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Photocatalytic Metal Oxide-Based Nanocomposites for Environmental Decontamination and Pollution Abatement: A Comprehensive Review

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Abstract: The rapid growth of industrialization, urbanization, and agricultural activities has resulted in the large-scale release of hazardous organic and inorganic pollutants into the environment, posing serious risks to ecosystems and human health. Among various advanced treatment technologies, photocatalysis based on metal oxide–derived nanocomposites has emerged as an efficient and environmentally benign strategy for environmental decontamination and pollution abatement. Compared to single-component photocatalysts, metal oxide–based nanocomposites exhibit superior photocatalytic activity due to enhanced charge separation, extended light absorption range, and improved surface redox reactions. This comprehensivereview critically discusses recent advances in the design, synthesis, characterization, and photocatalytic applications of metal oxide–based nanocomposites for the removal of dyes, pharmaceuticals, pesticides, and other emerging contaminants from water and air. The role of heterojunction engineering, defectmodulation, morphology control, and reaction mechanisms is systematically analyzed. Furthermore, current challenges, scalability issues, and future perspectives for practical environmental applications are highlighted. This review aims to provide a consolidated platform for researchers to develop next-generationphotocatalysts for effective pollution control.

Keywords: Metal oxide nanocomposites; Photocatalysis;Environmental decontamination; Pollution abatement; Advanced oxidation processes.

I. INTRODUCTION

Environmental pollution has become one of the most pressing global challenges due to the continuous discharge of industrial effluents, agricultural runoff, and domestic waste into natural ecosystems [1,2]. Toxic organic dyes, pharmaceuticals, endocrine-disrupting chemicals, and volatile organic compounds persist in the environment and exhibit high chemical stability, carcinogenicity, and bioaccumulation potential [3–5]. Conventional treatment technologies, including adsorption, biological degradation, membrane filtration, and coagulation–flocculation, often suffer from limitations such as incomplete mineralization, sludge generation, and high operational costs [6,7]. Advanced oxidation processes (AOPs) have gained significant attention owing to their ability to generate highly reactive oxygen species capable of degrading recalcitrant pollutants into non-toxic end products [8]. Among AOPs, semiconductor-based photocatalysis is considered a sustainable and green technology as it can utilize solar energy under ambient conditions [9]. Metal oxides such as TiO_2, ZnO, Fe_2O_3, MnO_2, WO_3, and SnO_2 have been extensively investigated as photocatalysts due to their chemical stability, low toxicity, and strong oxidizing ability [10–12]. However, the practical applicability of single metal oxides is restricted by rapid electron–hole recombination and limited visible-light absorption [13].

To overcome these drawbacks, the development of metal oxide–based nanocomposites has emerged as an effective strategy. By coupling two or more semiconductors with appropriate band alignment, heterojunctions can be formed that promote efficient charge separation and interfacial electron transfer [14–16]. Recent research has demonstrated that metal oxide nanocomposites exhibit significantly enhanced photocatalytic efficiency toward a wide range of pollutants [17–19]. This review provides an in-depth overview of recent progress in metal oxide–based nanocomposites for environmental decontamination and pollution abatement, focusing on synthesis strategies, structure–property relationships, photocatalytic mechanisms, and future perspectives.

II. CLASSIFICATION AND DESIGN STRATEGIES OF METAL OXIDE NANOCOMPOSITES

Metal oxide–based nanocomposites can be broadly classified into binary, ternary, and multicomponent systems depending on their composition and functional complexity [20]. Binary nanocomposites such as TiO_2–ZnO, MnO_2–ZnO, Fe_2O_3–TiO_2, SnO_2–ZnO, and MnO_2–TiO_2 are widely investigated owing to their facile synthesis routes and effective heterojunction formation [21–23]. These systems improve interfacial charge transfer and suppress electron–hole recombination.Ternary nanocomposites incorporate a third component, such as another metal oxide, noble metal, or carbon-based material, to further enhance visible-light absorption and catalytic performance [24]. Examples include ZnO–TiO_2–MnO_2 and Fe2O3–TiO_2–rGO systems. Multicomponent hybrid nanocomposites combine metal oxides with polymers, biochar, or graphene derivatives to achieve multifunctionality [25]. Design strategies such as morphology control, defect engineering, surface modification, and band-gap tuning are critical for optimizing photocatalytic efficiency [26–28].

