Recent Trends and Development of Nanocomposite with GCN/C-Dots and its Applications

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Abstract

Nanocomposites are potential multifunctional materials due to their unique physicochemical features caused by nanoscale dispersion and strong matrix-filler interactions. Nanoscale reinforcements improve surface area, charge transfer efficiency, mechanical strength, thermal stability, and catalytic performance over bulk materials. These features make nanocomposites ideal for medical and environmental applications. Nanocomposite-based dye photocatalytic degradation systems have shown promise in recent years. Due to greater light absorption and electron-hole recombination inhibition, they produce more reactive oxygen species (ROS) that mineralize organic pollutants. Nanocomposites are essential for pharmaceutical contaminant degradation. Advanced oxidation methods break down persistent drug compounds into safer substances. Biomedical nanocomposites generate reactive oxygen species (ROS), rupture membranes, and release metal ions in a regulated manner, making them antimicrobial. This makes them excellent for coatings, medicinal dressings, and water disinfection. Current nanocomposites manufacturing advances, their architectures' effects on their properties, and their prospective use in color, medicinal, and microbial degradation are examined in this research. The obstacles and potential for sustainable design and widespread implementation are also examined.

Keywords: Nanocomposites, GCN, C-Dots, Photocatalytic, reactive oxygen species (ROS), and Nanocatalyst.

1. INTRODUCTION

Materials research has demonstrated that the dimensions of materials significantly influence their physical, chemical, and electrical properties [1]. When a substance is diminished to the nanometer scale (1–100 nm), its properties markedly diverge from those of the bulk material. The disparities arise from quantum confinement effects, an increased surface-to-volume ratio, and alterations in surface energetics [2]. At the nanoscale, a substantial fraction of atoms resides on the surface rather than in the bulk, leading to heightened reactivity, modified electronic band structures, and diminished thermodynamic stability [3]. Quantum confinement is particularly significant when the particle's dimensions approach the exciton Bohr radius. In certain environments, the electronic energy levels become discrete rather than continuous, resulting in tunable optical and electrical properties [4]. This phenomenon is frequently utilized in semiconductor nanoparticles for optoelectronic and photocatalytic applications. Furthermore, the increased surface energy of nanoscale materials enhances catalytic activity, adsorption capacity, and interfacial interactions [5]. Nanotechnology is a discipline that integrates various fields of research to construct and utilize materials and technologies at the nanoscale. These size-dependent phenomena underpin nanotechnology.

Nanotechnology entails the deliberate alteration and regulation of materials with dimensions under 100 nm in at least one dimension to enhance their functionality or enable whole new applications. This field utilizes chemistry, physics, biology, and engineering to develop novel materials with certain properties. In the last twenty years, nanotechnology has revolutionized various industries, such as electronics, renewable energy, healthcare, environmental engineering, aerospace, and defense [8]. Nanofabrication methods, including sol-gel processing, hydrothermal synthesis, chemical vapor deposition, electrospinning, and in-situ polymerization, have progressed markedly in a short timeframe. This has facilitated precise regulation of the dimensions, configuration, and composition of particles. As a result, materials have been engineered to demonstrate increased strength, exceptional electrical conductivity, greater catalytic efficiency, and the ability to deliver medications in a controlled manner [9]. Nanotechnology signifies a crucial scientific breakthrough of the twenty-first century, possessing the capacity to transform various facets of existence. Nanocomposites are presently immensely appealing due to their multifunctional properties.

2. Nanocomposites: Definition and Structural Features

Nanocomposites are materials consisting of many phases, with at least one dimension at the nanoscale. One phase constitutes a continuous matrix, while the other serves as a distributed reinforcing phase. Nanocomposites utilize nanoscale reinforcement to enhance performance, even at low filler concentrations (often 0.5–5 wt%). This differs from conventional composites, which typically incorporate micrometer-sized fillers. The matrix phase may consist of metal, ceramic, or polymer, depending on the requirement. Due to their lightweight, flexibility, and ease of fabrication, polymer matrices are extensively utilized. Metal and ceramic matrices are employed in structural or high-temperature applications requiring enhanced mechanical and thermal performance [10,11].

