



Nanostructured metal and Metal Oxide Materials for Advanced Water Filtration: Recent Progress and Perspectives

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Abstract : Nanostructured metal oxide nanoparticles have emerged as potential agents for water purification owing to their large specific surface areas and multifunctional properties. These NPs have been shown to efficiently adsorb heavy metals, degrade organic dyes, and inactivate pathogens in contaminated water. These nanoscale materials combine high adsorption capacity with strong photocatalytic and antimicrobial effects. TiO₂ and ZnO NPs efficiently degrade organic dyes under UV or visible light while Ag and Cu NPs enable rapid disinfection of pathogens. Advanced synthesis routes allow precise control of NP size, shape and composition to tailor their optoelectronic and surface properties. Integration of these NPs into hybrid matrices or membranes provides synergistic performance. Polymeric or ceramic nanocomposite membranes loaded with metal/oxide NPs show enhanced permeability, fouling resistance and mechanical stability. These nanocomposites can also impart antibacterial/antifouling properties, mitigating biofilm formation during filtration. For instance, Ag NP-polymer composites demonstrate simultaneous adsorption and photocatalytic dye removal, and magnetic Fe₃O₄ NPs enable facile recovery and reuse of the sorbent. However, practical deployment faces key challenges such as nanoparticle aggregation, leaching and ecotoxicity must be mitigated and scalable, cost-effective fabrication is needed for real-world use. Future work emphasizes green synthesis and life-cycle assessment to ensure truly environmentally benign operation. These advances promise multifunctional filtration such as adsorption, photocatalysis, disinfection, but addressing safety and sustainability is critical for large-scale implementation. This review emphasizes the recent progress in synthesis strategies, multifunctional mechanisms, and integration of metal and metal oxide nanoparticles for sustainable water purification applications.

IndexTerms - Metal oxide nanoparticles; water purification; photocatalysis; disinfection; adsorption; nanocomposite membranes

I.INTRODUCTION

Clean water is essential for health and development, yet human activities have made freshwater widely polluted. Rapid industrialization, intensive agriculture and urbanization have released a broad spectrum of contaminants into water resources from toxic heavy metals e.g. lead, mercury, arsenic and synthetic dyes from textile and paper industries to pathogens, pesticides and pharmaceuticals. As a result, water pollution is now a major global challenge. For example, an estimated 2.1 billion people lack access to safe drinking water sources, and about 4 billion experience periodic water shortages [1]. Around 6.0 billion people i.e 73% of the world's population have safely managed drinking water, but the other billions rely on unimproved or contaminated supplies. In 2022 alone, approximately 1.7 billion people were estimated to use drinking-water sources contaminated with faecal matter. Such microbial contamination causes waterborne diseases such as diarrhoea, cholera, typhoid, etc. and kills roughly 2 million people each year [2]. Overall, about 80% of global health problems can be traced to unsafe or polluted water [3]. Persistent toxic metals pose grave risks. For instance, naturally occurring arsenic in groundwater has poisoned tens of millions of people; an estimated 140 million people in ≥ 70 countries drink water with arsenic above WHO's 10 $\mu\text{g/L}$ guideline [4]. Chronic exposure to arsenic, lead, cadmium and other metals causes cancer, kidney disease and neurological disorders

[5]. Episodes like the Flint, USA lead-contamination crisis illustrate the devastating health effects of heavy metals in drinking water [6]. The textile, paper and dye industries are among the largest polluters of surface water. It is estimated that approximately 20% of global industrial water pollution comes from textile dyeing and finishing [7]. Tens of thousands of dye chemicals are produced, and globally approximately 2.8×10^5 tonnes of synthetic dyes are discharged to wastewater every year. These dyes are toxic, visible even at low concentration and many are carcinogenic or mutagenic. Inadequate sanitation and wastewater treatment mean many communities are exposed to fecal pathogens. Globally, poor water/sanitation causes an estimated 505,000 diarrhoeal deaths per year. In many low-income regions, routine waterborne pathogens like bacteria, viruses, protozoa remain the greatest hazard in drinking water [1]. Modern societies discharge vast amounts of drug residues into water. Over 3,000 active pharmaceutical compounds are in use worldwide, with production on the order of hundreds of tons per year [8]. Common drugs are only partially removed by conventional sewage treatment, so low levels of emerging contaminants are routinely found in treated effluents and even drinking water. In fact, only about 56% of the world's wastewater is treated safely; much of the rest is released without adequate purification [9]. Consequently, many populations are chronically exposed to cocktails of pharmaceuticals and personal-care chemicals through contaminated water.

