, and energy storage. Table 4 provides representative examples of metal oxide nanoparticles synthesized via electrochemical techniques, showcasing the method's versatility and precise control over particle characteristics.

Table 4 *Representative examples of MONPs synthesized using electrochemical synthesis*

Metal Oxide	Synthesis Technique	Electrolyte	Applied Potential Range	References
Titanium Dioxide	Electro deposition	Titanium salt solutions	1-5 V	[55]
Nickel Oxide	Electro deposition	Nickel salt solutions	1.5 -3 V	[56]
Manganese Oxide	Anodization	Manganese salt solutions	0.5-2 V	[57]
Indium Oxide	Electrochemical Precipitation	Indium salt solutions	-2 to -3 V	[58]

2.4.2 Advantages and Limitations

Electrochemical synthesis is a versatile technique for producing metal oxide nanoparticles (MONPs) utilizing electrochemical cells. It entails the reduction or oxidation of metal ions in solution, driven by an applied electric potential. Techniques such as electrodeposition, anodization, and electrochemical precipitation are commonly used. This method offers precise control over the nanoparticle characteristics by tuning parameters like voltage, current density, electrolyte composition, and pH [59]. Despite its advantages, including low-temperature processing and real-time monitoring, challenges exist in scaling up due to the need for specialized equipment and maintaining uniform conditions.

2.5 Microwave-Assisted Synthesis

2.5.1 Principle and Mechanism

Microwave-assisted synthesis is a cutting-edge technique for rapidly producing metal oxide nanoparticles (MONPs). This technique involves using microwave irradiation to heat the mixture of reactions, resulting in faster reaction rates due to the materials' selective dielectric heating capabilities [60]. The microwaves penetrate the solution, generating heat uniformly and efficiently within the mixture, which significantly reduces the reaction time and enhances the process yield. By adjusting parameters like power intensity and reaction time, one can control the size, shape, and crystallinity of the nanoparticles, making this method suitable for various applications [61]. The advantages and characteristics of different MONPs synthesized using this approach are highlighted in Table 5 Representative examples of MONPs synthesized using microwave-assisted synthesis. Despite its benefits, the method requires careful optimization of microwave settings to avoid overheating and non-uniform particle distribution.

Table 5 *Representative examples of MONPs synthesized using microwave-assisted synthesis*

Metal Oxide	Precursors	Microwave Power (Watt)	Reaction Time (Sec)	References
Zinc Oxide	Zinc acetate, ammonium hydroxide	540-680W	600-700	[62]
Iron Oxide	Iron salts, organic stabilizers	400-800 W	600-700	[63]
Titanium Dioxide	Titanium alkoxides, surfactants	800 W	300	[64]
Cerium Oxide	Cerium salts, organic solvents	1000 W	600-700	[65]

2.5.2 Advantages and Limitations

Microwave-assisted synthesis offers notable advantages for producing metal oxide nanoparticles (MONPs). This method enables rapid heating and high reaction rates, substantially shortening synthesis times, which is especially valuable for scaling up production [66]. The localized and controlled heating provided by microwaves enhances the reproducibility and uniformity of nanoparticles, while also requiring fewer reagents, making it a more environmentally sustainable approach [67]. However, limitations include the risk of overheating or thermal runaway, leading to nanoparticle agglomeration or undesired side reactions, necessitating careful optimization of reaction conditions and monitoring. Additionally, the penetration depth of microwaves can be limited, particularly for highly conductive materials, potentially affecting nanoparticle uniformity. Proper choice of microwave-transparent reaction vessels and absorbers is crucial for effective synthesis [67-68]. A comparative overview of the discussed chemical synthesis methods is presented in Table 6, which summarizes typical particle sizes, morphologies, advantages, and limitations. This provides a concise reference that complements the detailed descriptions in Section 2.

Table 6 *Overview of major chemical synthesis methods for MONPs with typical particle sizes, morphologies, advantages, and limitations*

Synthesis Method	Typical Particle Size (nm)	Common Morphology	Advantages	Limitations
Sol-gel	10–100	Uniform spherical/porous	High purity, homogeneity, fine size control, tunable surface chemistry	Multi-step, long processing time, costly precursors, limited scalability
Hydrothermal / Solvothermal	20–200	Crystalline rods, spheres, plates	Precise control over size/shape, high crystallinity, and dopant incorporation	Requires autoclaves, limited precursor/solvent choices
Thermal decomposition	5–50	Spherical, crystalline	Narrow size distribution, highly crystalline products	High temperature, by-products, scaling issues
Electrochemical	10–100	Nanowires, films, particles	Low-temperature, tunable composition, real-time control	Equipment demand, reproducibility and scale-up limits
Microwave-assisted	5–50	Uniform spherical	Very rapid synthesis, energy-efficient, good reproducibility	Risk of overheating, shallow penetration depth

J. of Sustainable Materials Processing and Management Vol. 5 No. 2 (2025) p. 51-73

3. Advantages of Chemical Synthesis Methods

Chemical synthesis techniques are critical in the manufacture of metal oxide nanoparticles (MONPs), providing great control over their size, shape, content, and surface properties. These technologies enable researchers to precisely modify the properties of nanoparticles, which is critical for maximizing their efficacy in a variety of applications. Such control enables the tailored design of nanoparticles with specific characteristics that enhance their performance in fields like catalysis, electronics, and optics, emphasizing the central role of chemical synthesis in advancing nanotechnology [69]. The main advantages of chemical synthesis methods are outlined in Fig. 2.

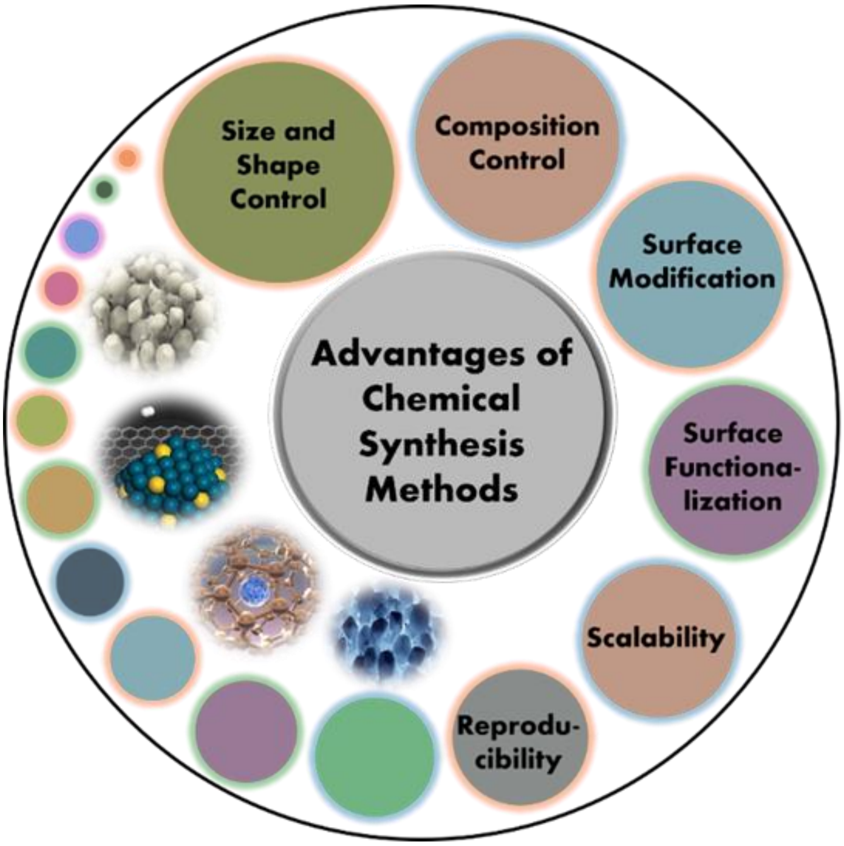

Fig. 2 *Key advantages of chemical synthesis approaches for MONPs, highlighting control of size, shape, composition, and surface functionalization*

3.1 Size and Shape Control

Chemical synthesis methods provide precise control over the size and shape of MONPs, which is critical for their intended features and applications. Temperature, precursor concentration, surfactant type, and reaction time can be adjusted to achieve uniform size and morphology. For instance, the sol-gel process enables uniform MONP synthesis through controlled hydrolysis and condensation [18], while hydrothermal and solvothermal techniques produce well-defined crystalline structures [70]. This flexibility enhances the nanoparticles' optical [71], catalytic [72], and electronic properties [73], allowing for superior application-specific performance.

3.2 Composition Control

The Chemical production methods provide for fine control over the composition of metal oxide nanoparticles (MONPs). By selecting suitable precursor materials and adjusting stoichiometry, researchers can synthesize MONPs with specific compositions and doping levels [74]. This compositional control allows for the modulation of critical properties, including band gap energy, magnetic behavior, and catalytic activity. For instance, incorporating dopants into metal oxide nanoparticles can enhance their catalytic efficiency, improve charge carrier mobility, or introduce unique magnetic properties. This ability to fine-tune composition facilitates the development of specialized materials designed for targeted applications across various fields.

3.3 Surface Modification and Functionalization

Chemical synthesis techniques also enable extensive surface modification and functionalization of MONPs. During the synthesis, functional groups, surfactants, or ligands can be introduced to the nanoparticle surface, enhancing stability, dispersibility, and compatibility with diverse environments [75]. Surface modifications can confer specific properties, such as increased biocompatibility, improved catalytic activity, or selective adsorption capabilities. In this regard, the functionalization of iron oxide nanoparticles with biocompatible coatings has extended their applications in magnetic resonance imaging (MRI) and targeted delivery of drugs [76]. The versatility of MONPs is significantly enhanced through such modifications, enabling their integration into various technological and biomedical systems.

3.4 Scalability and Reproducibility

Chemical synthesis methods provide significant advantages in terms of scalability and reproducibility, enabling the mass production of metal oxide nanoparticles (MONPs) while maintaining consistent quality [77]. These techniques can be easily scaled up to meet industrial demands, allowing for large-scale manufacturing without compromising nanoparticle integrity. By meticulously controlling reaction parameters and optimizing synthesis conditions, researchers can achieve reproducible results, ensuring uniformity in nanoparticle characteristics from batch to batch [78]. This consistency is crucial for the successful transition of MONPs from laboratory settings to commercial applications, particularly in industries that require high-quality nanomaterials for various applications. Recent advancements in automated synthesis and monitoring technologies further enhance scalability, providing a pathway for the efficient production of MONPs tailored to specific industrial needs.