The reinforcement phase may encompass:

a) Nanoparticles (entities devoid of dimensions)
b) Nanorods and nanotubes (one-dimensional entities)
c) Nanosheets and layered silicates are two-dimensional entities.
d) Three-dimensional nanonetworks

The morphology and distribution of these nanofillers significantly influence the overall behaviour of the composite. Uniform dispersion enhances surface contact and optimizes stress transmission, whereas agglomeration diminishes the efficacy of reinforcement [12,13].

2.1 Types of Nanocomposite

Nanocomposites can be categorized into four major types based on the nature of their matrix and reinforcement phases: ceramic–ceramic, metal–metal, metal–ceramic, and other non-polymer-based nanocomposites.

2.1.1. Ceramic–ceramic nanocomposites are made up of a ceramic matrix with an extra ceramic phase at the nanoscale. These materials show great resistance to wear and corrosion, high thermal stability, great hardness, and great fracture toughness. Al_2O_3/ZrO_2, TiO_2/ZnO, Si_3N_4/SiC, and $CdMoO_4/CdO$ systems are some examples. They are used a lot in photocatalysis, sensors, coatings, and structural parts that need to work at high temperatures.

2.1.2. Metal–metal nanocomposites are composed of a metallic matrix combined with another metal as reinforcement. Such systems enhance mechanical strength, ductility, corrosion resistance, and electrical and thermal conductivity. Typical examples include Cu/Ni, Al/Ag, Fe/Co, and Pt/Pd nanocomposites, commonly used in catalysis, aerospace parts, and electrical contacts.

2.1.3. Metal-ceramic nanocomposites comprise a combination of metals and ceramics, exhibiting the advantageous properties of both: they possess the toughness and conductivity of metals, alongside the hardness and heat resistance of ceramics. Al/Al_2O_3, Ni/SiC, Cu/ZrO_2, and Ag/TiO_2 exemplify materials exhibiting superior wear resistance, creep strength, and overall mechanical performance. Numerous automotive components, cutting tools, and intricate structural applications extensively utilize these materials.

2.1.4. Non-polymer-based nanocomposites comprise hybrid systems constructed from ceramic, metal, carbon, and metal-organic frameworks (MOFs) devoid of polymer matrices. These materials exhibit superior electrical properties, enhanced catalytic activity, and improved chemical and thermal stability. They are highly important for environmental remediation, photocatalysis, antimicrobial coatings, sensing applications, and energy storage.

