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Synthesis and Characterization of Metal Oxide Nanoparticles for Environmental Remediation and Wastewater Treatment

Sher Muhammad Ghoto

Assistant Professor (PhD in Environmental Engineering), Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

Email: ghotosher@quest.edu.pk**Sheeraz Ahmed Memon**

Professor, Institute of Environmental Engineering and Management, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan

Email: sheerazahmed.memon@faculty.muett.edu.pk**Habibullah Abbasi**

Assistant Professor, Center for Environmental Sciences, University of Sindh, Jamshoro, Pakistan

Email: habibullah.abbasi@usindh.edu.pk**Abdul Rehman Jatoti**

Professor, Department of Mechanical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

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Corresponding Author:**Sher Muhammad Ghoto****Email:**ghotosher@quest.edu.pk

Industrial production, urban growth, and agricultural intensification have been a source of toxic and persistent pollutants such as synthetic dyes, heavy metals, pharmaceutical compounds, pesticides, and pathogens to aqueous environments, challenging the conventional treatment processes for wastewater. Metal oxide nanoparticles (MONPs) such as TiO_2 , ZnO , CuO , Cu_2O , Fe_3O_4 , $\gamma\text{-Fe}_2\text{O}_3$, MnO_2 , and SnO_2 have been considered as attractive materials for environmental applications due to their high surface area to volume ratios, adjustable bandgaps, abundance of surface active sites, superparamagnetic behavior, and high catalytic efficiency. The present review summarizes the synthesis methods of MONPs covering both top-down and bottom-up approaches with particular focus on sol-gel process, hydrothermal synthetic route, chemical precipitation, and green plant mediated route. The effects of fundamental operating parameters such as the pH of reaction, temperature, precursor concentration, and duration of contact on particle size, morphology, crystallinity and surface chemistry are discussed in detail. Various advanced characterization techniques such as UV-Vis spectroscopy, FTIR, XRD, SEM/TEM, BET analysis, DLS and zeta potential analysis are discussed to correlate structure-function properties. The review also describes in greater detail the two main postulated detoxification processes of interfacial adsorption (physisorption and chemisorption) and photocatalytic degradation through the generation of reactive oxygen species. The evaluation of the performances of the modified MONP and the mixed-oxide heterostructure indicates a great efficiency in pollutant removal, with CuO obtaining fluoride adsorption capacity higher than 3000 mg/g and TiO_2 degrading more than 98% of dyes. Nonetheless, ecotoxicity, photocorrosion, particle agglomeration, catalyst recovery, and reproducibility of synthesis constitute severe obstacles for large-scale application. In conclusion, prospective research directions that focus on greener synthesis, improved reusability, and reduced environmental impact are suggested to further progress MONP-based wastewater treatment technologies.

Introduction

The rapid global industrialization, urbanization, and intensive agricultural practices have resulted in the widespread release of non-biodegradable and hazardous contaminants into natural aquatic ecosystems. Industrial wastewater streams often contain a complex mixture of persistent synthetic dyes, toxic heavy metal ions (e.g., $[\text{Cr}^{VI}]$, $[\text{Pb}^{II}]$, $[\text{Cd}^{II}]$, $[\text{Cu}^{II}]$, and $[\text{Ni}^{II}]$), pharmaceutical residues, pesticides, and pathogenic microorganisms (Akhtar et al., 2021). Common water purification methods such as coagulation-flocculation, chemical precipitation, activated sludge processes, and membrane filtration are frequently associated with technical and economic shortcomings. These include high energy consumption, incomplete removal of pollutants at low concentrations, high operational costs, and the production of secondary toxic sludge which needs further hazardous waste management (Saxena, 2025).

Engineered nanomaterials provide improved solutions for environmental remediation and water purification. MONPs (Metal Oxide Nanoparticles) such as titanium dioxide ($[\text{TiO}_2]$), zinc oxide ($[\text{ZnO}]$), copper oxide ($[\text{CuO}]$ and $[\text{Cu}_2\text{O}]$), iron oxides ($[\text{Fe}_3\text{O}_4]$ and $[\gamma\text{-Fe}_2\text{O}_3]$), manganese dioxide ($[\text{MnO}_2]$), and tin dioxide ($[\text{SnO}_2]$) have generated considerable scientific interest (Singh et al., 2025). MONPs exhibit unique physical and chemical properties that are different from their bulk materials when the structural dimensions are reduced to the nanoscale (generally below 100 nm). Large specific surface-area-to-volume ratios, tunable electronic bandgaps, high densities of surface-active sites, superparamagnetism, and enhanced catalytic activity (Hassan et al., 2025).