These contamination challenges expose serious limitations of conventional water treatment. Traditional technologies such as coagulation, sand filtration, activated carbon adsorption, chlorination, UV disinfection and even modern membranes can remove many pollutants, but often not completely or simultaneously. In practice, single-step treatments lack versatility, for example, sand filtration and settling remove particulates but do not eliminate dissolved dyes or pathogens; activated carbon adsorbs some organics but cannot oxidize them; and chlorination disinfects microbes but leaves chemical contaminants. Moreover, many micropollutants pass through standard treatments nearly unchanged, or end up in concentrated residuals rather than being destroyed [1]. Conventional processes also tend to be costly and lot of infrastructure is required. Multiple treatments are often cascaded to reach safety standards, incurring high energy and maintenance burdens. The need to handle ever more complex and emerging contaminants is outpacing the capabilities of existing treatment plants, driving the search for new approaches. Nanomaterials offer promising solutions. At the nanoscale, materials exhibit extraordinarily high surface-area-to-volume ratios, with all atoms at or near the surface available for reactions. This means enormous adsorption capacity. For example, a one nanometer particle has approximately thousand times more surface area per mass than a one micron sized particle. Nanoparticles' surface chemistry can be precisely tuned to target specific pollutants. Many metal and metal-oxide nanoparticles combine multiple treatment functions in one material: for example, TiO_2 and ZnO nanoparticles are strong photocatalysts that generate reactive oxygen species under UV or visible light, oxidizing organics and killing bacteria [10]. Noble metal NPs like gold and silver exhibit surface plasmon effects, enabling visible-light-driven photocatalysis and potent antimicrobial. Magnetic nanoferrites adsorb heavy metals and organics and can be swiftly recovered by magnets after use. Nanomaterials provide very large surface areas, high reactivity and tunable functionality that can greatly enhance pollutant removal. They enable multifunctional filtration. One can design a nanoparticle or composite that simultaneously adsorbs heavy metal ions, degrades organic molecules under light, and inactivates microbes. Such integrated action holds the promise of simpler, more efficient purification than multiple conventional steps.

In this review paper we focus on recent advances in metal- and metal-oxide nanoparticles for water purification. We examine how metallic NPs and metal-oxide NPs can serve as adsorbents, photocatalysts and antimicrobial agents. These nanomaterials have been widely studied for adsorbing heavy metals and dyes, for photocatalytic degradation of organic pollutants under light irradiation, and for disinfection of pathogens. We highlight key recent experimental results and data. By surveying current research on nanoparticle-based adsorption, photocatalysis and disinfection, this review aims to provide an up-to-date, comprehensive understanding of how nanotechnology can address the critical challenge of clean water supply.

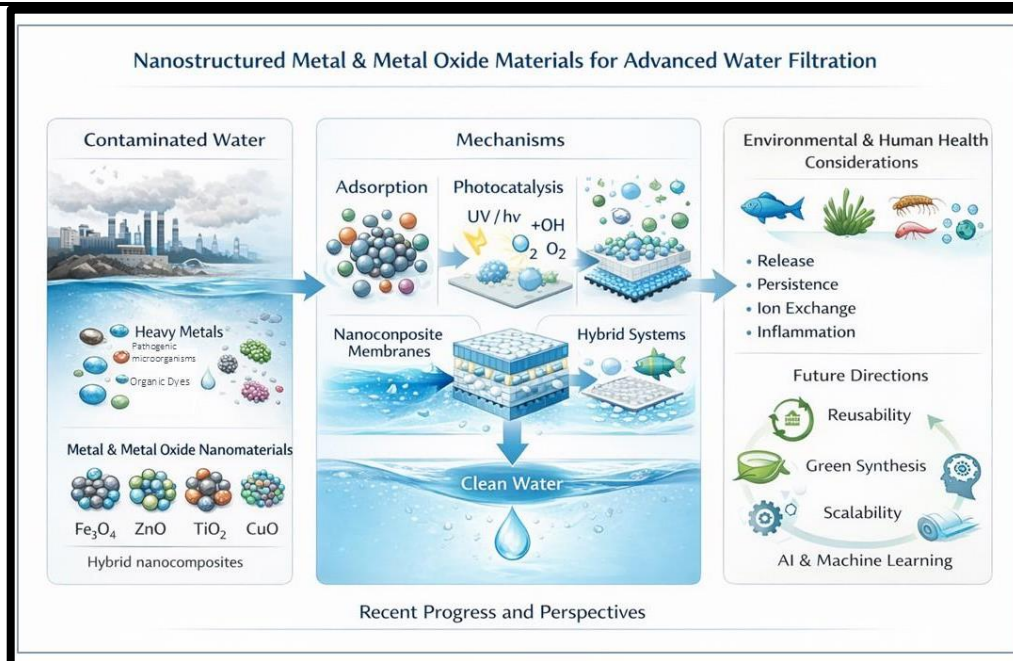


Figure 1: Nanostructured metal and metal oxides for advanced water filtration

1. Metal Oxide Nanoparticles for water treatment

Metal oxide nanoparticles (MONPs) have emerged as versatile and powerful materials in water treatment due to their tunable surface chemistry, catalytic activity, redox properties, and ability to be incorporated into multifunctional hybrid systems [11]. Their nanoscale dimensions allow high surface-area-to-volume ratios and abundant reactive sites, enabling rapid adsorption, photocatalysis, and disinfection of pollutants in contaminated water systems [12,13]. These materials are now widely studied for the removal of dyes, heavy metals, pharmaceuticals, pesticides, microbial contaminants, and emerging pollutants under different environmental conditions [14]. Among MONPs, the most extensively investigated for water purification include iron oxides (Fe_3O_4 and Fe_2O_3), zinc oxide (ZnO), titanium dioxide (TiO_2), copper oxides ($\text{CuO}/\text{Cu}_2\text{O}$), and manganese dioxide (MnO_2) [15,16]. These nanoparticles show strong performance in adsorption, photocatalytic degradation, Fenton and sulfate-radical-based advanced oxidation processes (SR-AOPs), and antimicrobial inactivation [17].