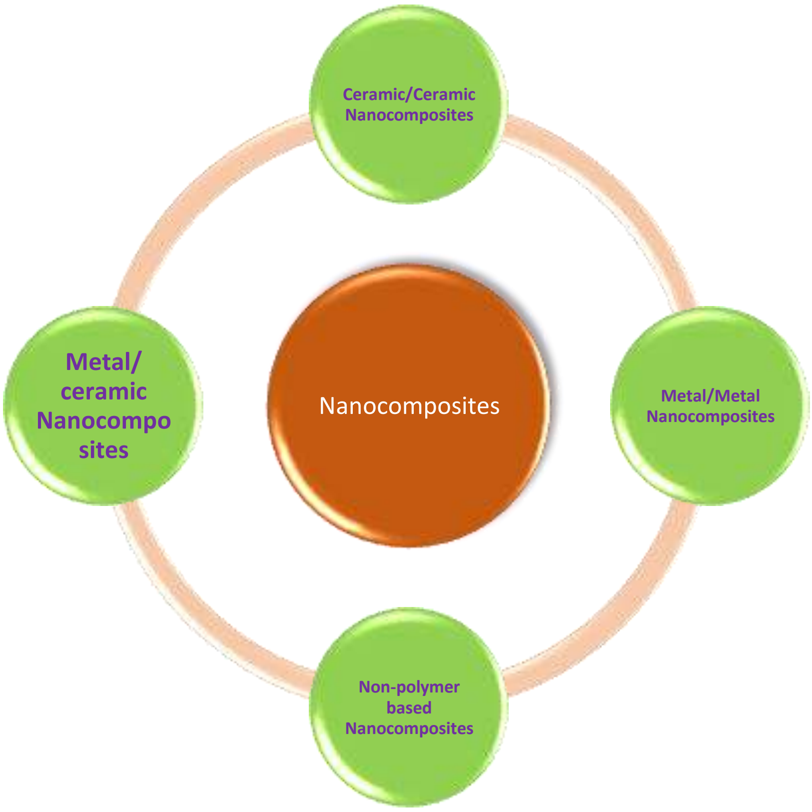

Fig.1. Types of Nanocomposites

3. Metal oxide nanocomposites

Metal oxide nanocomposites are advanced multifunctional materials made by combining metal oxide nanoparticles with other materials, such as polymers, carbon nanostructures, metals, or even more metal oxides, at the nanoscale. Reducing the size of particles to the nanoscale range greatly raises the surface-to-volume ratio and makes the surface more reactive. This makes the material better at conducting electricity, light, catalyzing reactions, and transferring heat than bulk materials. Some of the most frequent metal oxides used in nanocomposites are zinc oxide, titanium dioxide, indium (III) oxide, bismuth vanadate, and cadmium molybdate. Each of these oxides has its own set of functional characteristics and band gap energies. When these oxides are mixed with the right matrix or combined with other semiconductors, they produce heterojunctions. These heterojunctions help charge carriers move apart more easily and stop electrons and holes from recombining. This improvement makes the electrochemical efficiency, gas sensing capability, and photocatalytic activity much better. Metal oxide nanocomposites are used a lot in solar energy conversion systems, sensors, antimicrobial coatings, hydrogen generation, lithium-ion batteries, and supercapacitors. Their performance may be improved by controlling the methods used to make them, their shape, the number of defects, and the way they interact with each other. This makes them promising materials for future energy and environmental systems.

3.1 Oxides of Binary and Ternary Metals: The intentional combination of two distinct metal oxide semiconductors to mitigate the inherent constraints of single-phase materials is the fundamental characteristic of binary metal oxide nanocomposites. The interaction in these systems happens at the atomic interface where the two oxides come together. This is called a heterojunction. This interface creates an electric field that pushes photo-generated electrons and holes in different directions. Creating a p-n junction by putting an n-type oxide, like Zinc Oxide (ZnO), along with a p-type oxide, such as Copper Oxide (CuO), makes it much harder for charge carriers to recombine. This delay is what makes things work better since it makes more electrons available to help with chemical reductions or electrical impulses. So, binary composites aren't just mixtures; they're systems that fix the problems of one oxide, like poor conductivity or poor light absorption, by using the strengths of the other oxide.

3.2. Ternary nanocomposites are the next big thing in material design because they add a third component to make a multivariate synergy that binary systems can't match. The third phase, which could be a noble metal like Gold (Au), a carbon-based material like Graphene, or another metal oxide, acts as a stabilizer or middleman. When electrons traverse across three different energy levels, the electrical structure of some ternary systems is called a "cascade" or "Z-scheme." This setup makes it easier for the material to store electrical charge or use solar energy. The third part often has an important mechanical role in addition to its electronic one. It acts as a structural buffer, stopping metal oxide nanoparticles from coming together or breaking apart when they are put under a lot of physical stress from repeated chemical cycles. Trinary composites are stronger and more versatile than simpler materials. This is done by combining three separate property sets, one of which being the ability to detect gas and clean itself at the same time utilizing photocatalysis.