4. Applications of MONPs

Metal oxide nanoparticles (MONPs) have received a lot of interest as adaptable nanomaterials because of their distinct physicochemical features that set them apart from their bulk counterparts. These features make MONPs ideal for a variety of applications, including catalysis, where their large surface area and reactivity improve catalytic activity, as proven by Xing Yi and colleagues [79]. In energy storage, Haruna and colleagues have shown that MONPs improve charge capacity and cycling stability, leading to better battery performance [80]. Furthermore, Gomez-Aviles et al. highlight the potential of MONPs in sensing applications, enabling the detection of various analytes at low concentrations [81]. MONPs also serve an important role in environmental rehabilitation by adsorbing contaminants and aiding their breakdown, as documented by Naseem and co-researchers [82]. In the biomedical arena, Rarokar and their research team have proved their potential for targeted drug administration and as contrast agents in imaging techniques, hence improving diagnostic capacities [83]. This diverse set of applications highlights the importance of MONPs in developing technology across numerous areas. Figure 3 illustrates various applications of MONPs, highlighting their broad utility across areas like energy storage, catalysis, sensing, and environmental remediation.

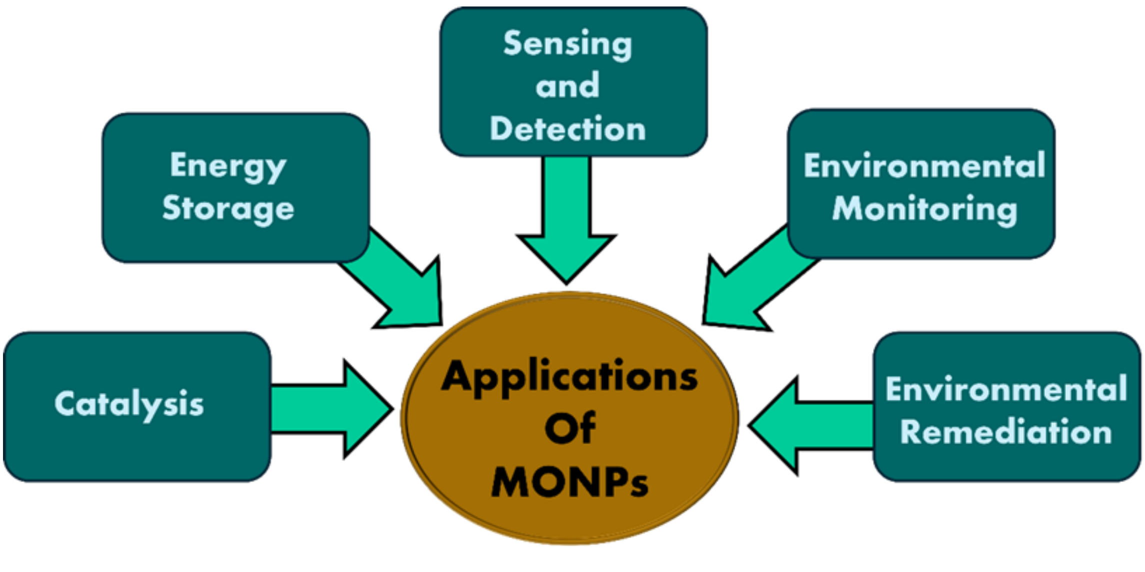

Fig. 3 *Diverse applications of MONPs in catalysis, energy storage, sensing, environmental remediation, and biomedical fields*

J. of Sustainable Materials Processing and Management Vol. 5 No. 2 (2025) p. 51-73

4.1 Catalysis

Metal oxide nanoparticles (MONPs) have substantially advanced the science of catalysis by improving performance and selectivity simply because of their high surface area-to-volume ratio and distinct surface characteristics. These characteristics promote efficient adsorption and activation of reactants, leading to enhanced reaction kinetics [84]. Their tunable size, shape, and composition allow for precise tailoring of catalytic behavior for specific reactions. For example, transition metal oxides such as iron oxide (Fe2O3) exhibit notable activity in oxidation, hydrogenation, and carbon-carbon bond formation [85]. MONPs also play a crucial role in environmental catalysis, enabling pollutant degradation and wastewater treatment. Titanium dioxide (TiO2) nanoparticles, known for their exceptional photocatalytic activity and stability, are commonly employed to degrade organic contaminants in photochemical processes. Recent reviews emphasize the pivotal role of transition metal oxides in catalysis, underlining how their tunable surface chemistry and mesoporosity enhance catalytic efficiency [86].

4.2 Energy Storage

Metal oxide nanoparticles (MONPs) have attracted a lot of attention in the field of energy storage because of their unique properties and potential to improve the efficiency of batteries and supercapacitors. These nanoparticles offer several benefits, including a large amount of surface area, higher electrochemical activity, and improved charge transport capabilities, all of which contribute to increasing the potential for energy storage [87]. As electrode materials to enhance the efficiency of lithium-ion battery cells (LIBs), MONPs have been extensively studied in the context of batteries [88] And even further. Lithium iron phosphate (LiFePO4) nanoparticles, for instance, have been used often as a cathode material in LIBs Because of their large theoretical potential, superior thermal stability, and extended cycle life [89]. Various synthesis approaches, such as sol-gel [90], hydrothermal [91], and solid-state reactions [92], have been utilized to prepare well-defined and highly crystalline LiFePO4 nanoparticles. These nanoparticles have better lithium-ion diffusion kinetics and high-rate performance, making them ideal for applications needing high-power output [93]. Similarly, metal oxide nanoparticles like manganese dioxide (MnO2) have shown promise as cathode and anode materials in LIBs [94]. MnO2 nanoparticles have a high theoretical capacity and a low cost, making them ideal for large-scale energy storage. However, due to poor cycling stability and slow kinetics, its practical application is limited [95]. The electrochemical performance of MnO2 nanoparticles has been improved by several methods, including adjusting particle size, altering surface chemistry, and adding carbonaceous elements. These modifications have resulted in enhanced capacity retention, improved cycling stability, and higher rate capability.

Supercapacitors, on the other hand, are especially effective in applications requiring short bursts of energy, such as electric vehicles and renewable energy systems. Additionally, supercapacitors can be charged and discharged much faster than traditional batteries, making them a popular choice for certain industrial and military applications. MONPs' massive specific surface area and strong electrical conductivity have made them appropriate electrode materials for supercapacitors [96]. For instance, ruthenium oxide (RuO2) nanoparticles have been widely studied for their excellent pseudocapacitive behavior, resulting in high specific capacitance and fast charge/discharge rates [97]. Various synthesis methods, such as hydrothermal [98], solvo thermal [99], and electro-deposition have been employed to prepare RuO2 nanoparticles with tailored properties. These nanoparticles exhibit outstanding cycling stability and long-term electrochemical performance, making them suitable for supercapacitor applications. Recent review work by Pazhamalai et al., emphasizes that composite electrode materials combining metal oxides with conductive supports significantly enhance energy storage performance. Such designs improve charge transport, capacity retention, and cycling stability, addressing key challenges in lithium-ion batteries and supercapacitors [100].

4.3 Sensing and Detection

Metal oxide nanoparticles (MONPs) are gaining popularity in sensing and detection technologies due to their nanoscale features, which include a high surface area-to-volume ratio, improved surface reactivity, and changeable electrical properties [101]. These features lead to remarkable sensitivity and selectivity, making MONPs suited for a wide range of applications including gas sensing, biosensing, and environmental monitoring. Significant gains in the efficiency, accuracy, and responsiveness of MONP-based sensors can be achieved by carefully controlling nanoparticle composition, size, and surface modification, making them essential for the development of next-generation sensing technologies.

4.3.1 Gas Sensing

MONPs have been widely used in gas-sensing applications due to their ability to detect and respond to a variety of gases with high sensitivity and rapid response times [102]. Gas sensors based on MONPs have several advantages, including low cost, miniaturization, and the capacity to detect multiple gases simultaneously. Tin oxide (SnO_2) nanoparticles [103] are commonly used in gas sensing devices for the detection of harmful gases, including carbon monoxide (CO) [104] and nitrogen dioxide (NO_2) [105]. SnO_2 nanoparticles exhibit high sensitivity to these gases, making them suitable for applications in environmental monitoring, industrial safety, and automotive exhaust control. The design and manufacturing of a CO gas sensor with greater sensitivity and selectivity, for instance, was demonstrated via the fabrication of SnO_2 nanoparticles [106]. The unique surface chemistry and morphology of SnO_2 nanoparticles enable efficient gas adsorption and promote enhanced sensing performance [107]. Other metal oxide nanoparticles, such as zinc oxide (ZnO) [108] and tungsten oxide (WO_3) [109], have also been employed in gas sensing applications. ZnO nanoparticle's wide surface area and strong electron mobility make them suitable for gas detection [110]. They have been utilized for the detection of various gases, including ethanol [111], ammonia [112], and hydrogen sulfide (H_2S) [113]. Similarly, WO_3 nanoparticles have been studied for the selective detection of gases such as ozone (O_3) [114] and nitrogen oxide (NO_x) [115] in environmental monitoring applications.

4.3.2 Bio-Sensing

MONPs are employed in bio-sensing, where they have significant applications, as labels or transducers for identifying biomolecules with great sensitivity. The large surface area and surface reactivity of MONPs facilitate the immobilization of biomolecules and amplify the relationship between the sensor surface and the desired analyst [116-117]. The detection of DNA, proteins, and illness biomarkers has been made possible by the use of iron oxide (Fe_3O_4) nanoparticles in bio-sensing applications [118]. The unique magnetic properties of Fe_3O_4 nanoparticles enable their use in magnetic biosensors, where the nanoparticles act as labels that can be manipulated and detected using external magnetic fields [119]. Miao et al. developed an ultrasensitive DNA-based biosensor Fe_3O_4 nanoparticles for the detection of cancer-related gene mutations [120].

ZnO nanoparticles have also been used in biosensors to detect a variety of biomolecules [121]. ZnO nanoparticles offer advantages such as high biocompatibility and easy surface functionalization. They have been employed in protein sensors, DNA sensors, and immune sensors for the detection of specific biomarkers. ZnO nanoparticle surface functionalization with particular recognition elements allows the very sensitive and specific detection of target biomolecules [122]. Recent studies by research group of Lawaniya et al., highlight the application of metal oxide gas sensors for detecting volatile organic compounds (VOCs) as biomarkers of foodborne pathogens. Such sensors demonstrate high sensitivity and selectivity, offering rapid and non-invasive monitoring strategies for food safety and public health [123].

4.4 Environmental Monitoring

Metal oxide nanoparticles (MONPs) have attracted substantial attention in the monitoring of environments due to their ability to detect and quantify contaminants in both air and water. Their high surface reactivity, catalytic activity, and sensitivity make them excellent materials for environmental sensors. Prominent examples include titanium dioxide (TiO_2) [124] and zinc oxide (ZnO) [125], which are frequently employed for detecting harmful gases, heavy metals, and organic pollutants.