2.1 Iron Oxide nanoparticles

Iron oxide nanoparticles are widely studied for heavy-metal adsorption, redox-based pollutant transformation, and catalytic oxidation due to their abundant surface hydroxyl groups and $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox-cycling capability [18,19]. These nanoparticles can be magnetically separated easily leading to reduced sludge production and ready to use multiple times [20]. Maghemite ($\gamma\text{-Fe}_2\text{O}_3$), Hematite ($\alpha\text{-Fe}_2\text{O}_3$), and Magnetite (Fe_3O_4) nanostructures interact strongly with arsenic, lead, cadmium, and chromium ions through inner-sphere complexation, electrostatic attraction, ion exchange, and surface precipitation. Several studies report that these nanoparticles remove Pb^{2+} , As(V), and Cr(III) both rapidly and in large amounts. Iron oxides also function in heterogeneous Fenton and photo-Fenton systems, generating hydroxyl radicals that efficiently degrade dyes, drug residues, and phenolic compounds [21,22]. Modifying these nanoparticles with carbon, polymers, or bio-based coatings helps boost electron transfer, maintain stable dispersion, and enhance their catalytic performance [23]. Green-synthesized Fe_3O_4 nanoparticles have shown dye-removal efficiencies exceeding 90%, along with good reusability in multiple studies [24,25].

2.2 Zinc Oxide (ZnO) nanoparticles

Zinc oxide is a wide-bandgap semiconductor (~ 3.2 eV) with notable photocatalytic and antimicrobial activity. Under Ultra violet light or sunlight, it produces electron-hole pairs that generate reactive oxygen species, including hydroxyl and superoxide radicals, which break down dyes, therapeutic compounds, pesticides, and other organic contaminants [26,27]. Nanostructured ZnO in the form of rods, plates, or flowers typically shows better photocatalytic activity, largely because of increased defect sites and more efficient charge separation [28]. Combining ZnO with graphene oxide or carbon materials improves charge mobility and lowers recombination, thereby accelerating pollutant degradation [29,30]. ZnO also shows strong antimicrobial activity through ROS generation, Zn^{2+} release, and membrane disruption, and these effects are further enhanced by metal or carbon-based doping, which can even extend activity into the visible-light range [31,32]. By combining amphoteric ZnO with oxygen-functional carbon surfaces, ZnO biochar composites

effectively adsorb heavy metals and simultaneously aid in removing organic pollutants [33]. ZnO exhibits different morphologies based on temperature, base concentration and precursor used [34,35,36,37,38].

2.3 Titanium Dioxide (TiO₂) nanoparticles:

TiO₂ remains a leading photocatalyst in water treatment because it is highly oxidative, stable, non-toxic, and inexpensive. Anatase TiO₂ performs particularly well under UV light, producing ROS like hydroxyl and superoxide radicals that can fully mineralize dyes, pharmaceutical compounds, and other organics to CO₂ and H₂O [39,40]. Mixed phase TiO₂ catalysts like P25 frequently exhibit higher photocatalytic activity than pure anatase or rutile. This is largely due to the anatase-rutile interface, which promotes electron-hole separation and limits the recombination, resulting in more efficient pollutant breakdown. Transition-metal doping, particularly with Fe, enhances TiO₂'s functionality. Fe-doped TiO₂ can convert As (III) to the more easily removable As(V) under illumination, improving overall arsenic removal efficiency [41,42]. Beyond chemical degradation, TiO₂ also exhibits strong antimicrobial properties. When exposed to light, TiO₂ nanoparticles can inactivate bacteria, including Gram-negative species, through ROS generation, membrane disruption, and other oxidative pathways, making them valuable for microbial decontamination of water [43]. TiO₂ based materials have also been evaluated using real wastewater streams. In UV-driven photocatalytic treatments of industrial and municipal effluents, TiO₂ has produced substantial reductions in COD, DOC, and other pollution indicators, demonstrating its practical effectiveness beyond model dye systems [44].

2.4 Copper Oxides (CuO and Cu₂O) nanoparticles:

CuO is a p-type semiconductor that absorbs visible light efficiently and exhibits high catalytic activity [45]. When illuminated under UV, CuO nanoparticles produce ROS capable of breaking down dyes and other organic contaminants in water [46]. Engineered Cu₂O/CuO heterostructures, including thin-film interfaces and mixed-phase composites, typically exhibit superior photocatalytic performance over their single-phase counterparts. This improvement arises from efficient charge separation and suppressed electron-hole recombination at the Cu₂O–CuO junction [47,48]. Despite its intrinsic visible-light activity, Cu₂O is limited by photocorrosion and rapid charge recombination. These drawbacks can be mitigated by pairing Cu₂O with more stable oxides or carbon-based supports, or by constructing heterojunctions, which substantially enhance its stability and photocatalytic efficiency [49]. In addition to their photocatalytic roles, both CuO and Cu₂O exhibit notable antimicrobial activity. This behaviour is commonly linked to ROS generation, the release of Cu²⁺/Cu⁺ ions, and disruption of microbial cell membranes, making copper-oxide nanoparticles effective for disinfection under appropriate conditions [50,51].

2.5 Manganese Oxide (MnO₂) nanoparticles:

MnO₂ nanoparticles act as powerful oxidants and can work efficiently in the absence of light, thanks to Mn(III)/Mn(IV) redox cycling that supports electron transfer and contaminant oxidation. They readily convert As(III) to As(V) and can remove several heavy metals and dyes by coupling adsorption with catalytic oxidation [52]. Composite materials such as magnetic Fe₃O₄-MnO₂ hybrids provide added benefits, allowing easy magnetic recovery and reuse while maintaining high pollutant removal efficiency, which supports their potential for scalable wastewater treatment [53]. In addition, MnO₂ nanostructures can activate oxidants such as peroxymonosulfate (PMS) to generate reactive oxygen species, thereby accelerating the degradation of dyes and other persistent organic pollutants [54].