Surface state control is crucial for the operational efficiency of MONPs in water treatment. The choice of certain synthetic parameters has a direct impact on crystallite dimensions, shape, crystal phase, surface charge, defect density and porosity. These structural elements determine the rate of adsorption, light harvesting efficiency, and photogenerated charge carrier dynamics (Bharani et al., 2024). Therefore, precise control over synthesis pathways, along with thorough physical and chemical characterization, is necessary to optimize MONP performance, mitigating potential ecotoxicological effects. This paper explores synthesis methods (chemical, physical and green biogenic routes), characterization techniques, important influencing parameters, and major remediation pathways for various wastewater contaminants (Pandey et al., 2026).

Synthesis Strategies for Metal Oxide Nanoparticles

Methods of nanoparticle synthesis are generally classified into top-down and bottom-up approaches. Top-down approaches, for example mechanical ball milling, lithography, and laser ablation, involve breaking down bulk precursors into nano-sized pieces. Even if top-down approaches for production may be feasible, they tend to result in irregular particle morphologies, wide size distributions, structural crystal defects and high energy requirements. Instead, bottom-up methods build nanomaterials from atomic or molecular building blocks through chemical or biological processes. Bottom-up methods allow for a full control over particle size, crystal phase, stoichiometry, surface chemistry, and even on spatial morphology (Niederberger, 2007).

Chemical Synthesis Routes

Chemical synthesis techniques are widely utilized due to their reproducibility and ability to yield highly crystalline MONPs with narrow size distributions. Among these, sol-gel processing and hydrothermal synthesis represent two major chemical pathways (Parashar et al., 2020).

Sol-gel processing is a wet-chemical procedure in which a liquid precursor solution ("sol") is converted into a three-dimensional solid inorganic network ("gel"). The starting materials are usually metal alkoxides ($[\text{M}(\text{OR})_n]$), or inorganic metal salts (e.g. metal nitrates or chlorides) dissolved in water or in an organic solvent or in both (Negrescu et al., 2022). The basic chemistry is outlined by the sequential hydrolysis and condensation reactions:



This condensation reaction leads to the formation of oxo- or hydroxo-bridges ($[\text{M--O--M}]$ or $[\text{M--OH--M}]$) and results in the formation of an inorganic polymer network. Controlled drying of the material removes the solvent and results in a xerogel or aerogel, which is then heated to high temperatures (300 °C–600 °C) to induce high crystallinity and to evaporate organic residues. Sol-gel processing provides low processing temperatures, chemical homogeneity and allows precise stoichiometric control over dopants (Kashif et al., 2026).

Hydrothermal chemistry reactions are carried out in a closed system (autoclave) at a temperature between 100 °C and 250 °C under autogenous pressure. The dielectric constant and the viscosity of water are dramatically decreased under

subcritical liquid condition, resulting that ionic mobility and solubility of precursors are enhanced (Tapak et al., 2022). These conditions lead to high rates of nucleation and controlled growth of crystals with no need for post-synthesis calcination. Hydrothermal processes provide an exquisite control over the morphology of nanoparticles leading to the formation of anisotropic nanoparticles such as nanorods, nanowires and nanosheets by varying concentrations of mineralizers, the reaction time or temperature of process (Okon et al., 2025).