Recent studies have highlighted the use of TiO_2 nanoparticles in wastewater treatment, particularly for their photo-catalytic properties, which enable the breakdown of organic pollutants under ultraviolet light [124]. TiO_2's ability to degrade pollutants such as formaldehyde and volatile organic compounds (VOCs) makes it especially valuable for indoor air quality monitoring, and advancements in synthesis techniques are enhancing its sensitivity and selectivity [126]. Surface modification and doping techniques, such as the inclusion of noble metals or nonmetals, boost TiO_2's photocatalytic efficacy, expanding its use in contaminated site rehabilitation [127]. Zinc oxide (ZnO) nanoparticles have emerged as key components in the detection of heavy metals in water sources, including lead (Pb) and mercury (Hg) [128]. Their enormous surface area enables efficient adsorption of metal ions, leading to great detection sensitivity. Recent discoveries involve combining ZnO with carbon-based materials like graphene or carbon nanotubes to improve conductivity and sensing capabilities. These hybrid materials enable rapid, reliable, and portable solutions for assessing water quality, thereby facilitating efficient pollutant degradation. Additionally, electrochemical methods utilizing ZnO-based sensors have demonstrated promising results for on-site monitoring of water pollutants, reflecting the growing interest in real-time environmental analysis [129].

5. Environmental Remediation

5.1 Environmental Remediation Using MONPs

Metal oxide nanoparticles (MONPs) have emerged as excellent environmental cleanup tools due to their distinct properties such as huge surface area, high reactivity, and catalytic capabilities. MONPs' features make them suitable for a variety of applications, including pollution removal, hazardous chemical degradation, and

J. of Sustainable Materials Processing and Management Vol. 5 No. 2 (2025) p. 51-73

environmental restoration. MONPs' versatility in adsorbing and breaking down toxins has led to their employment in a wide range of environmental applications, such as wastewater treatment, air purification, and soil remediation [130]. This section discusses the most recent developments and different uses of MONPs in environmental remediation as given below in Fig. 4.

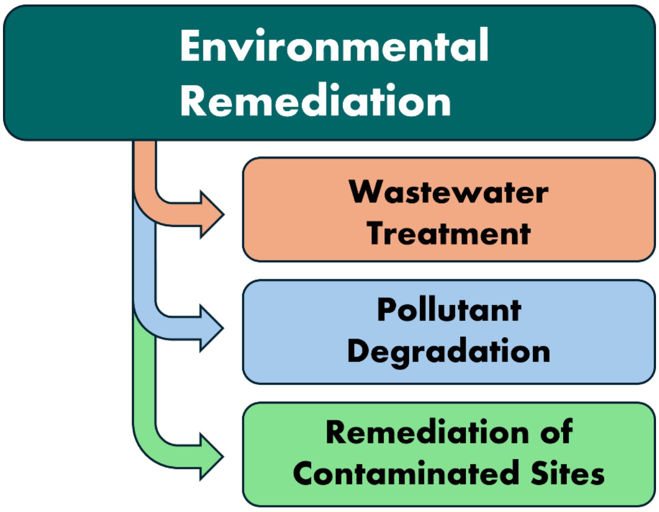

Fig. 4 *Role of MONPs in environmental remediation, illustrating their use in wastewater treatment, pollutant degradation, and contaminated site restoration*

5.1.1 Wastewater Treatment

MONPs have shown great potential in wastewater treatment due to their remarkable adsorption and catalytic properties. Their ability to efficiently remove a wide range of contaminants, including organic compounds, dyes, and heavy metals, makes them beneficial for improving water quality while reducing environmental impact [131]. For example, titanium dioxide (TiO_2) nanoparticles have been extensively researched for photocatalytic degradation of organic pollutants in wastewater [132]. When exposed to UV light, TiO_2 generates reactive oxygen species (ROS), such as hydroxyl radicals, which degrade organic contaminants, making it very effective at cleaning dye-laden industrial effluents [133].

In addition to TiO_2, iron oxide (Fe_3O_4) nanoparticles have demonstrated outstanding efficacy in adsorbing heavy metals from polluted water due to their strong affinity for metal ions Some instances include Pb, Cd, and Hg. Magnetic separation methods allow for facile recovery of these nanoparticles following treatment [133-134]. A recent study has also investigated the functionalization of Fe_3O_4 with biocompatible coatings, which improves adsorption capacity and selectivity, enabling the removal of several contaminants in a single operation [135].

5.1.2 Pollutant Degradation

In several environmental matrices, MONPs also play a significant part in the degradation of contaminants. Their catalytic activity and ability to generate reactive species make them effective in breaking down organic compounds and reducing the levels of hazardous substances in the environment [136]. One example is the use of zinc oxide (ZnO) nanoparticles for the breakdown of organic contaminants such as phenols and pesticides [137]. ZnO nanoparticles can produce ROS when exposed to UV or visible light, resulting in the destruction of organic molecules [138]. Additionally, the catalytic capabilities of cerium oxide (CeO_2) nanoparticles in the oxidation of organic pollutants, For example, hydrocarbons and volatile organic compounds (VOCs) [139].

MONPs' catalytic activity is critical in the degradation of many contaminants, including organic molecules and toxic chemicals, across a variety of environmental matrices. When triggered with UV or visible light, zinc oxide (ZnO) nanoparticles can degrade organic contaminants such as phenols, insecticides, and medicines. ZnO nanoparticles generate ROS, which oxidizes contaminants and converts them into less hazardous molecules [136-138]. Recent advances have focused on doping ZnO with metals (e.g., Ag, Cu) or incorporating it into composite nanostructures (e.g., ZnO-graphene), resulting in increased photocatalytic activity and stability [139]. The redox properties of cerium oxide (CeO_2) nanoparticles, which enable the catalytic oxidation of hydrocarbons and volatile organic compounds (VOCs) in water and air, are now gaining attention. According to studies, doping CeO_2 with transition metals greatly increases its catalytic efficiency, which qualifies it for use in air purification systems [140]. Furthermore, hybrid materials like CeO_2-TiO_2 composites have improved their potential for environmental application by expanding the spectrum of light wavelengths that can be used for pollutant degradation [141].

5.1.3 Remediation of Contaminated Sites

MONPs provide novel methods for remediating polluted soil and groundwater. Their adsorption and catalytic properties help to remove or neutralize contaminants such as heavy metals, herbicides, and industrial solvents, reducing toxicity and environmental risk. Silica-coated magnetite ($Fe_3O_4@SiO_2$) has been used to treat soil and groundwater, with the silica layer increasing dispersibility and adsorption effectiveness [140]. These nanoparticles successfully adsorb polycyclic aromatic hydrocarbons (PAHs) and other organic contaminants, indicating a high potential for remediating hydrocarbon-contaminated locations [141].

Zero-valent iron (ZVI) nanoparticles are commonly used to remediate groundwater contaminated with chlorinated organic chemicals like trichloroethylene (TCE) and heavy metals like arsenic and chromium. ZVI promotes reductive dechlorination and metal immobilization via adsorption and precipitation processes [142]. Emerging approaches include stabilizing ZVI nanoparticles with biopolymers or surfactants, which increases their stability and mobility in subterranean conditions, allowing for more effective contamination removal [141]. Metal oxide nanoparticles (MONPs) have made significant advances in environmental remediation, notably in novel applications such as nanocomposite creation, multifunctional catalysts, and hybrid systems. Recent research has looked into using MONPs in conjunction with carbon-based materials like graphene or activated carbon to improve adsorption and catalytic capabilities in wastewater treatment. MONPs have also been used in membrane technologies to degrade complex contaminants and selectively remove heavy metals. Novel research also focuses on doping MONPs with rare-earth elements to increase their photocatalytic efficacy in visible light, widen their environmental applications, and enable cost-effective solutions for long-term remediation [135-143]. Recent review work by Tereshkov et al., they emphasize the growing role of metal oxide-based sensors in ecological monitoring, where they provide sensitive, cost-effective, and portable solutions for detecting toxic gases and environmental pollutants [142].

6. Biomedical Applications

Metal oxide nanoparticles (MONPs) are becoming increasingly attractive in biomedical applications because to their unique properties, which include a large surface area, surface reactivity, and the ability to change physical and chemical properties. These features make MONPs excellent for a wide range of biological applications, such as medication administration, imaging, diagnostics, biosensing, and tissue engineering (as seen in Figure 5). Iron oxide nanoparticles have been shown to target cancer cells, and gadolinium oxide nanoparticles improve MRI imaging. MONP-based biosensors, such as those that use ZnO for biomarker detection, are extremely sensitive for early illness detection. Furthermore, advances in tissue engineering use MONP-infused scaffolds, such as hydroxyapatite-coated TiO_2 for bone regeneration, to boost cell proliferation and mechanical strength. Recent research has expanded the applicability of MONPs, making them vital instruments for biomedical advancement [144]. Examples of MONPs' use in biomedicine include the following session.

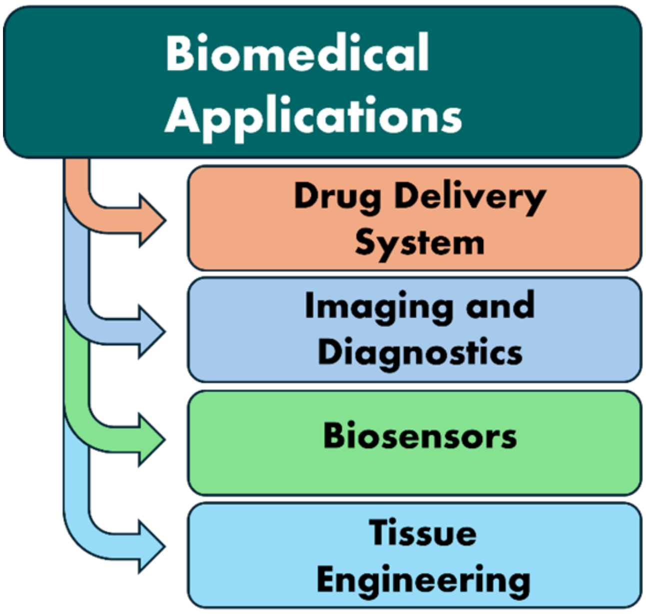

Fig. 5 *Biomedical applications of MONPs, including drug delivery, imaging, biosensing, and tissue engineering*

J. of Sustainable Materials Processing and Management Vol. 5 No. 2 (2025) p. 51-73

6.1 Drug Delivery Systems

MONPs, such as iron oxide and cerium oxide, have been studied in drug delivery due to their biocompatibility and ability to be functionalized with medicinal molecules. Surface changes enable targeted delivery and controlled drug release, as shown in research with Fe3O4 nanoparticles for chemotherapeutic medicines, which improve tumour site targeting while minimizing side effects [145,146]. Sun et al.'s study highlighted that metal-organic frameworks (MOFs), a type of MONP, are effective nanocarriers due to their high porosity and adjustable components. They allow for controlled drug release and can act as therapeutic agents. The tailored properties of MOFs make them suitable for targeted drug delivery, improving therapeutic efficiency while minimizing side effects [147]. Another research by Maria and the research team indicated that using MONPs like TiO2 and ZnO in drug delivery enhances pharmacological activity and stability. They can penetrate cells effectively, providing a platform for sustained and targeted release of therapeutic agents, thus improving bioavailability [148].