2.6 Magnesium Oxide (MgO) nanoparticles

MgO nanoparticles have wide applications in the field of catalyst support, agricultural products, paints, superconductor products, photonic devices and sensors[55]. MgO nanoflowers have demonstrated efficient removal of the antibiotic tetracycline (TC) through a combination of adsorption and photocatalytic degradation. Under optimized conditions, TC removal was substantial, highlighting MgO's potential beyond traditional heavy-metal and dye adsorption [56]. MgO nanoparticles have also been used to treat environmental waters contaminated with arsenic and dyes, where they achieved about 88 to 96% removal under optimized conditions and remained reusable across several treatment cycles [57]. MgO is a viable, cost-effective, and multifunctional metal-oxide for water purification, capable of addressing both organic pollutants and inorganic contaminants under accessible treatment conditions.

2.7 Cerium oxide (CeO₂) nanoparticles

CeO₂ nanoparticles have recently gained prominence as multifunctional agents for water purification, supported by their Ce³⁺/Ce⁴⁺ surface redox chemistry, oxygen-vacancy-rich structure, and inherent stability, which together enable efficient heavy-metal adsorption as well as photocatalytic and antimicrobial activity. Advanced CeO₂-based nanocomposites including CeO₂/graphene oxide, CeO₂/CNT assemblies, and various doped or heterostructured formulations exhibit strong degradation of dyes and pharmaceutical contaminants under both UV and visible irradiation maintaining good reusability [58,59]. Biosynthesized CeO₂ nanoparticles have demonstrated removal efficiencies frequently exceeding 95% for dyes, antibiotics, and

heavy metals, with adsorption capacities between 46 and 201 mg g⁻¹, underscoring their broad versatility. Additionally, CeO₂-GO composites show potent sunlight-driven antibacterial activity, indicating that CeO₂ materials can simultaneously support microbial disinfection and organic-pollutant degradation in water-treatment applications.

Taken together, these features position CeO₂ either as standalone nanoparticles or within composite and heterojunction architectures as a highly promising MONP for water purification, capable of supporting metal adsorption, organic pollutant oxidation, and microbial disinfection.

2.8 Emerging MONPs for Water Treatment

Researchers are increasingly investigating high-entropy oxide (HEO) nanoparticles a new class of metal oxides formed by incorporating multiple metal cations into a single crystalline lattice for water treatment applications. A recent study reported that a spinel-type HEO with the composition (FeCoNiCuZn)_aO_b degraded a binary mixture of antibiotics (sulfamethoxazole and ofloxacin) by approximately 97% and 95%, respectively, under visible-light irradiation within 90 minutes, even across different realistic water matrices. This exceptional performance is attributed to the presence of multiple active cation sites, abundant oxygen vacancies, broad visible-light absorption, and efficient charge separation intrinsic to the HEO structure. Furthermore, the mixed-cation framework and associated redox flexibility enable magnetic separation and reuse, addressing the common challenge of catalyst recovery faced by many conventional nano photocatalysts [60]. Beyond HEOs, broader surveys of metal oxide nanoparticles for environmental remediation highlight several lesser explored oxides beyond classical TiO₂, ZnO, and iron oxides as promising materials for adsorption, catalytic oxidation, and disinfection. These studies suggest that emerging MONPs could play an increasingly important role in next-generation water treatment, particularly when engineered for specific contaminants or environmental conditions [61,62].

2. Mechanisms of Water Purification

3.1 Adsorption

Adsorption is a surface-driven process in which contaminants are retained on the adsorbent through physical or chemical interactions without penetrating its internal structure. Physical adsorption occurs via weak forces such as van der Waals interactions and electrostatic attraction, whereas chemical adsorption involves stronger covalent or ionic bonding between the adsorbate and specific surface sites. The adsorption of water pollutants is governed by multiple mechanisms including electrostatic interactions, hydrogen bonding, π - π interactions, ion exchange, and acid-base reactions, often operating simultaneously. The efficiency of adsorption strongly depends on surface area, surface functional groups, surface charge, and surface energy of the adsorbent [63].

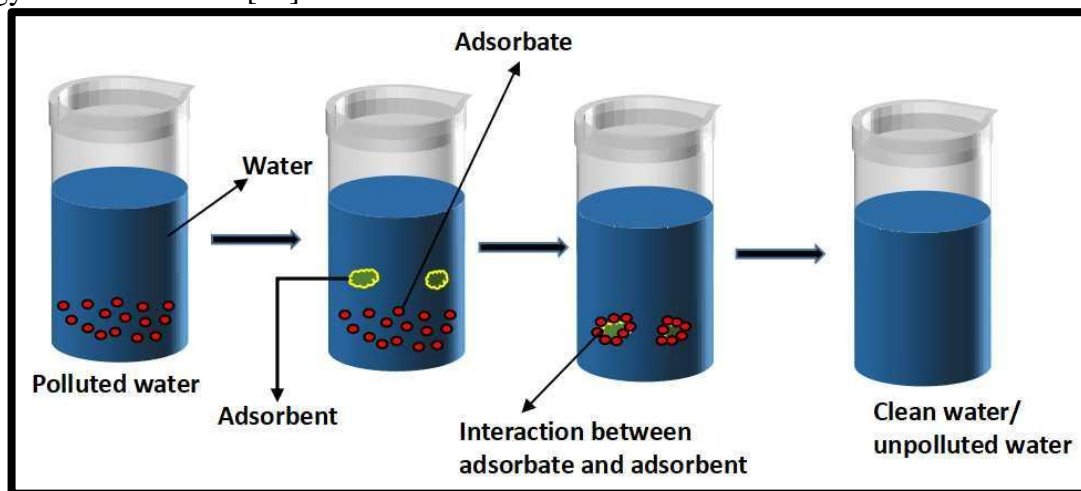


Fig 1: Process of Polluted water treatment by Adsorption.