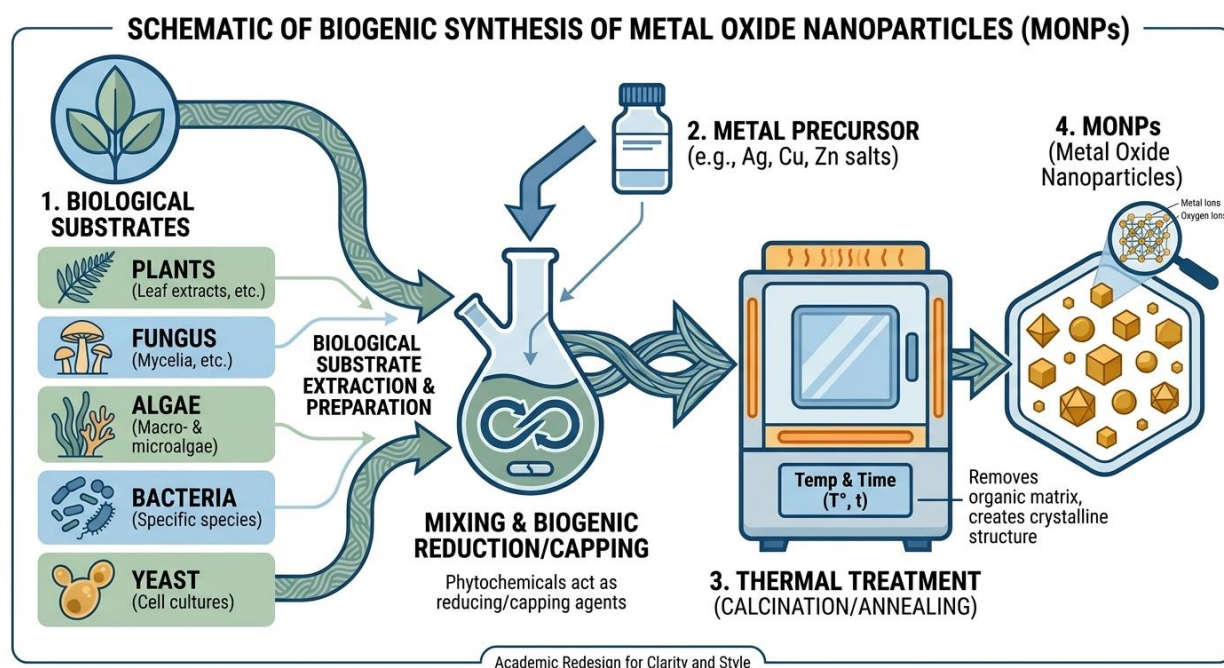
Green and Biological Synthesis Routes

Among the organic solvents that have been proven toxic are toluene, dichloromethane, chloroform, and chlorobenzene and among the harmful chemical reducing agents are sodium borohydride and hydrazine and the synthetic capping ligands. Green synthesis involves utilization of biological systems (plant leaf/flower/seed extracts, agricultural biowastes, fungi, bacteria, and microalgae) as reducing, capping, and stabilizing agents, which are non-toxic (Duan et al., 2015).

Plant mediated synthesis is very beneficial as it avoids the multistep tedious aseptic media preparations for microbial cultures, it enhances the rate of reactions, it needs ambient conditions and it is easily scalable (Varma, 2014). Plant extracts started to be used in the synthesis of compounds due to their rich amounts of secondary metabolites and phytochemicals such as flavonoids, polyphenols, terpenoids, alkaloids, amides and carbohydrates. Functional moieties found within these molecules, mainly hydroxyl ($-OH$), carboxyl ($-COOH$), carbonyl ($C=O$), and amine ($-NH_2$) moieties, act as electron donors that can reduce metal precursor ions to their lower valence or zero-valent forms in the form of intermediates. These reduced compounds then nucleate, oxidize and grow into stable metal oxide nanostructures (Osman et al., 2024).

Concomitantly, these phytochemical ingredients adhere to the surface of the forming nanoparticles. This capping phenomenon induces steric and electrostatic repulsions that prevent the agglomeration of nanoparticles, improve their colloidal stability in aqueous medium, and provide functional groups at the surface that can be involved in the binding of pollutants. However due to the challenges associated with green synthesis, some of the reported challenges include poly dispersity of the particles, lower purity and batch to batch variation as a result of variation in the plant extract Composition due to seasonal and geographical factors (sultan Alqahtani & Elbeltagi, 2025).

Figure 1: Schematic Representation of the Biogenic Synthesis Route for Metal Oxide Nanoparticles (MONPs)



Key Operational Parameters Governing Synthesis Control

The chemical/physical and structural/catalytic properties of MONPs are dependent on essential process factors in both chemical and biogenic synthesis (Kashif et al., 2026).

The pH of the reaction determines the ionization states of the functional groups in phytochemicals and metal precursor complexes in the solution. Deprotonation of functional groups in acidic media is generally hindered leading to slower nucleation, which produces larger or anisotropic nanoparticles (triangular, cylindrical, etc.). In contrast, basic conditions promote fast deprotonation and the nucleation is accelerated leading to formation of smaller, monodispersed, spherical NPs. pH variation

causes changes in surface plasmon resonance (SPR) band and peak absorption values are shifted to shorter wavelengths as particle size decreases (Pathak et al., 2023).