6.2 Imaging & Diagnostics

In imaging, MONPs such as gadolinium oxide (Gd_2O_3) are utilized to improve MRI contrast. Recent advancements include integrating MONPs with fluorescent dyes or quantum dots for multimodal imaging [149]. Cerium oxide nanoparticles, for example, have high X-ray attenuation qualities, which improve computed tomography (CT) imaging [150]. Recent developments have focused on using iron oxide nanoparticles in MRI contrast enhancement. These nanoparticles improve the quality of imaging due to their magnetic properties, making them ideal for non-invasive diagnostics. Research in 2023 by Zeyi and their team emphasized the role of surface modification in enhancing nanoparticle stability and biocompatibility for better imaging outcomes [147].

6.3 Biosensors

MONP-based biosensors, such as ZnO and TiO_2, are highly sensitive to detecting biomarkers. Integrating MONPs with electrical equipment has led in the development of enhanced biosensors for real-time monitoring of glucose levels, cancer markers, and infections, all of which have potential diagnostic applications. MONPs like ZnO and CuO have been used in biosensors for detecting glucose levels, as they offer high surface area and catalytic activity. Recent studies demonstrated their enhanced sensitivity and response time, providing rapid and accurate detection in biosensor applications by Nikolova and the team [148].

6.4 Tissue Engineering

MONPs, such as hydroxyapatite-coated TiO_2, are employed in bone tissue engineering because they have osteoconductive properties. Recent research focuses on nanocomposite scaffolds that combine MONPs and biopolymers to improve cell proliferation, differentiation, and mechanical strength in tissue regeneration, particularly for orthopaedic and neurological applications. Research published in 2023 by Sun et al. examined the incorporation of MONPs, like TiO_2 and silica nanoparticles, in scaffolds for bone tissue regeneration. These nanoparticles enhance mechanical strength and promote cell adhesion, leading to improved bone healing and regeneration [147].

7. Toxicity, Biocompatibility, and Safety Considerations

The translation of MONPs into biomedical and environmental applications requires careful assessment of their safety profiles. Recent studies emphasize that particle size, surface charge, solubility, and morphology strongly influence cytotoxic responses, with smaller particles (<20 nm) often generating higher levels of reactive oxygen species (ROS) that can trigger oxidative stress, DNA damage, and inflammation [151,154]. Predictive nano-(Q) SAR models are increasingly being applied to anticipate such toxicological outcomes and to support safer material design [151]. From an environmental perspective, exposure pathways and bioaccumulation remain critical concerns, particularly in aquatic systems where MONPs can affect microbial activity, plants, and higher organisms [152,153]. In human health contexts, solubility and ion release have been identified as key drivers of cytotoxicity in pulmonary and epithelial models [154]. To address these issues, strategies such as surface functionalization, polymeric coatings, and "safe-by-design" approaches are being developed to improve stability, reduce immunogenicity, and enhance overall biocompatibility [151-155]. These considerations highlight that alongside their wide utility, MONPs demand rigorous toxicological evaluation and responsible design for safe biomedical and environmental deployment.

8. Challenges and Future Directions in MONP Development for Multifunctional Applications

While MONPs have shown considerable potential in a variety of applications, there are still several difficulties and opportunities for advancement that must be addressed. Metal-oxide-nanoparticles (MONPs) have enormous potential for a variety of applications, but overcoming many difficulties is required to fully realize their possibilities. First and foremost, ensuring MONPs' biocompatibility and long-term safety is critical to their effective translation into clinical applications [156]. Further research is required to determine their possible toxicity [157], immunological response [158], and biodegradation mechanisms in biological systems [159]. Furthermore, scalability and cost-effectiveness are significant barriers, as large-scale synthesis with consistent characteristics is difficult and critical for industrial applications [160]. Stability concerns, such as agglomeration, necessitate advanced techniques to improve dispersion and nanoparticle stability [156].

Standardization remains critical for reliably assessing MONP physicochemical properties, allowing for better comparisons and a deeper knowledge of their structure-property interactions. In addition, regulatory problems must be addressed to ensure safe and responsible use in biological and environmental applications. Advances in functionalization strategies, such as surface modification [161], core-shell architectures [162], and composite materials [102], are critical for creating MONPs with specific features for specified applications. Recent concerns, such as scalability, remain critical, as do issues with manufacturing homogeneous batches [160]. Stability issues also degrade performance, highlighting the necessity for novel stabilization solutions [162]. The development of multifunctional platforms with imaging, therapy, and sensing capabilities has the potential to revolutionize theragnostic by improving disease monitoring, treatment, and diagnostics [163]. combining multiple MONPs or generating hybrid nanocomposites [164], core-shell structures [165], and heterostructures [166] may result in materials with improved properties. Recent research indicates that these hybrids can provide superior catalytic characteristics and targeting accuracy for medical applications. Advanced approaches, such as in situ imaging [167] and real-time monitoring, provide vital insights into the behavior of MONPs in complicated contexts, enabling further optimization. Addressing these issues through coordinated interdisciplinary research would enable the practical application of MONPs, accelerating progress in fields such as medicine, environmental science, and materials engineering.

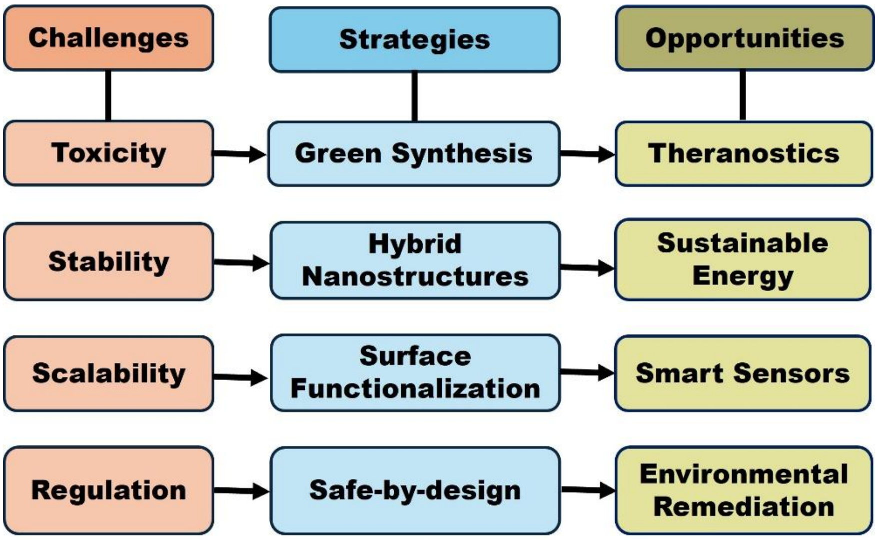

Fig. 6 *Challenges, strategies, and future opportunities for metal oxide nanoparticles (MONPs), highlighting key barriers to translation, potential approaches to overcome them, and emerging application domains*

In addition to technical challenges, sustainability and regulatory aspects must also be addressed for the successful translation of MONPs. Green synthesis strategies using plant extracts, microorganisms, and biopolymers are gaining momentum as eco-friendly alternatives to conventional chemical routes, reducing hazardous by-products and energy consumption while supporting circular economy practices [168]. These approaches align with the broader goal of sustainable nanotechnology, ensuring minimal environmental burden and enhanced societal acceptance. Furthermore, regulatory frameworks for nanomaterials remain fragmented across regions, with limited standardized protocols for evaluating safety, toxicity, and long-term environmental impact [169-170]. Developing harmonized guidelines and international policies will be essential to ensure responsible production, commercialization, and safe deployment of MONPs in the biomedical and environmental sectors. Integrating green synthesis with sustainability principles and regulatory oversight will therefore be central to advancing MONP applications in a socially and environmentally responsible manner. The interconnection between critical challenges, strategic approaches, and future opportunities for MONPs is summarized in Fig. 6, providing a visual roadmap for advancing their safe and sustainable development.

9. Conclusion

Metal oxide nanoparticles (MONPs) have emerged as multifunctional materials whose tunable size, morphology, crystallinity, and surface chemistry underpin their diverse applications in catalysis, energy storage, sensing, environmental remediation, and biomedicine. Advances in chemical synthesis approaches have enabled unprecedented control over these parameters, translating into enhanced performance across domains. Yet, widespread deployment requires overcoming key barriers, including toxicity, long-term stability, scalability, and the absence of harmonized regulatory frameworks. Addressing these challenges through green and sustainable synthesis strategies, rational surface engineering, hybrid nanostructures, and safe-by-design approaches will be essential to ensure responsible translation from laboratory to real-world applications. Looking ahead, the integration of interdisciplinary tools such as computational modeling, in situ monitoring, and standardized toxicological protocols can accelerate the design of nanoparticles that are not only efficient but also safe and environmentally compatible. By bridging innovation in synthesis with sustainability and regulatory responsibility, MONPs are poised to drive next-generation technologies and contribute meaningfully to sustainable development, global health, and environmental resilience.

Acknowledgement

The authors gratefully acknowledge the School of Applied Sciences and Technology, Gujarat Technological University, Ahmedabad-382424, Gujarat, India, and the Department of Nanoscience and Advanced Materials, Saurashtra University, Rajkot-360005, Gujarat, India, for their invaluable support and provision of laboratory facilities, which significantly contributed to the successful completion of this research work.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

All authors have contributed equally to prepare the paper.

References

[1] Alhoqail, W. A., Alothaim, A. S., Suhail, M., Iqbal, D., Kamal, M., Asmari, M. M., & Jamal, A. (2023). Husk-like zinc oxide nanoparticles induce apoptosis through ROS generation in epidermoid carcinoma cells: effect of incubation period on sol-gel synthesis and anti-cancerous properties. *Biomedicines*, 11(2), 320.

[2] Yusuf, J. Y., Soleimani, H., Chuan, L. K., Soleimani, H., Balogun, B. B., Abass, Z., & Adam, A. A. (2023). Hydrothermal synthesis of flake-like cobalt oxide nanoparticles for electromagnetic waves absorption at X-band (8.2–12.4 GHz) frequency. *Materials Science and Engineering: B*, 287, 116132.

[3] Huo, Y., Xiu, S., Meng, L. Y., & Quan, B. (2023). Solvothermal synthesis and applications of micro/nano carbons: A review. *Chemical Engineering Journal*, 451, 138572.

[4] Chavali, M. S., & Nikolova, M. P. (2019). Metal oxide nanoparticles and their applications in nanotechnology. *SN applied sciences*, 1(6), 607.

[5] Soltys, L., Olkhovyy, O., Tatarchuk, T., & Naushad, M. (2021). Green synthesis of metal and metal oxide nanoparticles: Principles of green chemistry and raw materials. *Magnetochemistry*, 7(11), 145.