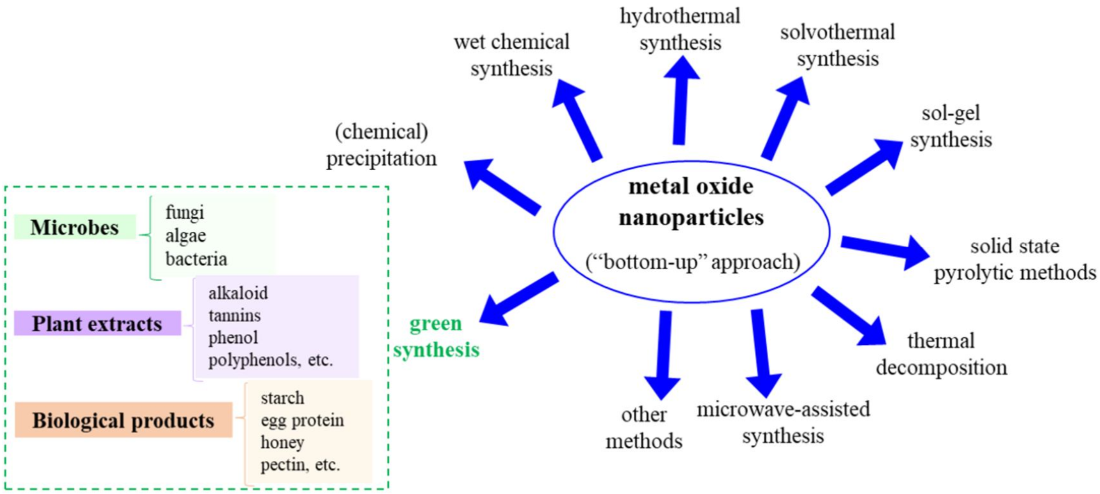

Fig.1 : Design Strategies of Metal Oxide Nanocomposites

III. EXPERIMENTAL METHODS (SYNTHESIS AND CHARACTERIZATION)

Metal oxide–based nanocomposites have been synthesized using a variety of physical, chemical,and green routes to tailor their structural and photocatalytic properties [29–31]. Among these, chemical methods are most widely adopted due to their simplicity, scalability, and cost-effectiveness.

1) Co-precipitation Method: This is one of the most commonly employed techniques for synthesizing binary and ternary metal oxide nanocomposites. Stoichiometric amounts of metal precursor salts are dissolved in aqueous medium followed by controlled pH adjustment using alkaline agents such as NaOH or NH4OH. The resulting precipitate is aged, filtered, washed, dried, and calcined to obtain crystalline nanocomposites with intimate interfacial contact [32–34].

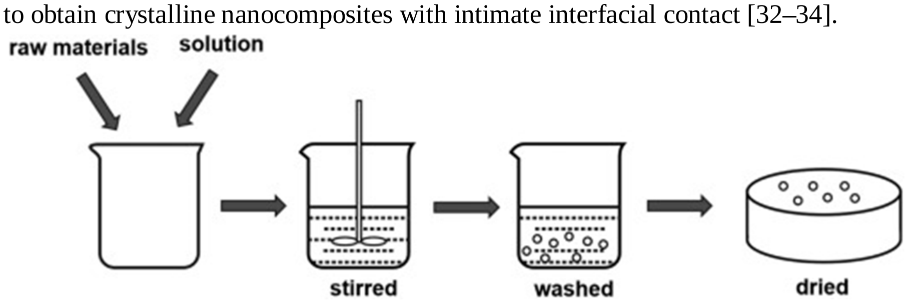

Fig .2 : An overview of Co-precipitation method

2) Sol–gel Method: In this method, metal alkoxides or inorganic salts undergo hydrolysis and condensation reactions to form a homogeneous gel network. Subsequent drying and calcination yield nanocomposites with uniform particle size distribution and high surface area [35].