The temperature of the reaction has a direct impact on the efficiency of conversion of the precursor and the rate of nucleation. It has been found that increasing reaction temperature increases the nucleation rate, thereby decreasing the mean particle size, until a certain system-specific temperature. Nonetheless, too much heat can also lead to Ostwald ripening and particle aggregation. Green biogenic synthesis necessitates mild heating ($\sim 100^{\circ}\text{C}$), in general addressing the need for heat during chemical processing, moderate temperatures are imperative while for the processing of physical nature needs temperature higher than 350°C (Kher et al., 2025).

Ratio between nucleation seeds and growing crystals is controlled by precursor and extract concentration. Elevated plant extract concentrations have higher amount of bioreducing agents leading to faster nucleation as compared to crystal growth resulting in smaller nanoparticles. The contact duration of the metal salt with reducing agents has an effect on the growth as well, since prolonged contact time permits full chemical conversion but may contribute to secondary particle aggregation as time goes (Mwangi et al., 2026).

Table 1: Comparative Evaluation of Synthesis Routes for Metal Oxide Nanoparticles

Synthesis Route	Key Precursors / Reagents	Operating Conditions	Particle Attributes	Primary Advantages	Operational Limitations
Sol-Gel Processing	Metal alkoxides, inorganic salts, alcohol solvents	20°C -- 80°C reaction; calcination at 300°C -- 600°C	Spherical, high surface area, narrow size range (5--50 nm)	High chemical purity, precise stoichiometric control	Uses organic solvents; long gelation times
Hydrothermal Method	Metal nitrates/chlorides, mineralizers (NaOH, NH_4OH)	Autoclave at 100°C -- 250°C , autogenous pressure	Crystalline, anisotropic morphologies (rods, sheets)	High crystallinity without calcination; uniform growth	High equipment costs; pressure safety considerations
Green / Plant-Mediated	Metal salts, phytochemical plant leaf/flower extracts	25°C -- 100°C , ambient pressure	Biocapped, variable shapes (10--100 nm), moderate polydispersity	Eco-friendly, low cost, built-in surface passivation	Variable extract composition; slower reaction rates
Chemical Precipitation	Metal inorganic salts, chemical bases (NaOH, NaBH_4)	20°C -- 90°C , ambient pressure	Polydisperse, aggregated powders (20--100 nm)	High scalability, simple equipment, low operating cost	Particle agglomeration; extensive washing required

Advanced Characterization Techniques for MONPs

Evaluating physical, chemical, structural, and optical properties is essential to establish structure-function relationships in environmental remediation applications (Joshi et al., 2023).

Spectroscopic and Optical Characterization

Ultraviolet-Visible (UV-Vis) absorption spectroscopy evaluates optical bandgap energies and monitors nanoparticle formation via Surface Plasmon Resonance (SPR). SPR occurs when conduction band electrons vibrate in resonance with incident light frequencies. For semiconductor MONPs, the optical bandgap (E_g) is derived using Tauc plot extrapolation based on the fundamental absorption edge:

$$(\alpha h\nu)^n = A(h\nu - E_g)$$

where α is the absorption coefficient, $h\nu$ represents photon energy, A is a material constant, and n corresponds to the electronic transition type ($n = 2$ for direct bandgap semiconductors such as ZnO and TiO_2) (Chandraker et al., 2022).

Fourier Transform Infrared Spectroscopy (FTIR) identifies surface chemical bonding environments and organic functional groups. Metal-oxygen vibrational modes (M--O) produce characteristic absorption bands in the fingerprint region below 800 cm^{-1} . In green-synthesized MONPs, FTIR spectra confirm the adsorption of biomolecular capping layers by revealing

distinct absorption peaks associated with hydroxyl groups ($\sim 3400\text{ cm}^{-1}$), carbonyl stretches ($\sim 1650\text{ cm}^{-1}$), and amine bends ($\sim 1550\text{ cm}^{-1}$) (Cushing et al., 2012).