[6] Li, C. H., Chan, M. H., Chang, Y. C., & Hsiao, M. (2023). Gold nanoparticles as a biosensor for cancer biomarker determination. *Molecules*, 28(1), 364.

[7] Torregrosa, D., Grindlay, G., de la Guardia, M., Gras, L., & Mora, J. (2023). Determination of metallic nanoparticles in air filters by means single particle inductively coupled plasma mass spectrometry. *Talanta*, 252, 123818.

[8] Yin, Z., Li, S., Li, X., Shi, W., Liu, W., Gao, Z., ... & Liu, Y. (2023). A review on the synthesis of metal oxide nanomaterials by microwave induced solution combustion. *RSC advances*, 13(5), 3265-3277.

[9] Radulescu, D. M., Surdu, V. A., Ficai, A., Ficai, D., Grumezescu, A. M., & Andronescu, E. (2023). Green synthesis of metal and metal oxide nanoparticles: a review of the principles and biomedical applications. *International Journal of Molecular Sciences*, 24(20), 15397.

[10] Belew, A. A., & Assege, M. A. (2025). Solvothermal synthesis of metal oxide nanoparticles: A review of applications, challenges, and future perspectives. *Results in Chemistry*, 16, 102438.

[11] Singh, J., Dutta, T., Kim, K. H., Rawat, M., Samddar, P., & Kumar, P. (2018). 'Green'synthesis of metals and their oxide nanoparticles: applications for environmental remediation. *Journal of nanobiotechnology*, 16(1), 84.

[12] Zadehnazari, A. (2025). Chemical synthesis strategies for metal oxide nanoparticles: A comprehensive review. *Inorganic and Nano-Metal Chemistry*, 55(6), 734-773.

[13] Liu, R., Luo, C., Pang, Z., Zhang, J., Ruan, S., Wu, M., ... & Gao, H. (2023). Advances of nanoparticles as drug delivery systems for disease diagnosis and treatment. *Chinese chemical letters*, 34(2), 107518.

[14] Honeybone, D., Peace, H., & Green, M. (2023). Infrared emitting and absorbing conjugated polymer nanoparticles as biological imaging probes. *Journal of Materials Chemistry C*, 11(24), 7860-7871.

[15] Wang, C., Wang, Q., Wang, H., Li, Z., Chen, J., Zhang, Z., ... & Li, Z. (2023). Hydroxyethyl starch-folic acid conjugates stabilized theranostic nanoparticles for cancer therapy. *Journal of Controlled Release*, 353, 391-410.

[16] Deng, Y., Zhou, C., Fu, L., Huang, X., Liu, Z., Zhao, J., ... & Shao, H. (2023). A mini-review on the emerging role of nanotechnology in revolutionizing orthopedic surgery: challenges and the road ahead. *Frontiers in Bioengineering and Biotechnology*, 11, 1191509.

[17] Rex, A., & Dos Santos, J. H. Z. (2023). The use of sol–gel processes in the development of supported catalysts. *Journal of Sol-Gel Science and Technology*, 105(1), 30-49.

[18] Mohammed, K. J., Hadrawi, S. K., & Kianfar, E. (2023). Synthesis and modification of nanoparticles with ionic liquids: a review. *BioNanoScience*, 13(2), 760-783.

[19] Kwaśny, J., & Balcerzak, W. (2017). Characteristics of selected methods for the synthesis of nanometric zirconium oxide–critical review Charakterystyka wybranych metod syntezy nanometrycznego tlenku cyrkonu–przegląd. *Technical Transactions*, 105.

[20] Feng, G., Jiang, W., Liu, J., Zhang, Q., Wu, Q., & Miao, L. (2017). A novel green nonaqueous sol-gel process for preparation of partially stabilized zirconia nanopowder. *Processing and Application of Ceramics*, 11(3), 220-224.

[21] Khalid, H. S., Mawlud, S. Q., & Fakhre, N. A. (2022). Characterizations and Environmental Applications of Various Synthesized Aluminum Oxide Nanoparticles Using Sol-Gel Technique: A Review. *Eurasian Journal of Science and Engineering*, 8(3), 74-93.

[22] Rukhsar, M., Ahmad, Z., Rauf, A., Zeb, H., Ur-Rehman, M., & Hemeg, H. A. (2022). An overview of iron oxide (Fe3O4) nanoparticles: from synthetic strategies, characterization to antibacterial and anticancer applications. *Crystals*, 12(12), 1809.

[23] Sharma, S., Kumar, N., Makgwane, P. R., Chauhan, N. S., Kumari, K., Rani, M., & Maken, S. (2022). TiO2/SnO2 nano-composite: New insights in synthetic, structural, optical and photocatalytic aspects. *Inorganica Chimica Acta*, 529, 120640.

[24] Droepenu, E. K., Wee, B. S., Chin, S. F., Kok, K. Y., & Maligan, M. F. (2022). Zinc oxide nanoparticles synthesis methods and its effect on morphology: A review. *Biointerface Res. Appl. Chem* 12 (2022) 4261-4292.

[25] Rex, A., & Dos Santos, J. H. Z. (2023). The use of sol–gel processes in the development of supported catalysts. *Journal of Sol-Gel Science and Technology*, 105(1), 30-49.

[26] Kumari, N., Sareen, S., Verma, M., Sharma, S., Sharma, A., Sohal, H. S., ... & Mutreja, V. (2022). Zirconia-based nanomaterials: recent developments in synthesis and applications. *Nanoscale Advances*, 4(20), 4210-4236.

[27] Dassie, P. I., Haddad, R., Lenez, M., Chaumonnot, A., Boualleg, M., Legriel, P., ... & Boissiere, C. (2023). Coupling of solvent-free synthesis and reactive extrusion of alumina: an ecologically efficient integration for heterogenous catalyst synthesis. *Green Chemistry*, 25(7), 2800-2814.

[28] Mohamed, S. S. M., Vuksanović, M. M., Vasiljević-Radović, D. G., Janković Mandić, L., Jančić Heinneman, R. M., Marinković, A. D., & Mladenović, I. O. (2024). Sol–Gel Derived Alumina Particles for the Reinforcement of Copper Films on Brass Substrates. *Gels*, 10(10), 648.

[29] Kumar, N., Banerjee, A. M., Pai, M. R., Meena, S. S., Patra, A. K., Sastry, P. U., & Tripathi, A. K. (2023). Sol-gel mediated synthesis and characterization of hierarchically porous Fe2O3/SiO2 monolithic catalyst for high temperature sulfuric acid decomposition. *Catalysis Communications*, 179, 106686.

[30] Desai, R. S., Jadhav, V. S., Patil, P. S., & Dalavi, D. S. (2024). Recent advances in hydrothermally and solvothermally grown Co 3 O 4 nanostructures for electrochemical energy storage (EES) applications: a brief review. *Materials Advances*, 5(3), 920-960.

[31] Raha, S., & Ahmaruzzaman, M. (2022). ZnO nanostructured materials and their potential applications: progress, challenges and perspectives. *Nanoscale advances*, 4(8), 1868-1925.

[32] Naik, R. L., & Narsaiah, T. B. (2023). Hydrothermal synthesis and characterization of nanocrystalline zinc vanadate (Zn2V2O7) on graphene oxide scaffolds. *Materials Today: Proceedings*, 72, 268-273.

[33] Wiston, B. R., Preethi, M., & Ashok, M. (2023). Supercapacitor performance of β-cobalt hydroxide prepared via a one-pot hydrothermal method. *Journal of Electronic Materials*, 52(3), 1644-1651.

[34] Khairy, M., & Mahmoud, K. G. (2023). In-situ growth of nanostructured nickel sulphides on nickel foam platform for boosting the electrocatalytic activity of overall water splitting. *Journal of Alloys and Compounds*, 935, 168056.

[35] Huang, T., Mao, S., Zhou, G., Wen, Z., Huang, X., Ci, S., & Chen, J. (2014). Hydrothermal synthesis of vanadium nitride and modulation of its catalytic performance for oxygen reduction reaction. *Nanoscale*, 6(16), 9608-9613.

[36] Kumar, S. A., Shankar, J. S., Gouthaman, S., & Periyasamy, B. K. (2023). Effect of electrosteric stabilization of TiO2 nanoparticles on photophysical properties of organic/inorganic hybrid nanocomposite. *Materials Today Communications*, 35, 105533.

[37] Noviyanti, A. R., Asyiah, E. N., Permana, M. D., Dwiyanti, D., Suryana, & Eddy, D. R. (2022). Preparation of hydroxyapatite-titanium dioxide composite from eggshell by hydrothermal method: characterization and antibacterial activity. *Crystals*, 12(11), 1599.

[38] Liu, J., Jiang, L., & Qian, L. (2022). Achievement of sub-nanometer surface roughness of bearing steel via chemical mechanical polishing with the synergistic effect of heterocyclic compounds containing N and S. *Journal of Applied Electrochemistry*, 52(2), 357-373.

[39] Abdel-Fattah, E. M., Alshehri, S. M., Alotibi, S., Alyami, M., & Abdelhameed, D. (2024). Hydrothermal Synthesis of ZnO Nanoflowers: Exploring the Relationship between Morphology, Defects, and Photocatalytic Activity. *Crystals*, 14(10), 892.

[40] Belew, A. A., & Assege, M. A. (2025). Solvothermal synthesis of metal oxide nanoparticles: A review of applications, challenges, and future perspectives. *Results in Chemistry*, 16, 102438.

[41] Rao, M. S., Rakesh, B., Ojha, G. P., Sakthivel, R., Pant, B., & Sankaran, K. J. (2024). Hydrothermally Grown Globosa-like TiO2 Nanostructures for Effective Photocatalytic Dye Degradation and LPG Sensing. *Molecules*, 29(17), 4063.

[42] Ashour, M. M., Mabrouk, M., Soliman, I. E., Beherei, H. H., & Tohamy, K. M. (2021). Mesoporous silica nanoparticles prepared by different methods for biomedical applications: Comparative study. *IET nanobiotechnology,* 15(3), 291-300.

[43] Liu, Y., Li, S., & Yu (2022) Hydrothermal synthesis of monodisperse SiO_2 nanospheres: morphology control and surface modification, *Materials Advances* 3 4567–4576.

[44] Banger, A., Gautam, S., Jadoun, S., Jangid, N. K., Srivastava, A., Pulidindi, I. N., ... & Srivastava, M. (2023). Synthetic methods and applications of carbon nanodots. *Catalysts*, 13(5), 858.

[45] Moharramnejad, M., Ehsani, A., Shahi, M., Gharanli, S., Saremi, H., Malekshah, R. E., ... & Mohammadi, M. (2023). MOF as nanoscale drug delivery devices: Synthesis and recent progress in biomedical applications. *Journal of Drug Delivery Science and Technology*, 81, 104285.

[46] Vidya, Y. S., & Manjunatha, H. C. (2023). Zirconium titanate nanoparticles: Brief review on the synthesis. *Inorganic Chemistry Communications*, 153, 110772.