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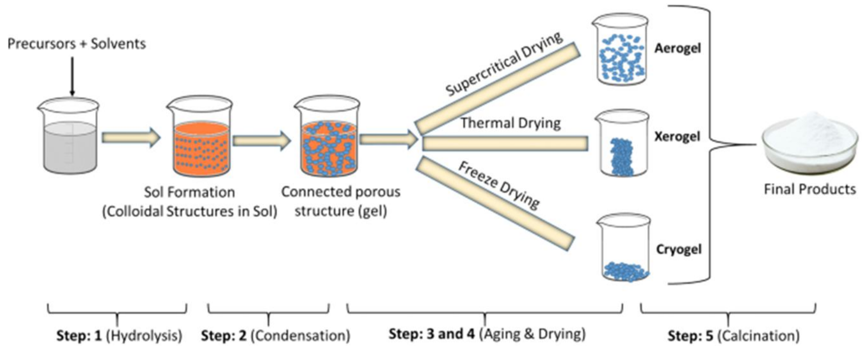

Fig.3 : Metal oxides nanoparticles by Sol–gel method

3) Hydrothermal and Solvothermal Methods: These techniques involve crystallization of nanocomposites in sealed autoclaves under high temperature and pressure. They provide excellent control over morphology, crystallinity, and phase purity, leading to enhanced photocatalytic performance [36,37].

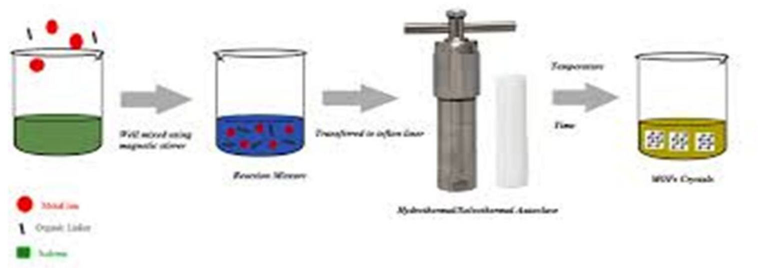

Fig.4 : Schematic representation of the solvothermal and hydrothermal process

4) Green synthesis approaches: Recently, environmentally benign synthesis routes utilizing plant extracts, biopolymers, or microorganisms have gained attention to reduce chemical consumption and environmental impact [38].

A. *Characterization Techniques*

Comprehensive characterization is essential to establish structure–property relationships in metal oxide nanocomposites. X-ray diffraction (XRD) is employed to identify crystalline phases, lattice parameters, and crystallite size. Surface morphology and particle distribution are examined using scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

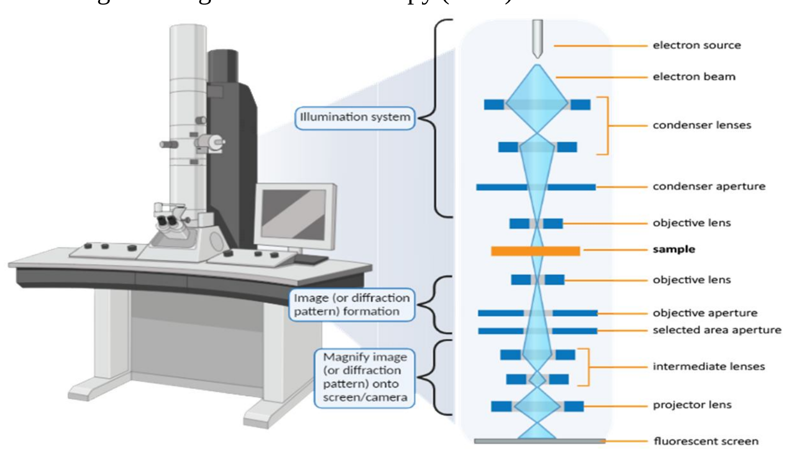

Fig. 5 : Simplified schematic of a transmission electron microscope (TEM) with principal components

Fourier transform infrared spectroscopy (FTIR) provides information on chemical bonding and functional groups, while Raman spectroscopy offers insights into structural defects and lattice vibrations. UV–visible diffuse reflectance spectroscopy (DRS) is used to determine optical absorption behavior and band gap energy.