Structural and Morphological Characterization

Powder X-Ray Diffraction (XRD) is used to determine crystal structure, space group symmetry, phase purity and crystallite size. Phase identification differentiates between various structural polymorphs, for example, anatase, rutile and brookite phases of TiO_2 . The mean crystallite dimension (D) is estimated from the Debye-Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta}$$

where K is the shape factor of crystallite (~ 0.9), λ is the wavelength of source of X-ray ($\text{Cu K}\alpha = 0.15406\text{ nm}$), β is the full width at half maximum (FWHM) of the diffraction peak in radian, and θ is Bragg diffraction angle (Caira, 1999).

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) offer the means to image surface topography and internal structure, respectively. HRTEM Atomic lattice fringe spacing, grain boundary dislocation density and crystal growth angle are resolvable by HRTEM, while elemental distribution and material purity is confirmed by EDS (Unruh & Forbes, 2019).

Surface Area, Porosity, and Electrokinetic Metrics

Brunauer-Emmett-Teller (BET) surface area determination using N_2 adsorption-desorption isotherms at 77 K is also employed to evaluate the specific surface area (m^2/g), pore volume and pore size distributions. The higher the specific surface areas, the higher was the density of exposed active sites, resulting in improved pollutant adsorption capacity (Priya et al., 2021).

Dynamic Light Scattering (DLS) provides a hydrodynamic particle diameter for particles in liquid suspension, which includes any solvated layers as well as the degree of particle aggregation. The zeta potential (ζ) evaluates the electrokinetic charge in the slipping plane, and it is a measure of the stability of a colloidal dispersion. The magnitude of the zeta potential above $|30|\text{ mV}$ is sufficient to provide an electrostatic repulsive force strong enough to prevent the aggregation of particles in the solution. The pH dependence of the zeta potential in turn allows one to determine the isoelectric point (pI) or point of zero charge (pzc), which is the pH at which the surface has no net electric charge (Labbez et al., 2003).

Mechanisms of Environmental Remediation and Wastewater Treatment

The use of metal oxide nanoparticles to clean wastewater is based on the adsorption of pollutants at solid-liquid interfaces in combination with photodegradation (Gupta & Ali, 2012).

Adsorption Mechanisms

Adsorption is a surface mass-transfer process in which dissolved contaminants are concentrated at the solid-liquid interface of nanomaterials. The process occurs through physical adsorption (physisorption) or chemical adsorption (chemisorption). Physisorption occurs by weak and reversible intermolecular forces i.e. van der Waals interactions, dipole-dipole interactions, hydrogen bonding. Chemisorption is the electron sharing or chemical bonding between the adsorbate molecules and active surface functional groups, such as coordination through surface complexation, inner-sphere coordination, and ion exchange (Duan et al., 2018).

Surface hydroxyl groups ($\text{M}-\text{OH}$) on MONPs display amphoteric behavior in water, protonating or deprotonating based on solution pH relative to the material's pH_{pzc} :



When solution pH is below pH_{pzc} , the positively charged nanoparticle surface ($\text{M}-\text{OH}_2^+$) electrostatically attracts anionic pollutants, such as reactive azo dyes (Methyl Orange, Congo Red) and oxyanionic heavy metal complexes (such as chromate CrO_4^{2-}) (Xiao et al., 2025). Conversely, when solution pH exceeds pH_{pzc} , the deprotonated negative surface ($\text{M}-\text{O}^-$) binds cationic heavy metal ions (Cu^{2+} , Ni^{2+} , Pb^{2+} , Cd^{2+}) and cationic dyes (such as Methylene Blue and Rhodamine B) via electrostatic attraction and ion exchange. Adsorption equilibria and reaction rates are evaluated using Langmuir and Freundlich isotherm models alongside pseudo-first-order and pseudo-second-order kinetic equations (Rasool et al., 2025).

Photocatalytic Degradation Mechanisms

Photocatalysis utilizes light-activated semiconductor processes to degrade persistent organic contaminants into non-toxic inorganic end-products, primarily carbon dioxide, water, and mineral acids (Mohamed et al., 2025).