[47] Gavilán, H., Rizzo, G. M., Silvestri, N., Mai, B. T., & Pellegrino, T. (2023). Scale-up approach for the preparation of magnetic ferrite nanocubes and other shapes with benchmark performance for magnetic hyperthermia applications. *Nature Protocols*, 18(3), 783-809.

[48] Wang, D., Ma, Q., & Yang, P. (2012). Synthesis of Fe3O4 nanoparticles with tunable and uniform size through simple thermal decomposition. *Journal of Nanoscience and Nanotechnology*, 12(8), 6432-6438.

[49] Farhadi, S., Javanmard, M., & Nadri, G. (2016). Characterization of cobalt oxide nanoparticles prepared by the thermal decomposition. *Acta Chimica Slovenica*, 63(2), 335-343.

[50] Bakhtiari, F., & Darezereshki, E. (2011). One-step synthesis of tenorite (CuO) nano-particles from Cu4 (SO4)(OH) 6 by direct thermal-decomposition method. *Materials Letters*, 65(2), 171-174.

[51] Hajiashrafi, S., & Kazemi, N. M. (2019). Preparation and evaluation of ZnO nanoparticles by thermal decomposition of MOF-5. *Heliyon*, 5(9).

[52] Moharramnejad, M., Ehsani, A., Malekshah, R. E., Shahi, M., Qezelje, H. H., Nekoeifard, M., ... & Parsimehr, H. (2023). Cobalt-based electroactive compounds: synthesis and their electrochemical and pseudocapacitance performance. *Journal of Materials Science: Materials in Electronics*, 34(6), 499.

[53] Ourefelli, A., Hajjaji, A., Trabelsi, K., Khezami, L., Bessais, B., Aminabhavi, T. M., ... & Rtimi, S. (2023). Innovative electrochemical synthesis of highly defective Ta2O5/Cu2O nanotubes inactivating bacteria under low-intensity solar irradiation. *Chemical Engineering Journal*, 468, 143769.

[54] Bouakaz, H., Abbas, M., Benallal, S., Brahimi, R., & Trari, M. (2023). Semiconducting and electrochemical properties of the spinel FeCo2O4 synthetized by co-precipitation. Application to H2 production under visible light. *Journal of Photochemistry and Photobiology A: Chemistry*, 438, 114543.

[55] Kavan, L. (2012). Electrochemistry of titanium dioxide: some aspects and highlights. *The Chemical Record*, 12(1), 131-142.

[56] Navale, S. T., Mali, V. V., Pawar, S. A., Mane, R. S., Naushad, M., Stadler, F. J., & Patil, V. B. (2015). Electrochemical supercapacitor development based on electrodeposited nickel oxide film. *RSC advances*, 5(64), 51961-51965.

[57] Chen, Y., Wang, J. W., Shi, X. C., & Chen, B. Z. (2013). Pseudocapacitive characteristics of manganese oxide anodized from manganese coating electrodeposited from aqueous solution. *Electrochimica Acta*, 109, 678-683.

[58] Liu, Y., Shu, Y., Sun, B., Zeng, X., Zhu, J., Yi, J., & He, J. (2019). Electrochemical synthesis of In2O3 nanoparticles for fabricating ITO ceramics. *Ceramics International*, 45(15), 19068-19076.

[59] Wu, T., Fan, W., Zhang, Y., & Zhang, F. (2021). Electrochemical synthesis of ammonia: Progress and challenges. *Materials Today Physics*, 16, 100310.

[60] Rodríguez-Carríllo, C., Benítez, M., El Haskouri, J., Amorós, P., & Ros-Lis, J. V. (2023). Novel microwave-assisted synthesis of COFs: 2020–2022. *Molecules*, 28(7), 3112.

[61] Kaur, N., Singh, A., & Ahmad, W. (2023). Microwave assisted green synthesis of silver nanoparticles and its application: a review. *Journal of Inorganic and Organometallic Polymers and Materials*, 33(3), 663-672.

[62] Hasanpoor, M., Aliofkhazraei, M., & Delavari, H. J. P. M. S. (2015). Microwave-assisted synthesis of zinc oxide nanoparticles. *Procedia Materials Science*, 11, 320-325.

[63] Aivazoglou, E., Metaxa, E., & Hristoforou, E. (2018). Microwave-assisted synthesis of iron oxide nanoparticles in biocompatible organic environment. *AIP Advances*, 8(4).

[64] Jena, A., Vinu, R., Shivashankar, S. A., & Madras, G. (2010). Microwave assisted synthesis of nanostructured titanium dioxide with high photocatalytic activity. *Industrial & engineering chemistry research*, 49(20), 9636-9643.

[65] Mahmoud, W. E., & Faidah, A. (2012). Microwave assisted hydrothermal synthesis of engineered cerium oxide nanopowders. *Journal of the European Ceramic Society*, 32(13), 3537-3541.

[66] Phan, P. T., Hong, J., Tran, N., & Le, T. H. (2023). The properties of microwave-assisted synthesis of metal–organic frameworks and their applications. *Nanomaterials*, 13(2), 352.

[67] Yadav, A. R., & Mohite, S. K. (2020). A brief review: Microwave chemistry and its applications. *Research Journal of Pharmaceutical Dosage Forms and Technolo*gy, 12(3), 191-197.

[68] Meera, G., Rohit, K. R., Saranya, S., & Anilkumar, G. (2020). Microwave assisted synthesis of five membered nitrogen heterocycles. *RSC advances*, 10(59), 36031-36041.

[69] Becerra-Paniagua, D. K., Díaz-Cruz, E. B., Baray-Calderón, A., Garcia-Angelmo, A. R., Regalado-Pérez, E., del Pilar Rodriguez-Torres, M., & Martínez-Alonso, C. (2022). Nanostructured metal sulphides synthesized by microwave-assisted heating: A review. *Journal of Materials Science: Materials in Electronics*, 33(29), 22631-22667.

[70] Yadav, P., Bhaduri, A., & Thakur, A. (2023). Manganese oxide nanoparticles: an insight into structure, synthesis and applications. *ChemBioEng Reviews*, 10(4), 510-528.

[71] Dheyab, M. A., Aziz, A. A., Khaniabadi, P. M., Jameel, M. S., Oladzadabbasabadi, N., Rahman, A. A., ... & Mehrdel, B. (2023). Gold nanoparticles-based photothermal therapy for breast cancer. *Photodiagnosis and photodynamic therapy*, 42, 103312.

[72] Bhattacharjee, K., & Prasad, B. L. (2023). Surface functionalization of inorganic nanoparticles with ligands: A necessary step for their utility. *Chemical Society Reviews*, 52(8), 2573-2595.

[73] Jaberi, S. Y. S., Ghaffarinejad, A., Khajehsaeidi, Z., & Sadeghi, A. (2023). The synthesis, properties, and potential applications of CoS2 as a transition metal dichalcogenide (TMD). *International Journal of Hydrogen Energy*, 48(42), 15831-15878.

[74] Maciulis, V., Ramanaviciene, A., & Plikusiene, I. (2022). Recent advances in synthesis and application of metal oxide nanostructures in chemical sensors and biosensors. *Nanomaterials*, 12(24), 4413.

[75] Dubadi, R., Huang, S. D., & Jaroniec, M. (2023). Mechanochemical synthesis of nanoparticles for potential antimicrobial applications. *Materials*, 16(4), 1460.

[76] Rodà, F., Caraffi, R., Picciolini, S., Tosi, G., Vandelli, M. A., Ruozi, B., ... & Duskey, J. T. (2023). Recent advances on surface-modified GBM targeted nanoparticles: targeting strategies and surface characterization. *International Journal of Molecular Sciences*, 24(3), 2496.

[77] Adam, A., & Mertz, D. (2023). Iron oxide@ mesoporous silica core-shell nanoparticles as multimodal platforms for magnetic resonance imaging, magnetic hyperthermia, near-infrared light photothermia, and drug delivery. *Nanomaterials*, 13(8), 1342.

[78] Caldara, M., van Wissen, G., Cleij, T. J., Diliën, H., van Grinsven, B., Eersels, K., & Lowdon, J. W. (2023). Deposition methods for the integration of molecularly imprinted polymers (MIPs) in sensor applications. *Advanced Sensor Research*, 2(7), 2200059.

[79] Yi, X., Wang, Y., Zou, Z., He, Y., Lv, L., Tang, W., ... & Tang, S. (2024). Controllable preparation of metal oxide nanoparticles and Ni/CeO2 catalysts by microdroplets extraction and separation technology in mini-channel. *Chemical Engineering Journal*, 494, 153043.

[80] Haruna, A., Zango, Z. U., Tanimu, G., Izuagie, T., Musa, S. G., Garba, Z. N., & Merican, Z. M. A. (2024). A critical review on recent trends in metal-organic framework-based composites as sustainable catalysts for environmental applications. *Journal of Environmental Chemical Engineering*, 12(5), 113542.

[81] Gómez-Avilés, A., Rodríguez Solís, R., García-Frutos, E. M., Bedia, J., & Belver, C. (2023). Novel isoreticular UiO-66-NH2 frameworks by N-cycloalkyl functionalization of the 2-aminoterephtalate linker with enhanced solar photocatalytic degradation of acetaminophen. *Chemical Engineering Journal* 461, (2023): 141889.

[82] Naseem, K., Aziz, A., Tahir, M. H., Ameen, A., Ahmad, A., Ahmad, K., ... & Rao, E. (2024). Biogenic synthesized nanocatalysts and their potential for the treatment of toxic pollutants: environmental remediation, a review. *International Journal of Environmental Science and Technology, 21(2), 2163-2194.*

[83] Rarokar, N., Yadav, S., Saoji, S., Bramhe, P., Agade, R., Gurav, S., ... & Kumarasamy, V. (2024). Magnetic nanosystem a tool for targeted delivery and diagnostic application: Current challenges and recent advancement. *International Journal of Pharmaceutics: X*, 7, 100231.

[84] Akbari, A., Amini, M., Tarassoli, A., Eftekhari-Sis, B., Ghasemian, N., & Jabbari, E. (2018). Transition metal oxide nanoparticles as efficient catalysts in oxidation reactions. *Nano-Structures & Nano-Objects*, 14, 19-48.

[85] Suppiah, D. D., Julkapli, N. M., Sagadevan, S., & Johan, M. R. (2023). Eco-friendly green synthesis approach and evaluation of environmental and biological applications of Iron oxide nanoparticles. *Inorganic Chemistry Communications*, 152, 110700.

[86] Sahoo, S., Wickramathilaka, K. Y., Njeri, E., Silva, D., & Suib, S. L. (2024). A review on transition metal oxides in catalysis. *Frontiers in chemistry*, 12, 1374878.