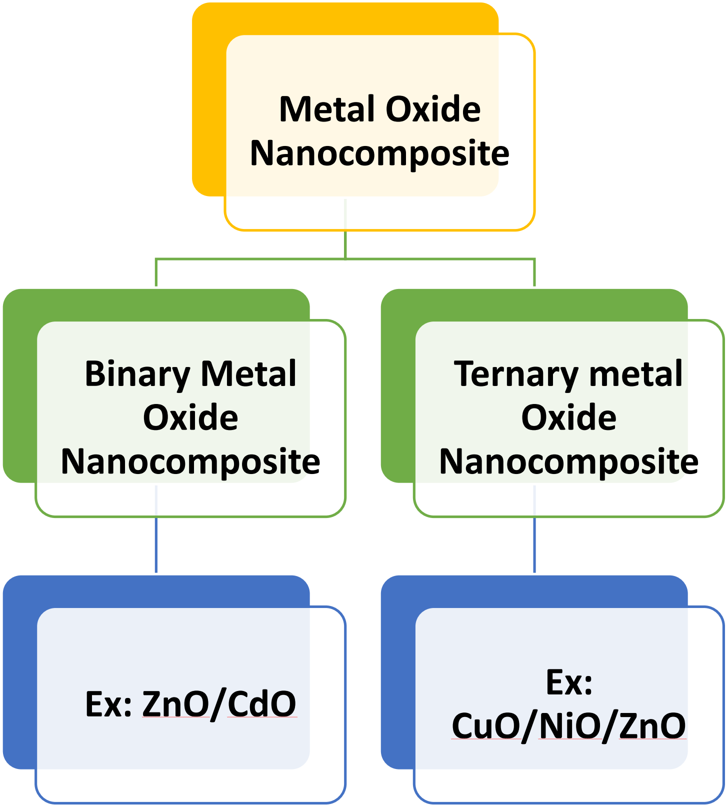

Fig. 3. Showing various classifications with examples of metal oxide nanocomposites

4. Properties of Nanocomposites

The enhanced performance of nanocomposites arises from nanoscale dispersion and strong matrix–filler interactions.

4.1.1. Properties of Mechanics Nanocomposites show big improvements in how well they work mechanically, such as better tensile strength, Young's modulus, toughness, hardness, and wear resistance. In certain settings, nanocomposite materials have been recorded to demonstrate toughness several orders of magnitude superior to that of their bulk counterparts. The improvement is mostly due to the matrix and nanoscale reinforcement being able to transfer loads more effectively.

4.1.2. Thermal Properties: Adding nanoscale fillers makes things more thermally stable and less likely to break down when exposed to heat. Nanocomposites provide better flame resistance and higher heat distortion temperatures. In carbon-based nanocomposites, conductive channels significantly improve heat conductivity.

4.1.3. Electric Properties Nanocomposites exhibit enhanced dielectric properties, increased electrical conductivity, and reduced percolation thresholds. The way conductive nanofillers are spread out makes it possible to make networks that are connected to each other, which improves the flow of charge. These qualities make nanocomposites good for use in capacitors, flexible electronics, and devices that store energy.

4.1.4. Optical and Magnetic Properties: Quantum confinement processes at the nanoscale create band gaps that can be changed and change how light is absorbed. Nanocomposites may exhibit non-linear optical properties and superparamagnetic features, making them beneficial for sensing and biological applications.

4.1.5. The chemical and barrier properties. Adding stacked nanofillers creates a complicated path for gas and liquid diffusion, which greatly improves the barrier properties. Nanocomposites are more resistant to corrosion and chemicals.

5. Uses of Nanocomposites

5.1. Photocatalytic Breakdown of Dyes Nanocomposites derived from semiconductors, such as

Table 1. Illustrate various nanocomposites that exhibit dye degradation

Nanocomposite	Target Dye	Degradation (%)	Time	Source
CdO/ZnO	Methylene Blue	83.14%	3 h	Weldegebrieal et al.
CdO nanowires	Congo Red	57%	-	Rane et al.
CdO nanowires	Ponceau-S	39%	-	Rane et al.
CdO nanowires	Indigo Carmine	30%	-	Rane et al.
In2O3/RGO	Methylene Blue	90%	-	Singh et al.
g-C3N4/BiVO4	Rhodamine B	97%	40 min	Al-keisy et al.
g-C3N4/BiVO4	Methyl Orange	88%	40 min	Al-keisy et al.
CdMoO4/CdO	Reactive Red 2	95.93%	90 min	Chen et al.
CdS/CdMoO4/g-C3N4	Congo Red	29× higher than g-C3N4	-	Lahootifar et al.
CdS/CdMoO4/g-C3N4	Methylene Blue	16.1× higher than g-C3N4	-	Lahootifar et al.
CdMoO4 hollow spheres	Rhodamine B	High activity	-	Zhen et al.
ZnWO4/CoWO4/g-C3N4	Methylene Blue	94.6%	120 min	Parasuraman et al.
p-BiOBr/n-ZnWO4	Rhodamine B	99.4%	25 min	Santana et al.