When incident photon energy ($h\nu$) equals or exceeds the semiconductor bandgap (E_g), electrons (e^-) excite across the bandgap from the valence band (VB) to the conduction band (CB), generating positively charged holes (h^+) in the valence band:



These photogenerated charge carriers (e_{CB}^- and h_{VB}^+) migrate to the nanoparticle surface, initiating redox reactions with adsorbed water, hydroxyl ions, and dissolved oxygen molecules:



The generated Reactive Oxygen Species (ROS) specifically hydroxyl radicals ($\cdot\text{OH}$) and superoxide radical anions ($\text{O}_2^{\cdot-}$) possess high oxidation potentials ($E^\circ(\cdot\text{OH}/\text{H}_2\text{O}) \approx +2.80 \text{ V vs. SHE}$) (Mohamadpour & Amani, 2024). These are species that degrade complex organic pollutant molecules non-selectively to smaller intermediates and end products of mineralization:



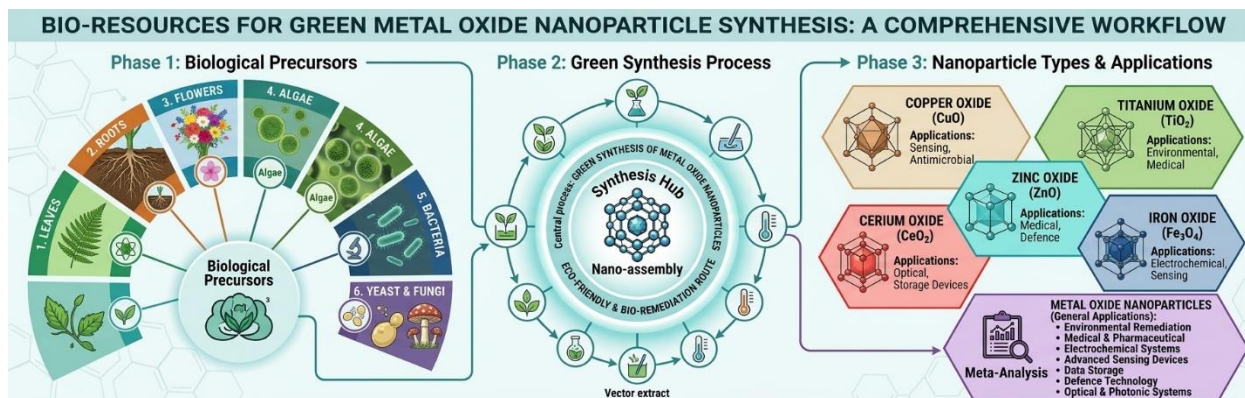
I Interfacial adsorptions is the prior step for high photocatalytic degradation. Gathering pollutant molecules at the nanoparticle surface to maximize their contact with short-lived surface-bound radicals ($(\cdot\text{OH})$, lifetime $\sim 10^{-9} \text{ s}$) reduces charge carrier recombination and enhances the photocatalytic output (Tahir et al., 2021).

Performance Evaluation of Key Metal Oxide Nanoparticles

Titanium Dioxide (TiO_2)

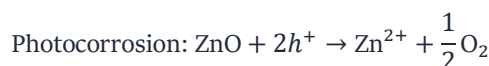
Due to its high chemical stability, non-toxic nature, good corrosion resistance and cost-effective utilization, titanium dioxide has been widely used as a photocatalyst. There are three common titanium dioxide crystal phases for (anatase (tetragonal, $E_g \approx 3.2 \text{ eV}$), rutile (tetragonal, $E_g \approx 3.0 \text{ eV}$), and brookite (orthorhombic). Anatase exhibited higher photocatalytic activity than rutile attributed to its larger bandgap energy and lower electron recombination rates (Haider et al., 2019). Phase junctions of anatase and rutile phases (e.g. the commercial Degussa P25, with an $\sim 80:20$ phase ratio) run better than their single phase counterparts, as spatial charge transfer between phases leads to suppression of electron-hole recombination. Nevertheless, the wide bandgap of pure $[\text{TiO}_2]$ limits optical response within ultraviolet region ($\lambda < 387 \text{ nm}$) which accounts for less than 5% of solar energy (Negrescu et al., 2022).

Figure 2: Comprehensive Workflow of Bio-Resources, Synthesis Mechanisms, and Targeted Applications of Green Metal Oxide Nanoparticles



Zinc Oxide (ZnO)

Zinc oxide is a direct wide-bandgap semiconductor ($E_g \approx 3.37$ eV) with a high exciton binding energy (60 meV) at room temperature. ZnO commonly exhibits higher initial quantum efficiency and dye degradation rates than TiO_2 Under ultraviolet irradiation, as a result of its fast electron mobility (Sagadevan et al., 2022). The main drawback of using ZnO for continuous remediation in aqueous phase is that it undergoes photocorrosion when illuminated with light:



This photocorrosion process produces soluble Zn^{2+} ions in water matrices, which decreases the life of the catalyst and causes secondary toxicity. Surface modification, elemental doping, and heterojunction formation inhibit photocorrosion and enhance durability (Al Saleh, 2025).