[87] Zhou, W., Tang, Y., Zhang, X., Zhang, S., Xue, H., & Pang, H. (2023). MOF derived metal oxide composites and their applications in energy storage. *Coordination Chemistry Reviews*, 477, 214949.

[88] Ullah, K., Shah, N., Wadood, R., Khan, B. M., & Oh, W. C. (2023). Recent trends in graphene based transition metal oxides as anode materials for rechargeable lithium-ion batteries. *Nano Trends*, 1, 100004.

[89] He, J., Meng, J., & Huang, Y. (2023). Challenges and recent progress in fast-charging lithium-ion battery materials. *Journal of Power Sources*, 570, 232965.

[90] Su, K., Yang, F., Zhang, Q., Xu, H., He, Y., & Lin, Q. (2023). Structure and magnetic properties of AO and LiFePO4/C composites by sol-gel combustion method. *Molecules*, 28(4), 1970.

[91] Wang, Y., Cui, C., Cheng, R., Wang, J., & Wang, X. (2023). Tannic acid-derived carbon coating on LiFePO4 nanocrystals enables high-rate cathode materials for lithium-ion batteries. *ACS Applied Nano Materials*, 6(11), 9124-9129.

[92] Mohanty, D., Huang, P. H., & Hung, I. M. (2023). Preparation and characterization of a LiFePO4-lithium salt composite cathode for all-solid-state Li-metal batteries. *Batteries*, 9(4), 236.

[93] Chang, R. (2022). A review of the cathode materials development for lithium-ion batteries. *2nd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2022)*, 12326, pp. 81-90.

[94] Rajagopalan, K., Ramasubramanian, B., Velusamy, S., Ramakrishna, S., Kannan, A. M., Kaliyannan, M., & Kulandaivel, S. (2022). Examining the economic and energy aspects of manganese oxide in Li-ion batteries. *Materials Circular Economy, 4(1), 22.*

[95] Ruan, H., Barreras, J. V., Engstrom, T., Merla, Y., Millar, R., & Wu, B. (2023). Lithium-ion battery lifetime extension: A review of derating methods. *Journal of Power Sources*, 563, 232805.

[96] Yaqoob, A. A., Ahmad, A., Ibrahim, M. N. M., Karri, R. R., Rashid, M., & Ahamd, Z. (2022). Synthesis of metal oxide–based nanocomposites for energy storage application. *Sustainable Nanotechnology for Environmental Remediation*, 611-635.

[97] Banik, U., Malik, M. T. U., Rahat, S. S. M., & Mallik, A. K. (2023). Performance enhancement of ruthenium ‐ based supercapacitors: A review. *Energy Storage*, 5(3), e380.

[98] Zhao, J., Zhang, J., Yin, H., Zhao, Y., Xu, G., Yuan, J., ... & Wang, F. (2022). Ultra-fine ruthenium oxide quantum dots/reduced graphene oxide composite as electrodes for high-performance supercapacitors. *Nanomaterials*, 12(7), 1210.

[99] Lian, Z., Pei, Y., Ma, S., Lu, Y., & Liu, Q. (2022). Anchoring Ru/RuO2 Nanoparticles on Porous Carbon Shell as An Efficient Cathode Catalyst for Li ‐ CO2 Battery. *ChemistrySelec*t, 7(7), e202104549.

[100] Pazhamalai, P., Krishnan, V., Mohamed Saleem, M. S., Kim, S. J., & Seo, H. W. (2024). Investigating composite electrode materials of metal oxides for advanced energy storage applications. *Nano Convergence*, 11(1), 30.

[101] Li, Q., Zeng, W., & Li, Y. (2022). Metal oxide gas sensors for detecting NO2 in industrial exhaust gas: Recent developments. *Sensors and Actuators B: Chemical*, 359, 131579.

[102] Krishna, K. G., Parne, S., Pothukanuri, N., Kathirvelu, V., Gandi, S., & Joshi, D. (2022). Nanostructured metal oxide semiconductor-based gas sensors: A comprehensive review. *Sensors and Actuators A: Physical*, 341, 113578.

[103] He, X., Ying, Z., Zhou, X., Li, L., Wen, F., Zheng, X., ... & Wang, G. (2023). A sensitive SO2 gas sensor based on nanocellulose prepared tin dioxide under UV excitation. *Journal of Materials Science*, 58(7), 3249-3259.

[104] Rzaij, J. M., Nawaf, S. O., & Ibrahim, A. K. (2022). A review on tin dioxide gas sensor: The role of the metal oxide doping, nanoparticles, and operating temperatures. *World J. Adv. Res. Rev*, 14(01), 051.

[105] Eom, T. H., Cho, S. H., Suh, J. M., Kim, T., Yang, J. W., Lee, T. H., ... & Jang, H. W. (2022). Visible light driven ultrasensitive and selective NO2 detection in tin oxide nanoparticles with sulfur doping assisted by l ‐ cysteine. *Small*, 18(12), 2106613.

[106] Huang, J., Meng, C., Wang, H., Ren, H., Lu, X., & Joo, S. W. (2022). Preparation of cross-linked porous SnO2 nanosheets using three-dimensional reduced graphene oxide as a template and their gas sensing property. *Journal of Alloys and Compounds*, 910, 164763.

[107] Furhan, & Ramesan, M. T. (2022). Zinc oxide reinforced poly (para-aminophenol) nanocomposites: Structural, thermal stability, conductivity and ammonia gas sensing applications. *Journal of Macromolecular Science, Part A,* 59(10), 675-688.

[108] Zhang, M., Yang, C., Zhang, Z., Tian, W., Hui, B., Zhang, J., & Zhang, K. (2022). Tungsten oxide polymorphs and their multifunctional applications. *Advances in Colloid and Interface Science*, 300, 102596.

[109] Varudkar, H. A., Kathwate, L. H., Awale, M. B., Lokhande, S. D., Umadevi, G., Dargad, J. S., & Mote, V. D. (2022). Structural, morphological, and gas sensing properties of Co-doped ZnO nanoparticles. *Journal of the Australian Ceramic Society*, 58(3), 793-802.

[110] Gai, L. Y., Lai, R. P., Dong, X. H., Wu, X., Luan, Q. T., Wang, J., ... & Xie, W. F. (2022). Recent advances in ethanol gas sensors based on metal oxide semiconductor heterojunctions. *Rare Metals*, 41(6), 1818-1842.

[111] Norizan, M. N., Abdullah, N., Halim, N. A., Demon, S. Z. N., & Mohamad, I. S. (2022). Heterojunctions of rGO/metal oxide nanocomposites as promising gas-sensing materials—a review. *Nanomaterials*, 12(13), 2278.

[112] Verma, G., & Gupta, A. (2022). Sensing performance of room temperature operated MEMS gas sensor for ppb level detection of hydrogen sulfide: A review. *Journal of Micromechanics and Microengineering*, 32(9), 094002.

[113] Yadav, A., Singh, P., & Gupta, G. (2022). Dimension dependency of tungsten oxide for efficient gas sensing. *Environmental Science: Nano*, 9(1), 40-60.

[114] Karpe, S. B., Bang, A. D., Adhyapak, D. P., & Adhyapak, P. V. (2022). Fabrication of high sensitive proto-type NOx sensor based on Pd nanoparticles loaded on WO3. *Sensors and Actuators B: Chemical*, 354, 131203.

[115] Idris, A. O., Akanji, S. P., Orimolade, B. O., Olorundare, F. O. G., Azizi, S., Mamba, B., & Maaza, M. (2023). Using nanomaterials as excellent immobilisation layer for biosensor design. *Biosensors*, 13(2), 192.

[116] Tığ, G. A., & Pekyardımcı, Ş. (2023). Nanostructured Electrochemical Biosensors for Medical Applications. In *Emerging Technologies in Biophysical Sciences: A World Scientific Reference*: Volume 3: Emerging Technologies for Diagnostics (pp. 157-174).

[117] Ezema, F. I., Lokhande, C. D., & Lokhande, A. C. (Eds.). (2023). Chemically Deposited Metal Chalcogenide-Based Carbon Composites for Versatile Applications. Heidelberg, Germany: Springer International Publishing.

[118] Shakil, M. S., Hasan, M. A., & Sarker, S. R. (2019). Iron oxide nanoparticles for breast cancer theranostics. *Current drug metabolism*, 20(6), 446-456.

[119] Chen, M., Hou, C., Huo, D., Fa, H., Zhao, Y., & Shen, C. (2017). A sensitive electrochemical DNA biosensor based on three-dimensional nitrogen-doped graphene and Fe3O4 nanoparticles. *Sensors and Actuators B: Chemical*, 239, 421-429.

[120] Miao, P., Tang, Y., & Wang, L. (2017). DNA modified Fe3O4@ Au magnetic nanoparticles as selective probes for simultaneous detection of heavy metal ions. *ACS applied materials & interfaces*, 9(4), 3940-3947.

[121] Sytu, M. R. C., & Hahm, J. I. (2024). Principles and applications of ZnO nanomaterials in optical biosensors and ZnO nanomaterial-enhanced biodetection. *Biosensors*, 14(10), 480.

[122] Acharya, B., Moharana, S., Behera, A., & Maharana, T. (2025). Zinc and zinc oxide nanoparticles used in biosensors. *Materials and Components of Biosensors in Healthcare* (pp. 229-248). Academic Press.

[123] Lawaniya, S. D., Awasthi, A., Menezes, P. W., & Awasthi, K. (2025). Detection of Foodborne Pathogens Through Volatile Organic Compounds Sensing via Metal Oxide Gas Sensors. *Advanced Sensor Research*, 4(1), 2400101.

[124] Ahmed, M. M., Zhao, R., Du, J., & Li, J. (2022). Nanostructural ZnO-based electrochemical sensor for environmental application. *Journal of The Electrochemical Society*, 169(2), 020573.

[125] Rani, M., & Shanker, U. (2020). Green synthesis of TiO2 and its photocatalytic activity. In *Handbook of Smart Photocatalytic Materials* (pp. 11-61). Elsevier.

[126] Nunes, D., Fortunato, E., & Martins, R. (2022). Flexible nanostructured TiO2-based gas and UV sensors: A review. *Discover Materials*, 2(1), 2.

[127] Orizu, G. E., Ugwuoke, P. E., Asogwa, P. U., & Offiah, S. U. (2023, May). A review on the inference of doping TiO2 with metals/non-metals to improve its photocatalytic activities. *IOP Conference Series: Earth and Environmental Science*, 1178, p. 012008.

[128] Raj, V. J., Ghosh, R., Girigoswami, A., & Girigoswami, K. (2022). Application of zinc oxide nanoflowers in environmental and biomedical science. *BBA advances*, 2, 100051.

[129] de Jesus, R. A., de Assis, G. C., de Oliveira, R. J., Costa, J. A. S., da Silva, C. M. P., Bilal, M., ... & Figueiredo, R. T. (2021). Environmental remediation potentialities of metal and metal oxide nanoparticles: mechanistic biosynthesis, influencing factors, and application standpoint. *Environmental Technology & Innovation*, 24, 101851.