The high cost and complexity of pristine graphene synthesis have driven interest toward graphene oxide and reduced graphene oxide, whose physicochemical properties can be strategically modified to achieve comparable adsorption performance. Future research must therefore focus on improving the surface area, structural stability, and functional efficiency of GO-based materials while enabling environmentally benign and economically scalable transition from laboratory to industrial applications [64].

3.2 Photocatalytic degradation

There are two processes involved in photocatalysis mechanism viz. mineralization and degradation of organic pollutants under UV/Visible light. Under the degradation process, the organic pollutants are decomposed into several products and during the mineralization process, organic pollutants are eradicated into water, carbon dioxide and various inorganic ions [65].

Titanium dioxide is widely used as a photocatalyst due to its high photochemical stability, strong oxidative power, non-toxicity, and ability to completely mineralize organic pollutants under UV irradiation. Zinc oxide exhibits excellent photocatalytic efficiency owing to its high electron mobility, strong generation of reactive oxygen species, and effective degradation of dyes and pharmaceutical pollutants. Magnetite (Fe_3O_4) enhances photocatalytic systems by improving charge separation, promoting pollutant adsorption, and enabling easy magnetic recovery of the catalyst after treatment. Iron oxide contributes to visible-light photocatalysis due to its narrow band gap, abundance, and role in photo-Fenton-like reactions for organic pollutant degradation. Copper oxide acts as an efficient visible-light-responsive photocatalyst because of its narrow band gap and strong redox activity toward organic contaminants. Tungsten oxide is valued for its visible-light absorption and strong oxidative holes, making it suitable for the degradation of refractory organic pollutants. Bismuth oxide is effective in

photocatalysis under visible light due to its narrow band gap, high charge carrier mobility, and strong oxidation capability. Ag_2O : Silver oxide enhances photocatalytic degradation by facilitating electron trapping and improving light absorption, thereby accelerating redox reactions [65]. Metal oxide-based photocatalysts such as ZnO , TiO_2 , and iron oxides play a crucial role in water filtration by generating reactive oxygen species under light irradiation, enabling effective degradation and mineralization of organic pollutants, dyes, pesticides, and pharmaceutical residues [66,67,68].

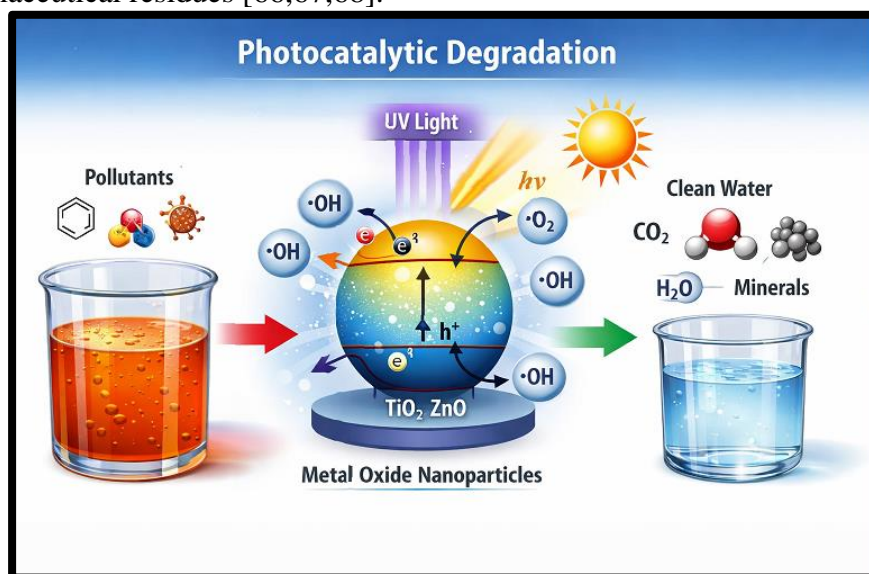


Figure 2: Photocatalytic activity of metal oxide nanoparticles

The incorporation of iron oxides ($\text{Fe}_3\text{O}_4/\text{Fe}_2\text{O}_3$) with ZnO or TiO_2 further improves photocatalytic performance by facilitating visible-light activation, promoting adsorption of pollutants, and enabling magnetic recovery of catalysts, which is highly beneficial for reusable water filtration systems [69]. The Fe_3O_4 - ZnO composite enhances photocatalytic performance by slowing down charge recombination, increasing reactive radical formation, improving pollutant adsorption, and enabling magnetic recovery, making it a considerable material for sustainable water purification. The presence of ferrite promotes magnetic recovery and reusability [70]. Photodegradation of tetracycline under solar irradiation was enhanced using a $\text{ZnO}/\gamma\text{-Fe}_2\text{O}_3$ nanocomposite, where the iron oxide modified ZnO morphology without altering the crystalline phases and improved porosity and adsorption behavior. The presence of $\gamma\text{-Fe}_2\text{O}_3$ enabled easy magnetic recovery of the photocatalyst and enhanced photocatalytic efficiency by $\sim 20\%$, achieving over 88% tetracycline degradation. These features make the $\text{ZnO}/\gamma\text{-Fe}_2\text{O}_3$ nanocomposite promising for large-scale, recyclable water treatment applications. When transition metals like lanthanum is incorporated into ZnO La^{3+} ions introduce defect levels and oxygen vacancies in the ZnO lattice, which considerably suppress electron-hole recombination. This leads to prolonged charge-carrier lifetimes and enhanced generation of reactive oxygen species such as $\bullet\text{OH}$ and $\bullet\text{O}_2^-$, which are responsible for pollutant degradation. And La incorporation increases surface basicity and adsorption affinity toward organic pollutants, while slightly narrowing the effective band gap, thereby improving light absorption and overall photocatalytic performance under UV and visible irradiation [71].