Copper Oxide (CuO and Cu₂O)

Cupric oxide ("CuO", monoclinic, $E_g \approx 1.2$ – 1.7 eV) and cuprous oxide (Cu_2O , cubic, $E_g \approx 2.1$ eV) are p-type semiconductors which can absorb visible light. Biosynthesized "CuO" NPs have a high surface reactivity for the elimination of heavy metals and inorganic anions. At the optimal working conditions, green "CuO" nanoparticles can be an excellent candidate for fluoride adsorption more than 3000 mg/g (Maruyama, 1998). When tested on complex industrial effluent such as tanning effluent, biosynthesized "CuO" nanoparticles resulted in over 90% reduction in major water quality parameters such as Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and electrical conductivity (Balik et al., 2019).

Iron Oxide Nanoparticles (Fe₃O₄ and γ -Fe₂O₃)

Magnetite (Fe_3O_4) and maghemite (γ -Fe₂O₃) are also good adsorbents and heterogeneous catalysts. Iron oxide nanoparticles become superparamagnetic when their sizes are less than 20 nm. Superparamagnetic nanoparticles are very sensitive to external magnetic fields but have no permanent magnetization once the field is removed (Ajinkya et al., 2020). This feature allows for quick, inexpensive magnetic separation of treated water slurries using external magnets, overcoming the recovery problems of non-magnetic nanoscale catalysts. In addition, Fe_3O_4 catalyzes heterogeneous photo-Fenton reactions, in which hydrogen peroxide is converted into hydroxyl radicals through active $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox cycles (Zhang et al., 2013).

Mixed Oxide Composites and Heterostructures

Single-component MONPs are often limited by operational challenges, including fast charge recombination, narrow solar absorption, or post-treatment separation. These performance bottlenecks are overcome by the use of multi-component heterostructures, for example, "CuO/ZnO" p-n junctions or composite structures such as "CTS@SnO₂@Fe₃O₄" (chitosan-tin oxide-magnetite). Heterojunction interfaces can realign energy band structures, which push photogenerated electrons and holes into separate material domains. At the same time, the presence of magnetic cores (Fe_3O_4) guarantees quick magnetic retrievability and efficient adsorption (Kim et al., 2025).

Table 2: Remediation Performance and Operational Parameters of Various Metal Oxide Nanoparticles for Water Treatment

Metal Oxide System	Synthesis Method		Target Pollutant	Primary Mechanism	Operational Parameters	Removal Efficiency / Adsorption Capacity
TiO ₂ Nanoparticles	Sol-Gel		Methylene Blue / Azo Dyes	Photocatalytic Degradation	Catalyst loading 1.0 g/L ; UV light; pH 7.0	> 98% degradation within 120 min
ZnO Nanoparticles	Green mediated	Plant-	Textile Industry Effluent	Photocatalysis & Adsorption	pH 8.0 ; 150 min contact; solar irradiation	60%--99% dye removal
CuO Nanoparticles	Biosynthesis (extract)		Fluoride / Industrial Tanning Wastewater	Chemisorption & Redox Precipitation	pH 6.0 ; ambient temp; 0.1 g/L dosage	Max capacity 3152 mg/g ; > 90% COD/BOD reduction
Fe ₃ O ₄ --Polymer Composite	Green/Polymer Co-precipitation		Heavy metals (Cu ²⁺ , Ni ²⁺)	Electrostatic Adsorption & Ion Exchange	Polymer-mineral interface; magnetic separation	High ion removal with multi-cycle reusability
CTS@SnO ₂ @Fe ₃ O ₄ Composite	Hydrothermal/Sol-Gel		Synthetic dyes & Toxic heavy metal ions	Dual Adsorption & Magnetic Recovery	Acidic to neutral pH; magnetic retrieval	Superior reusability & high adsorption capacity

Biotoxicology, Environmental Safety, and Technical Challenges

Although MONPs have the ability to treat wastewaters, applying them raises ecotoxicological issues as well as technical concerns in engineering systems (Yang et al., 2016).