[130] Naseem, T., & Durrani, T. (2021). The role of some important metal oxide nanoparticles for wastewater and antibacterial applications: A review. *Environmental Chemistry and Ecotoxicology*, 3, 59-75.

[131] Abel, S., Jule, L. T., Belay, F., Shanmugam, R., Dwarampudi, L. P., Nagaprasad, N., & Krishnaraj, R. (2021). Application of titanium dioxide nanoparticles synthesized by sol‐gel methods in wastewater treatment. *Journal of Nanomaterials*, 2021(1), 3039761.

[132] Ngoepe, N. M., Hato, M. J., Modibane, K. D., & Hintsho‐Mbita, N. C. (2020). Biogenic synthesis of metal oxide nanoparticle semiconductors for wastewater treatment. *Photocatalysts in advanced oxidation processes for wastewater treatment*, 1-31.

[133] Nezhadheydari, H., Tavabe, K. R., Mirvaghefi, A., Heydari, A., & Frinsko, M. (2019). Effects of different concentrations of Fe3O4@ ZnO and Fe3O4@ CNT magnetic nanoparticles separately and in combination on aquaculture wastewater treatment. *Environmental Technology & Innovation*, 15, 100414.

[134] Mozaffari, M., Khodabakhshi, A., & Azizi, A. (2023). Evaluation of Pb (II) Removal by Tea Pulp Modified with Magnetite Nanoparticle. *Journal of Chemistry*, 2023(1), 7011995.

[135] Nagajyothi, P. C., Prabhakar Vattikuti, S. V., Devarayapalli, K. C., Yoo, K., Shim, J., & Sreekanth, T. V. M. (2020). Green synthesis: photocatalytic degradation of textile dyes using metal and metal oxide nanoparticles-latest trends and advancements. *Critical Reviews in Environmental Science and Technology*, 50(24), 2617-2723.

[136] Batra, V., Kaur, I., Pathania, D., & Chaudhary, V. (2022). Efficient dye degradation strategies using green synthesized ZnO-based nanoplatforms: a review. *Applied Surface Science Advances*, 11, 100314.

[137] Mohamed, W. A., Abd El-Gawad, H. H., Mekkey, S. D., Galal, H. R., & Labib, A. A. (2021). Zinc oxide quantum dots: Confinement size, photophysical and tunning optical properties effect on photodecontamination of industrial organic pollutants. *Optical Materials*, 118, 111242.

[138] Wang, J., Quan, X., Chen, S., Yu, H., & Liu, G. (2019). Enhanced catalytic ozonation by highly dispersed CeO2 on carbon nanotubes for mineralization of organic pollutants. *Journal of hazardous materials*, 368, 621-629.

[139] Vu, K. A., & Mulligan, C. N. (2023). Remediation of organic contaminated soil by Fe-based nanoparticles and surfactants: a review. *Environmental Technology Reviews*, 12(1), 60-82.

[140] Wang, L., Rinklebe, J., Tack, F. M., & Hou, D. (2021). A review of green remediation strategies for heavy metal contaminated soil. *Soil Use and Management*, 37(4), 936-963.

[141] Guo, Y., Li, X., Liang, L., Lin, Z., Su, X., & Zhang, W. (2021). Immobilization of cadmium in contaminated soils using sulfidated nanoscale zero-valent iron: Effectiveness and remediation mechanism. *Journal of Hazardous Materials*, 420, 126605.

[142] Tereshkov, M., Dontsova, T., Saruhan, B., & Krüger, S. (2024). Metal oxide-based sensors for ecological monitoring: Progress and perspectives. *Chemosensors*, 12(3), 42.

[143] Truong, T. T., Mondal, S., Doan, V. H. M., Tak, S., Choi, J., Oh, H., ... & Oh, J. (2024). Precision-engineered metal and metal-oxide nanoparticles for biomedical imaging and healthcare applications. *Advances in colloid and interface science*, 332, 103263.

[144] de Jesus, R. A., de Assis, G. C., de Oliveira, R. J., Costa, J. A. S., da Silva, C. M. P., Iqbal, H. M., & Ferreira, L. F. R. (2024). Metal/metal oxide nanoparticles: A revolution in the biosynthesis and medical applications. *Nano-Structures & Nano-Objects*, 37, 101071.

[145] Truong, T. T., Mondal, S., Doan, V. H. M., Tak, S., Choi, J., Oh, H., ... & Oh, J. (2024). Precision-engineered metal and metal-oxide nanoparticles for biomedical imaging and healthcare applications. *Advances in colloid and interface science*, 332, 103263.

[146] García, M. C., Torres, J., Córdoba, A. V. D., Longhi, M., & Uberman, P. M. (2022). Drug delivery using metal oxide nanoparticles. In *Metal oxides for biomedical and biosensor applications* (pp. 35-83). Elsevier.

[147] Sun, Z., Li, T., Mei, T., Liu, Y., Wu, K., Le, W., & Hu, Y. (2023). Nanoscale MOFs in nanomedicine applications: from drug delivery to therapeutic agents. *Journal of Materials Chemistry B*, 11(15), 3273-3294.

[148] Nikolova, M. P., & Chavali, M. S. (2020). Metal oxide nanoparticles as biomedical materials. *Biomimetics*, 5(2), 27.

[149] Zeng, Y., Li, H., Li, Z., Luo, Q., Zhu, H., Gu, Z., ... & Luo, K. (2020). Engineered gadolinium-based nanomaterials as cancer imaging agents. *Applied materials today*, 20, 100686.

[150] Naha, P. C., Hsu, J. C., Kim, J., Shah, S., Bouché, M., Si-Mohamed, S., ... & Cormode, D. P. (2020). Dextran-coated cerium oxide nanoparticles: a computed tomography contrast agent for imaging the gastrointestinal tract and inflammatory bowel disease. *ACS nano,* 14(8), 10187-10197.

[151] Roy, J., & Roy, K. (2023). Evaluating metal oxide nanoparticle (MeOx NP) toxicity with different types of nano descriptors mainly focusing on simple periodic table-based descriptors: a mini-review. *Environmental Science: Nano,* 10(11), 2989-3011.

[152] Biswas, S., & Bellare, J. (2022). Bioactivity, biocompatibility, and toxicity of metal oxides. In *Metal Oxides for Biomedical and Biosensor Applications* (pp. 3-33). Elsevier.

[153] Wang, F., Zhou, L., Mu, D., Zhang, H., Zhang, G., Huang, X., & Xiong, P. (2024). Current research on ecotoxicity of metal-based nanoparticles: from exposure pathways, ecotoxicological effects to toxicity mechanisms. *Frontiers in Public Health*, 12, 1390099.

[154] Kumah, E. A., Fopa, R. D., Harati, S., Boadu, P., Zohoori, F. V., & Pak, T. (2023). Human and environmental impacts of nanoparticles: a scoping review of the current literature. *BMC public health*, 23(1), 1059.

[155] Nowak-Jary, J., & Machnicka, B. (2024). Comprehensive analysis of the potential toxicity of magnetic iron oxide nanoparticles for medical applications: cellular mechanisms and systemic effects. *International Journal of Molecular Sciences*, 25(22), 12013.

[156] Manimaran, M., & Kannabiran, K. (2017). Actinomycetes ‐ mediated biogenic synthesis of metal and metal oxide nanoparticles: progress and challenges. *Letters in applied microbiology*, 64(6), 401-408.

[157] Sengul, A. B., & Asmatulu, E. (2020). Toxicity of metal and metal oxide nanoparticles: a review. *Environmental Chemistry Letters*, 18(5), 1659-1683.

[158] Soetaert, F., Korangath, P., Serantes, D., Fiering, S., & Ivkov, R. (2020). Cancer therapy with iron oxide nanoparticles: Agents of thermal and immune therapies. *Advanced drug delivery reviews*, 163, 65-83.

[159] Maurya, A. K., de Souza, F. M., Dawsey, T., & Gupta, R. K. (2024). Biodegradable polymers and composites: Recent development and challenges. *Polymer Composites*, 45(4), 2896-2918.

[160] Kwon, H. J., Shin, K., Soh, M., Chang, H., Kim, J., Lee, J., ... & Hyeon, T. (2018). Large ‐ scale synthesis and medical applications of uniform ‐ sized metal oxide nanoparticles. *Advanced Materials*, 30(42), 1704290.

[161] Murtaza, G., Ahmed, Z., Valipour, M., Ali, I., Usman, M., Iqbal, R., ... & Tariq, A. (2024). Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants. *Scientific Reports*, 14(1), 217.

[162] Malavekar, D., Pujari, S., Jang, S., Bachankar, S., & Kim, J. H. (2024). Recent development on transition metal oxides ‐ based core‐shell structures for boosted energy density supercapacitors. *Small*, 20(31), 2312179.

[163] Gao, Y., Wang, K., Zhang, J., Duan, X., Sun, Q., & Men, K. (2023). Multifunctional nanoparticle for cancer therapy. *MedComm*, 4(1), e187.

[164] Sanchis-Gual, R., Coronado-Puchau, M., Mallah, T., & Coronado, E. (2023). Hybrid nanostructures based on gold nanoparticles and functional coordination polymers: Chemistry, physics and applications in biomedicine, catalysis and magnetism. *Coordination Chemistry Reviews*, 480, 215025.

[165] Sonia, Kumari, H., Suman, Chahal, S., Devi, S., Kumar, S., ... & Kumar, A. (2023). Spinel ferrites/metal oxide nanocomposites for waste water treatment. *Applied Physics A*, 129(2), 91.

[166] Meng, F. J., Xin, R. F., & Li, S. X. (2022). Metal oxide heterostructures for improving gas sensing properties: a review. *Materials*, 16(1), 263.

[167] Mu, C., Lv, C., Meng, X., Sun, J., Tong, Z., & Huang, K. (2023). In situ characterization techniques applied in photocatalysis: a review. *Advanced Materials Interfaces*, 10(3), 2201842.

[168] Radulescu, D. M., Surdu, V. A., Ficai, A., Ficai, D., Grumezescu, A. M., & Andronescu, E. (2023). Green synthesis of metal and metal oxide nanoparticles: a review of the principles and biomedical applications. *International Journal of Molecular Sciences*, 24(20), 15397.

[169] Rajpal, V. R., Dhingra, Y., Khungar, L., Mehta, S., Minkina, T., Rajput, V. D., & Husen, A. (2024). Exploring Metal and metal-oxide nanoparticles for nanosensing and biotic stress management in plant systems. *Current Research in Biotechnology*, 7, 100219.

[170] Gujjar, S., Kukal, S., Jayabal, P., Balaji, N., Sainger, S., Roy, S., ... & Mathapati, S. (2025). Nanomaterials for Biomedical Applications: Addressing Regulatory Hurdles and Strategic Solutions. *Nano Trends*, 100127.