TiO_2/graphene, ZnO/CNT, and g-C_3N_4, have remarkable photocatalytic efficiency for the degradation of organic dyes in wastewater. When light hits the valence band, electrons go up to the conduction band, which makes holes. The charge carriers that are created by light interact with water and dissolved oxygen to make reactive oxygen species (ROS), such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$). These oxidize dye molecules into CO_2, H_2O, and mineralization products [14], [15]. Making nanocomposites makes photocatalytic effectiveness better by:

I. Stopping electron–hole recombination
II. Making it easier for light to be absorbed into the visible spectrum
III. Making it easier for dye molecules to stick to the surface

Improving the stability and reusability of catalysts. These systems have shown a high level of effectiveness in breaking down dyes like methylene blue, rhodamine B, and methyl orange [16].

5.2. Photocatalytic Drug Degradation

Antibiotics, analgesics, and anti-inflammatory drugs are examples of pharmaceutical compounds that persist in aquatic environments for extended periods. This is detrimental to both the environment and public health. Nanocomposite photocatalysts are frequently employed in advanced oxidation processes (AOPs) for the destruction of contaminants. Nanocomposites generate highly reactive radicals upon exposure to light. These radicals decompose complex medicinal compounds into smaller, less toxic intermediates, subsequently mineralizing them [17]. Graphene-based and metal oxide nanocomposites have demonstrated superior efficacy in degrading pharmaceuticals such as tetracycline, diclofenac, ibuprofen, and paracetamol [18].

Key advantages include:

- Rapid degradation kinetics
- Lower catalyst loading requirements
- Enhanced visible-light activity
- Improved reusability and reduced secondary pollution

Table 2. Illustrate various nanocomposites that exhibit drug degradation

Nanocomposite	Target Drug	Degradation (%)	Time	Source
S-g-C3N4 (5%)	Tetracycline	4× higher than pristine	-	Prerna Attri et al.
g-C3N4/BiVO4	Acetaminophen	74%	-	Luevano-Hipolito et al.
g-C3N4/BiVO4	Tetracycline	87%	-	Luevano-Hipolito et al.
Green BiVO4	Metronidazole	71.04%	40 min	Abhale et al.

BiVO4	Oxytetracycline	83%	240 min	Senasu et al.
CdMoO4/CdO (3:4)	Tetracycline HCl	96.33%	90 min	Chen et al.
CdMoO4/CdO	Oxytetracycline	95.38%	90 min	Chen et al.
CdMoO4/CdO	Norfloxacin	88.48%	90 min	Chen et al.
CdMoO4/CdO	Levofloxacin	77.30%	90 min	Chen et al.
CdS/CdMoO4/g-C3N4	Tetracycline	41.6× higher than g-C3N4	-	Lahootifar et al.
ZnWO4	Meloxicam	75.7%	120 min	Xu et al.
Cu-BTC/ZnWO4	Tetracycline	100%	60 min	Jeyaprakash et al.
ZnO	Progesterone	92.3%	-	Sabouni & Gomaa
ZnO	Ibuprofen	94.5%	-	Sabouni & Gomaa
ZnO	Naproxen	98.7%	-	Sabouni & Gomaa
Biogenic ZnO	Amoxicillin	85.7%	-	Isa et al.
Biogenic ZnO	Paracetamol	96.8%	-	Isa et al.

5.3. Antimicrobial Applications

Nanocomposites containing silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO_2), and graphene oxide exhibit strong antimicrobial activity against Gram-positive and Gram-negative bacteria. Their antimicrobial mechanism is attributed to:

- Generation of reactive oxygen species
- Disruption of bacterial cell membranes
- Interaction with intracellular proteins and DNA
- Release of metal ions (e.g., Ag^+) that interfere with metabolic processes [19], [20]

These materials are increasingly used in:

- Antibacterial coatings for medical devices
- Wound dressings and implants
- Water purification systems
- Food packaging materials
- Antimicrobial textiles

Nanocomposite-based antimicrobial systems provide sustained activity with reduced toxicity compared to bulk materials.

Table 3. Illustrate various nanocomposites that exhibit antimicrobial activity.