3.3 Nanocomposite Membranes and Hybrid Systems

Nanofiltration (NF) membrane is one of the most prominent methods for removing heavy metals and pharmaceutical compounds from wastewater because of its efficient, cost effective and customizable operation and design [72]. The following are typical rejection mechanisms for NF membranes:

1. Surface wetting through the creation of hydrogen bonds between the membrane and water molecules enhances the passage of water and the entrapment of pollutants through the membrane

2. Electrostatic repulsion or adsorption of pollutants via membranes with micro-porosity and heterogeneous properties as predicted by the Donnan equilibrium model.

3. Dissolving the solute and solvents in a selected layer of homogeneous and dense NF membrane, followed by diffusion transfer across the membrane.

4. Identifying the transportation by partitioning between bulk and pore fluids in a dense membrane that is punctured by pores.

5. Presenting metal-complexing ligand on the surface of the NF membrane to collect the pollutant and improve separation performance.

6. Modifying the membrane's surface by incorporating a nanostructured TFC to absorb heavy metals.

Embedding of the nanoparticles especially metal oxides like TiO_2 , ZnO , GO , Al_2O_3 , SiO_2 in casting solution for mixed matrix membrane fabrication could be better solution to improve hydrophilicity and solute selectivity for permeation, antifouling behaviour and catalytic activity, enabling multifunctional separation.

Samavati Z. et al. explained that metal-oxide nanofillers improve charge density, adsorption capability, and selective rejection of heavy metals, provided they are uniformly dispersed to avoid agglomeration. Their superior flux, stability and contaminant removal efficiency standing them the key materials for one of the next generation water treatment technologies [63]. In recent years, poly(ether sulfone) (PES), poly(sulfone) (PSf), Poly(vinylidene fluoride) (PVDF), cellulose acetate (CA), poly(acrylonitrile) (PAN) like several polymers or their combination have been considered to prepare membranes with desired structure [73].

A. Gholami et al. studied that incorporated Fe_3O_4 metal-oxide nanoparticles into a PVC/CA nano filtration membrane significantly improves hydrophilicity, water flux, and lead-ion removal efficiency. The optimal membrane containing 0.1 wt% Fe_3O_4 achieved much higher Pb^{2+} rejection due to enhanced adsorption sites and better pore structure, while higher nanoparticle loading caused agglomeration and reduced performance. Overall, the results highlight how metal-oxide incorporation can greatly enhance membrane functionality for heavy-metal remediation [74].

With the addition of 2wt% TiO_2 in the formation of polyvinyl chloride nanocomposite ultra filtration membrane and bovine serum albumin (BSA) as a foulant water flux was increased as of hydrophilic behaviour of nanoparticles [75]. 3 wt% ZnO nanoparticles improved the capability water flux which was included PEG as a pore forming agent and NMP as a solvent in PVC UF membrane. The membranes were fabricated via the phase inversion method [76].

Thin film coated membranes with Iron oxide implanted are prepared by pre-seeding interfacial polymerization method to overcome FeO nanoparticles agglomeration problem and studied the ability of anti-fouling, and separation performance. Synthesized nano- ZnO particles (≈ 20 nm) using an ultrasound-assisted coprecipitation method and incorporated them into PVC membranes by phase inversion method to enhance permeability and pollutant removal. Adding 1 wt% ZnO improved membrane hydrophilicity, doubled water flux, enhanced antifouling behavior, and achieved the highest ibuprofen removal efficiency of about 67%. Higher nanoparticle loading caused agglomeration and denser structures, leading to reduced performance [77]. The following observations across multiple polymer-metal-oxide systems clearly demonstrate that metal-oxide nanoparticles act as versatile enhancers, enabling membranes to address complex wastewater challenges more effectively than pristine polymer membranes. TiO_2 in PES/PSf membranes increases hydrophilicity and flux. ZnO in PVC or PVDF membranes improves antifouling and pollutant removal. Fe_3O_4 in CA/PVC membranes enhances heavy-metal rejection and enables magnetic cleaning. Al_2O_3 / SiO_2 in UF/NF membranes strengthens mechanical stability and regulates pore size [78].

Modified Polyphenylsulfone (PPSU) membranes with TiO_2 which was prepared by Phase inversion method was proved to be much efficient than pure PPSU membrane to separate oil from water. [79] The embedding of TiO_2 nanoparticles into PPEES-PEG nanofiltration membranes substantially enhanced membrane hydrophilicity, leading to an unexpected rise in water flux from 15.72 to 133.85 $\text{L/m}^2\cdot\text{h}$. Mechanical strength and water uptake also improved with increasing TiO_2 loading, while salt rejection initially decreased at low nanoparticle levels but recovered at higher concentrations. Overall, TiO_2 served as an effective inorganic additive that modified membrane structure and performance across permeability, selectivity, and stability [80].

3. Environmental and Toxicological Aspects:

Nanostructured metals and metal oxide materials such as silver (Ag), zinc oxide (ZnO), Copper oxide, iron oxide (Fe_3O_4) and cerium oxide CeO_2 are widely researched for water purification due to their high surface area, enhanced surface reactivity and multifunctionality (adsorption, photocatalysis, antimicrobial activity and catalytic degradation) [81,82].