Ecotoxicity and Cytotoxic Pathways

Owing to their much smaller size and high reactivity, MONPs can penetrate through cell membranes and interact within biological systems. The underlying toxicological mechanisms in aquatic species are:

Intense surface ROS production induces intracellular oxidative stress, leading non-target aquatic organisms, microalgae, and invertebrates to cell membrane, protein, and nuclear DNA damage (Du et al., 2020). Physical contact between microbial cell walls and the sharp edges of nanoparticles leads to membrane disintegration, depolarization, and leakage of cytoplasmic content. In addition, partial chemical dissolution of metastable oxide matrices ("ZnO", "CuO") entails the release of free divalent metal ions (["Zn"] ^{^(2+)}, ["Cu"] ^{^(2+)}) into aquatic environments, contributing to metal ion toxicity. These intersecting vectors potentially allow for bioaccumulation throughout aquatic food chains (Li et al., 2022).

Engineering and Operational Bottlenecks

The engineering problem in slurry reactors is the strong aggregation of unpassivated MONPs under van der Waals attraction and magnetic forces. Aggregation of the specific surface accesses reduces the surface specific area, which results in reduced colloidal stability and photocatalytic efficiency (Bilinovics-Sipos et al., 2023).

Loading of the catalyst in photocatalytic systems exhibits a parabola performance pattern. Higher concentration MONPs favor faster degradation since more active surface sites are available and more reactive radicals' species are produced at the

beginning of the decay process. But with too high a catalyst loading an aggregation of solid particles and light scattering occur. Over amount of suspended matter incident light is scattered and turbidity is enhanced, the system is self-shaded, and depth of penetration of light is limited, which causes overall quantum efficiency to decrease (Zhao et al, 2026).

It is a technical challenge to retrieve non-magnetic nano-scale catalysts from processed effluents. Conventional post-treatment filtration and centrifugation methods are energy intensive and costly at scale. Insufficient retrieval could result in the release of engineered nanoparticles into receiving natural water bodies, causing secondary contamination. Furthermore, biogenic synthesis routes for products standardisation D the challenges: change with seasons, geo- graphical regions, species specific in plant extract composition are factors that hinder process reproducibility (Hale et al., 2016).

Conclusion

Metal oxide nanoparticles are a revolutionary type of material that can be utilized for environmental clean-up and purification of wastewater, their distinctive physicochemical characteristics make it possible to effectively eliminate various pollutants suspended in water by means of adsorption and photocatalytic degradation. This review has comprehensively covered synthesis processes including traditional chemical methods such as sol-gel process, hydrothermal synthesis, chemical precipitation and green synthesis using plant materials and biological molecules. All these methods have different pros and cons in terms of control over particle size, crystallinity, scalability and environmental friendliness, with green synthesis showing promise as a sustainable method but still facing problems with batch-to-batch consistency. Important parameters of the process, like the pH, temperature, concentration of precursor and time of contact can also have profound effects in the structure, morphology and functionality of the MONPs and thus in the efficiency of the detoxification. In order to determine the true cause of the structure-function relationship, and to predict the properties of tailor-made nanoparticles for a specific application, a comprehensive characterization by spectroscopic, structural, morphological as well as electrokinetic methods is indispensable. Key MONPs exhibit remarkable performance: TiO_2 dye degradation $\rightarrow$ 98%+ (UV irradiation), ZnO demonstrates high electron mobility (high quantum efficiency), CuO NPs possess extraordinary fluoride adsorption ability (3000+ mg/g) and superparamagnetic iron oxides facilitates an easy magnetic recovery. Mixed oxide composites and heterostructures exhibit further enhanced performance due to promoted charge separation, extended solar absorption and magnetic retrievability. However, there are significant challenges. Challenges such as risk of release of nanoparticles into the environment and their potential ecotoxicity, photo-corrosion of ZnO, performance deterioration due to agglomeration, energy intensive catalyst recovery, reproducibility issues of biogenic synthesis, still need to be tackled by further investigations. Prospective work consists of devising experimental conditions based on green chemistry principles for high-yield and large-scale production of water-dispersible HAs with good visible-light-activity, engineering new and stable HAs-based heterostructures with a clearly improved performance, conducting LCA to guarantee the environmental friendliness of the HAs-based photocatalytic production for water purification and preparation of novel hybrid systems (combining adsorption and photocatalysis) for a stepwise/complete decontamination of the pollutants. Solving these challenges will allow MONP-based technologies to transition from laboratory promise to site-based, sustainable solutions for global water and environmental protection.

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