Nanocomposite	**Target Organism**	**Reported Activity**	**Source**
S-g-C3N4	S. aureus	Strong antibacterial activity	Prerna Attri et al.
ZnWO4/CoWO4/g-C3N4	S. aureus	Significant inhibition	Parasuraman et al.
ZnWO4/CoWO4/g-C3N4	E. coli	Significant inhibition	Parasuraman et al.

6. An overview of GCN/Metal Oxides:

6.1. Graphitic Carbon Nitride ($g\text{-}C_3N_4$)

Graphitic carbon nitride ($g\text{-}C_3N_4$) is a polymeric semiconductor that doesn't contain any metals. It is made up mostly of carbon and nitrogen arranged in a layered, graphitic structure. It has a band gap of about 2.7 eV, which is reasonable and allows photocatalytic activity in visible light. $g\text{-}C_3N_4$ has attracted significant interest in environmental and energy applications owing to its remarkable chemical and thermal stability, cost-effectiveness, and the simplicity of its synthesis from nitrogen-rich precursors such as melamine or urea. It is widely used in photocatalytic degradation of colors and drugs, making hydrogen, reducing CO_2, and fighting germs.

However, its photocatalytic efficacy is often limited by rapid electron–hole recombination and a small surface area. This can be improved by nanostructuring or creating heterojunction nanocomposites with metal oxides as

TiO_2, ZnO, or $ZnWO_4$ [21]. A systematic study by A. Thomas et al. on the structure and shape of graphitic carbon nitride (g-C_3N_4). Thermal polymerization of nitrogen-rich precursors such cyanamide, dicyandiamide, and melamine made the compound. The study showed that the conditions of the reaction had a big effect on the amount of condensation, the order of the structure, and the surface properties. The polymer that was first made, called melon, changes into a denser graphitic structure made up of tri-s-triazine (C_6N_7) units with two-dimensional layers that are larger. Various nanostructures, including mesoporous types, were made, which made it easier to control the surface area and catalytic capabilities. The scientists highlighted the semiconducting characteristics and nitrogen-rich framework of g-C_3N_4, which enable metal-free heterogeneous catalytic activities such as benzene activation and CO_2 conversion. This study elucidated the structural foundation and catalytic properties of g-C_3N_4, thereby promoting its further development in photocatalysis and environmental applications.

Prerna Attri et al. recorded the synthesis of sulfur-doped exfoliated graphitic carbon nitride (S-gCN) by a two-step calcination procedure to enhance visible-light photocatalytic efficiency. Structural examination confirmed the crystalline properties of the materials, but adding 5% sulfur significantly increased the surface area from 10.294 to 61.185 m^2g^{-1}. FE-SEM measurements showed that adding sulfur and exfoliation changed densely packed nanosheets into loosely structured layered structures, making the surface easier to reach. The band gap got smaller, going from 2.81 eV to 2.63 eV, which made it easier for the material to absorb visible light. The lower photoluminescence intensity meant that electron-hole recombination was slowed down, which made photocatalytic efficiency better. Notably, 5% S-gCN broke down tetracycline, chlorpyrifos, and Eriochrome Black T dye about four times faster than pure gCN. It also had strong antibacterial effects against S. aureus. The study underscores the synergistic effect of sulfur doping and exfoliation in improving the structural, optical, and catalytic properties of g-C_3N_4 for environmental remediation applications.

Ping Niu et al. recorded the creation of graphene-like g-C_3N_4 nanosheets using a simple top-down thermal oxidation etching technique. Because the layers didn't interact strongly with each other, bulk g-C_3N_4 was easily broken down into ultrathin nanosheets that were around 2 nm thick. The resulting two-dimensional structures exhibited a significantly enhanced specific surface area (306 $m^2\ g^{-1}$), an enlarged band gap (about 0.2 eV), expedited in-plane electron transport, and an elongated charge carrier lifespan due to quantum confinement effects. The changes to the structure and electrical properties led to a big improvement in photocatalytic activity, especially when it came to making hydroxyl radicals and hydrogen. The study showed how important dimensional engineering is for making g-C_3N_4's physicochemical and photocatalytic properties better.