In order to improve filtering efficiency and possibly lower environmental concerns, recent advancements have concentrated on creating hierarchical nanostructures, hybrid composites, and functionalised nanomaterials. For example, magnetic nanoparticles reduce environmental release by making recovery and reuse simple [83]. Toxicological and environmental effects require close examination notwithstanding performance advantages.

5.1 Environmental Considerations

Release and Persistence

The inadvertent release of nanomaterials during the production, use, or disposal of water treatment systems is a major environmental concern. After being released, nanoparticles can survive in aquatic environments, change through processes including dissolution, aggregation, or surface coating alteration, and perhaps bioaccumulate in living things [84,85]. Cross trophic levels to penetrate cells and tissues by breaking through biological barriers. possibly build up through food chains, impacting ecosystems and aquatic ecology [86].

Particle size, surface charge, coating materials, pH, ionic strength, and the presence of natural organic matter are some of the variables that affect how metal oxide nanoparticles behave in the environment. For instance, TiO₂ nanoparticles tend to agglomerate in natural waterways, which affects their transport and bioavailability, whereas silver nanoparticles can disintegrate to release harmful Ag⁺ ions [87].

5.2. Toxicological Consideration:

5.2.1. Toxicological mechanism

Nanostructured metal/oxide materials can exert toxicity via:

(i) Ion Exchange: Metal ions that contribute to toxicity are released when nanoparticles dissolve. Particularly vulnerable to dissolving in acidic or oxidising environments are silver, copper, and zinc oxide nanoparticles (Xiu et al., 2012) and (e.g., Ag⁺ from Ag NPs), which is intrinsically toxic to microbes and higher organisms [88].

(ii) Physical Interactions: Through nano-bio interactions, nanoparticles can directly contact with cell membranes, causing mechanical damage, compromising membrane integrity, and interfering with cellular functions [80]. Physical contact with membranes that might cause cell lysis or disrupt metabolic functions. Aquatic creatures have been shown to experience toxic effects that result in cellular damage, behavioural abnormalities, and enzyme inhibition [86].

(iii) Inflammatory Responses: Inhaling or consuming nanoparticles can cause inflammatory reactions in mammals, which may have long-term health consequences. Research on occupational exposure during the production of nanomaterials has sparked worries about systemic and respiratory toxicity [90].

(iv) Oxidative stress: Through surface reactions or ion release, many metal oxide nanoparticles produce reactive oxygen species (ROS), which cause DNA damage, damaging cellular components, lipid peroxidation, and protein oxidation. This is an organism-wide main toxicity pathway [88,91].

5.2.2. Human & Ecological Health Risks

Pollutant removal is the main focus of water purification research, yet there is still a dearth of information on health risks. Among the worries are: Human exposure via bioaccumulation and drinking water unintentional byproducts produced when nanomaterials undergo environmental change or photocatalysis. interactions between natural and artificial ecosystems' microbial populations (e.g., wastewater treatment performance) [86,88].

5.2.3. Ecotoxicological Effects

Research has shown that metal and metal oxide nanoparticles have a variety of harmful impacts on aquatic creatures at various trophic levels:

(i) Microorganisms: Although they are useful for disinfection, silver and copper oxide nanoparticles' potent antibacterial qualities can upset the beneficial microbial communities in natural waterways and wastewater treatment systems [92].

(ii) Fish: Oxidative stress, genotoxicity, histopathological abnormalities, and behavioural changes can result from the accumulation of metal oxide nanoparticles in fish tissues. Zebrafish embryos showed signs of harm from copper oxide nanoparticles through aberrant development and elevated mortality [93,94].

(iii) Algae and Aquatic Plants: Through processes such as oxidative stress, membrane damage, and suppression of photosynthesis, ZnO and CuO nanoparticles have demonstrated phytotoxicity to algae. Numerous algae species have experienced growth suppression at concentrations as low as 1–10 mg/L [95,96].

(iv) Invertebrates: At environmentally relevant concentrations, Daphnia species treated to TiO₂ and silver nanoparticles showed decreased reproduction, changed behaviour, and mortality. Particle size frequently affects toxicity, with smaller particles typically exhibiting higher toxicity [93,97].

6. Challenges and Future Perspectives:

Because of their remarkable qualities, which include high surface-to-volume ratios, adjustable reactivity, and multifunctional capabilities, nanostructured metal and metal oxide materials have completely changed water treatment technology. Notwithstanding notable progress, a number of obstacles need to be overcome in order to facilitate extensive commercial deployment and guarantee long-term adoption. This thorough analysis looks at present challenges and considers potential future paths for water filtering systems based on nanomaterials.

6.1 Major Challenges

(i) **Stability & Aggregation:** High surface energy and van der Waals forces cause nanoparticles to agglomerate, which drastically lowers their effective surface area and filtration efficiency. Over time, this aggregation reduces the effectiveness of filtering. They continue to have poor mechanical stability in dynamic aquatic settings, particularly when used over extended periods of time [98]. Stability can be improved by surface functionalisation with polymers, surfactants, or biomolecules, however these changes may come with extra expenses and complexity. Therefore, it should be noted that maintaining colloidal stability in a variety of water chemistries is still a significant difficulty [99].

(ii) **Scalability and Cost-Effectiveness:** Although lab-scale performance is excellent, complex methods and high energy, cost requirements make it difficult to synthesise nanostructures on an industrial scale (Frontiers). Metal and metal oxide nanoparticle manufacturing frequently requires costly precursors, intricate steps, and energy-intensive processes. Although hydrothermal, sol-gel, and chemical vapour deposition techniques produce high-quality nanomaterials, they are not cost-effective for large-scale manufacturing. For commercial viability, it is essential to develop economical, environmentally friendly synthesis pathways using biological extracts or waste materials [100].