Photoluminescence (PL) spectroscopy helps evaluate charge carrier recombination efficiency. Surface area and porosity are measured using Brunauer–Emmett–Teller (BET) analysis, which is crucial for photocatalytic reactions .

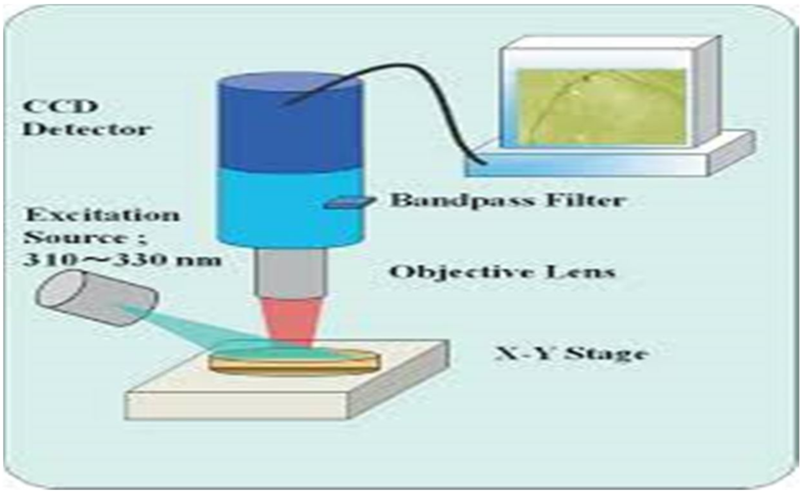

Fig 6 : Photoluminescence (PL) spectroscopy

B. *Photocatalytic Activity Evaluation*

Photocatalytic experiments are typically carried out using organic dyes or pharmaceutical compounds as model pollutants under UV or visible light irradiation. The degradation efficiency is monitored by UV–visible spectroscopy, and reaction kinetics are analyzed using pseudo-first-order rate equations. Radical scavenging experiments are conducted to identify the dominant reactive species involved in the degradation mechanism .

IV. PHOTOCATALYTIC APPLICATIONS IN ENVIRONMENTAL DECONTAMINATION

A. *Degradation of Organic Dyes*

Organic dyes such as methylene blue, rhodamine B, methyl orange, and Congo red are commonly used as model pollutants to evaluate photocatalytic activity [29]. Metal oxide nanocomposites exhibit enhanced degradation efficiency due to increased surface area and effective charge carrier separation [30,31].

B. *Removal of Pharmaceuticals and Emerging Contaminants*

Pharmaceutical residues and personal care products have emerged as critical environmental contaminants[32]. Photocatalytic nanocomposites have demonstrated promising results in degrading antibiotics, analgesics, and endocrine-disrupting compounds [33,34].

C. *Air Purification and Gas-Phase Applications*

In addition to water treatment, metal oxide nanocomposites have been explored for air purification, including degradation of volatile organic compounds and nitrogen oxides [35,].

V. PHOTOCATALYTIC MECHANISM AND CHARGE TRANSFER PATHWAYS

The enhanced photocatalytic activity of metal oxide nanocomposites is primarily attributed to efficient charge separation at the heterojunction interface . Upon light irradiation, photogenerated electrons and holes migrate across the interface, reducing recombination losses and increasing the lifetime of charge carriers. Reactive oxygen species such as hydroxyl and superoxide radicals play a dominant role in pollutant degradation .

VI. CHALLENGES AND FUTURE PERSPECTIVES

Despite remarkable advancements, several challenges hinder the large-scale application of metal oxide–based nanocomposites. These include limited long-term stability, catalyst recovery, potential ecotoxicity, and reduced efficiency in real wastewater matrices . Future research should focus on solar-driven photocatalysis, environmentally benign synthesis routes, immobilized catalyst systems, and pilot-scale studies.

VII. CONCLUSIONS

This review systematically highlights the recent progress in metal oxide–based nanocomposites for environmental decontamination and pollution abatement. The enhanced photocatalytic performance arises from effective heterojunction formation, improved charge separation, and extended light absorption. With continued advancements in material design and process optimization, these nanocomposites hold strong potential for next-generation environmental cleanup technologies.

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