Juan Liu and his team wrote about how they made a carbon nanodot–carbon nitride (C_3N_4) nanocomposite that doesn't use any metals and can split water effectively with the help of sunlight. The study addressed the ongoing challenges of low quantum efficiency and poor stability in visible-light photocatalysts. The combination of carbon nanodots and g-C_3N_4 led to better light harvesting and charge separation because of the way they worked together at the interface. The nanocomposite had very high quantum efficiencies of 16% at 420 ± 20 nm, 6.29% at 580 ± 15 nm, and 4.42% at 600 ± 10 nm. It also had a total solar energy conversion efficiency of 2.0%. The catalyst was made out of cheap, plentiful, and eco-friendly materials and was very stable. This study showed a good way to make metal-free photocatalysts that work well and last a long time for making solar hydrogen.

6.2. CdO Metal oxide:

Cadmium oxide (CdO) is an n-type semiconductor with a bandgap of about 2.2–2.5 eV, which is not too high. It has good electrical conductivity and improves visible absorption when combined with other semiconductors. It also helps charge transfer in composites. Researchers have looked into using CdO-based nanocomposites for photocatalysis and sensing, but because cadmium is hazardous, they need to be handled and thought about very carefully when used in the environment. Empirical studies and analyses demonstrate enhanced dye degradation and gas sensing performance in CdO-based heterostructures [22].

G. K. Weldegebrieal et al. synthesized CdO/ZnO nanocomposites via chemical co-precipitation followed by thermal treatment, evaluating their photocatalytic effectiveness in the degradation of methylene blue. Response surface methodology (RSM) using a central composite design (CCD) enhanced process parameters such catalyst dosage, dye concentration, and pH. The highest expected degradation efficiency was 81.6%, however the actual result was 83.14% after 3 hours of exposure to natural sunlight in perfect conditions (30 mg catalyst, 13 ppm dye, pH 10). Radical scavenging studies confirmed the involvement of hydroxyl (•OH) and superoxide ($O_2{\bullet}^-$) radicals in the breakdown process. The nanocomposite also kept about 96% of its activity after four cycles, which shows that it is very stable and could be useful for treating wastewater.

P. S. Kumar et al. recorded the creation of CdO nanospheres with a different bandgap using a simple precipitation method to make them better for photocatalytic use. The synthesized CdO exhibited an elevated bandgap of 2.59 eV compared to commercial CdO (2.4 eV), indicating modified electronic properties. The photocatalytic test with

Rhodamine B dye showed better degradation efficiency when exposed to visible light without adding oxidants. The better performance was due to changes in the nanoscale structure and bandgap, which improved how light is absorbed and how charge carriers move. The study highlights the potential of customized CdO nanospheres as cost-effective and environmentally benign photocatalysts for solar-powered wastewater treatment.

Rane et al. (2019) synthesized CdO nanowires (NWs) with a simple soft chemical method and evaluated their photocatalytic efficiency under visible light for the degradation of toxic pigments. The nanowires were annealed at temperatures between 350 and 450 °C, and their crystallinity improved up to 400 °C. FESEM analysis revealed a morphological transformation into earthworm-like chain structures upon annealing. As the temperature of the annealing process went up, optical tests showed that the direct band gap dropped from 2.17 to 1.55 eV. This made the material better at absorbing visible light. The CdO NWs that were heated to 400 °C had a higher photocatalytic activity, breaking down 57% of Congo red, compared to 39% of Ponceau-S and 30% of Indigo carmine. This shows that they could be used as photocatalysts for cleaning up wastewater using visible light.

Kumar et al. (2015) reported the synthesis of CdO nanospheres by a straightforward precipitation method and demonstrated their enhanced photocatalytic performance for the first time through band gap modification. The produced CdO exhibited a band gap of 2.59 eV, which is larger than that of commercial CdO (2.4 eV), due to nanoscale effects. We tested the photocatalytic effectiveness by breaking down Rhodamine B in visible light without adding any oxidants. The results showed that the degrading efficiency was improved, which suggests that CdO nanospheres with a certain band gap could be a cheap and eco-friendly way to use sunlight to treat wastewater.