(iii) **Reusability & Regeneration:** Nanomaterial regeneration following pollution loading is challenging. The practical lifetime and cost-effectiveness of many materials are limited by their degradation or loss of activity across reuse cycle (18). Developing robust regeneration methods that maintain material integrity is vital for economic feasibility [101].

(iv) **Integration with Existing Systems:** Many nanomaterials are not easily integrated with conventional water treatment infrastructure, limiting field-scale deployment [102,103]. Adoption may be delayed because the operational parameters, maintenance needs, and safety procedures must conform to industry standards [104].

6.2 Future Perspectives

(i) **Hybrid and Composite Materials:** Hybrid structures with synergistic features are produced by combining metal oxides with carbon-based materials (graphene, carbon nanotubes), polymers, or other nanoparticles. These composites can improve selectivity, increase mechanical strength, and stop aggregation. For example, composites of graphene oxide and metal oxide exhibit improved photocatalytic activities and adsorption capabilities [105].

(ii) **Advanced Functionalization Strategies:** Selectivity towards target contaminants can be enhanced by surface engineering through functionalisation with particular ligands, biomolecules, or molecular imprinting. Functionalised nanoparticles improve removal efficiency by identifying and binding certain contaminants even in complex matrices [106].

(iii) **Photocatalytic Enhancement:** Photocatalytic effectiveness can be greatly increased by doping metal oxides with non-metals or linking with narrow bandgap semiconductors to create visible light-active photocatalysts. This development would save energy costs by enabling solar-powered water filtration. Research on study on nitrogen-doped TiO₂ showed enhanced photocatalytic activity and visible light absorption [107].

(iv) **Nanofiber Membranes:** Metal oxide nanoparticle-infused electrospun nanofiber membranes combine mechanical flexibility, high porosity, and a large surface area. These membranes exhibit potential for low-pressure or gravity-driven filtration applications that are appropriate for decentralised water treatment in environments with limited resources [108].

(v) **Smart and Responsive Materials:** Self-regulating filtration systems with optimal performance under various situations may be made possible by the development of stimuli-responsive nanomaterials that alter characteristics in response to pH, temperature, or pollutant concentration [109].

(vi) **Green & Scalable Synthesis:** Development of eco-friendly synthesis methods promises scalable and low-cost production (MDPI). An eco-friendly substitute for chemical processes is biogenic synthesis, which uses plant extracts, microbes, or agricultural waste. Green synthesis creates biocompatible nanomaterials while lowering expenses, energy use, and hazardous waste.

(vii) Real-World Testing and Standardization: To validate laboratory results, extensive field testing in a variety of water sources with different contamination profiles is required. Regulatory approval and commercial acceptance will be facilitated by the establishment of standardised testing procedures, performance measures, and safety recommendations.

(viii) Artificial Intelligence and Machine Learning: Nanomaterial design can be optimised, performance can be predicted, and ideal operating parameters can be found by combining AI and machine learning. By eliminating experimental trial-and-error, computational modelling helps expedite the development of novel materials with desired features [110].

Conclusion

Nanostructured metal and metal oxide nanoparticles represent a powerful and versatile class of materials for next-generation water purification technologies. As comprehensively reviewed in this paper, materials such as iron oxides, ZnO, TiO₂, CuO, MnO₂, MgO, CeO₂, and emerging systems like high-entropy oxides demonstrate outstanding capabilities for the removal of a wide spectrum of water contaminants, including heavy metals, organic dyes, pharmaceutical residues, and pathogenic microorganisms. Their effectiveness arises from a unique combination of high surface area, tunable surface chemistry, redox activity, and photocatalytic and antimicrobial properties, enabling multifunctional treatment within a single material platform.

The review highlights that adsorption, photocatalytic degradation, and disinfection are not isolated mechanisms but often operate synergistically in metal oxide nanomaterials and their composites. Advanced strategies such as doping, defect engineering, heterojunction formation, and integration with carbon-based materials or polymers significantly enhance visible-light activity, charge separation, selectivity, and reusability. Furthermore, the incorporation of these nanoparticles into nanocomposite membranes and hybrid filtration systems offers practical advantages, including improved permeability, antifouling behavior, mechanical stability, and easier catalyst recovery, thereby bridging the gap between laboratory-scale studies and real-world applications.

Despite these promising advances, several critical challenges must be addressed before large-scale deployment becomes feasible. Key issues include nanoparticle aggregation, long-term stability, leaching and potential ecotoxicity, cost-effective and scalable synthesis, and compatibility with existing water treatment infrastructure. The environmental and toxicological assessment discussed in this work underscores the importance of life-cycle analysis, standardized toxicity testing, and careful control of nanoparticle release to ensure that the benefits of nanotechnology do not come at the expense of ecological or human health.

Looking forward, future research should prioritize green and scalable synthesis routes, rational design of hybrid and multifunctional materials, and extensive testing in real and complex water matrices rather than idealized laboratory systems. The development of smart, responsive materials, nanofiber-based membranes, and AI-assisted material design holds strong potential to further optimize performance and reduce costs. With continued interdisciplinary efforts spanning materials science, environmental engineering, toxicology, and policy, nanostructured metal and metal oxide materials can play a transformative role in delivering safe, sustainable, and energy-efficient water purification solutions to meet global water challenges.

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