6.3. In_2O_3 Metal Oxide:

Indium oxide (In_2O_3) is an n-type, wide-bandgap oxide (approximately 3.0–3.6 eV) that is very clear, has oxygen-vacancy chemistry, and can hold gas better than other materials. These properties make it an excellent choice for gas sensing applications. In_2O_3 forms effective heterojunctions with visible-active materials to improve photocatalysis and photoelectrochemical sensing. Recent reviews summarize the synthetic modulation of vacancy concentration and nanostructure to improve sensing and catalytic efficacy [23].

Zhao et al. created Mg-doped In_2O_3 nanotubes by electrospinning them and then heating them up, and they used XRD, TEM, and EDX tests to make sure that Mg was successfully added. Even though Mg acted as an acceptor dopant, the Mg–In_2O_3 nanotubes showed n-type conductivity. Compared to unmodified In_2O_3 nanotubes, the doped material had much better gas-sensing abilities. It was very sensitive and selective for H_2S at 150 °C and had a strong reaction to ethanol at 250–300 °C. The better performance was due to more oxygen vacancies and faster gas adsorption and desorption kinetics caused by adding Mg.

T.-T. Liang et al. wrote about how a microwave-assisted hydrothermal method sped up the making of rhombohedral In_2O_3 nanoparticles. The research assessed the gas-sensing performance of rhombohedral In_2O_3 relative to cubic and mixed-phase polymorphs. The rhombohedral nanoparticles had a far better ability to sense ethanol, with a response value of 43.1 at 300 °C, which was almost four times higher than that of cubic and mixed-phase nanoparticles (9.44–11.6). The rhombohedral phase showed great selectivity for ethanol compared to gases that could get in the way, like NH_3, CH_4, H_2, CO, CO_2, and NO_2. It also kept sensing performance stable for 21 days. The better sensing abilities were due to a higher capacity for gas adsorption, better particle sizes, and better electrical conductivity. This study underscores the critical role of crystal polymorphism in enhancing the gas-sensing properties of metal oxide nanoparticles for practical applications, such as breath alcohol detection.

C. Zhao et al. investigated the enhancement of gas-sensing properties in electrospun In_2O_3 nanotubes with Mg acceptor doping. Electrospinning and subsequent calcination were used to make magnesium-doped indium oxide nanotubes. Structural studies showed that magnesium had been successfully added to the indium oxide lattice. Even though Mg acted as an acceptor dopant, the Mg-In_2O_3 nanotubes still had n-type conductivity and showed a much better ability to sense things. The sensor was very sensitive and selective for H_2S at a low operating temperature of 150 °C. It also worked better at detecting ethanol at 250–300 °C than unmodified In_2O_3 nanotubes. The improved sensing capabilities were attributed to increased oxygen vacancies and modified gas adsorption-desorption dynamics induced by Mg doping. This study highlights the effectiveness of acceptor doping and nanostructuring methods in improving metal oxide gas sensors.

A. Singh et al. recorded the creation of In_2O_3/RGO nanocomposites using a single-step microwave-assisted hydrothermal method to boost photocatalytic and anticancer effectiveness. Structural and spectroscopic experiments confirmed the successful attachment of spherical In_2O_3 nanoparticles to reduced graphene oxide (RGO) sheets, along with a decrease in crystallite size and a modification in band gap energy after RGO incorporation. Photoluminescence studies showed decreased charge carrier recombination, which made the photocatalytic effectiveness better. The In_2O_3/RGO nanocomposites had a degradation efficiency of up to 90%

for methylene blue, exceeding that of pristine In_2O_3. Additionally, biological studies showed that the cytotoxic effects against HCT116 and HepG2 cancer cells were stronger while still being safe for normal PBMCs. The results show that adding RGO significantly improves the photocatalytic and biological properties of nanomaterials based on In_2O_3.

6.4. $BiVO_4$ Metal Oxides:

Bismuth vanadate ($BiVO_4$, bandgap ≈2.4 eV) is a common photocatalyst for visible light that may oxidize pollutants and produce oxygen. This is because it absorbs light well and has a good valence-band potential. To get over the problems of slow electron mobility and surface kinetics, people usually make heterojunctions (with g-C_3N_4, In_2O_3, or co-catalysts) or come up with Z-scheme designs that keep strong redox capabilities. In-depth studies of $BiVO_4$ heterojunctions show how to create them and how to use them to divide water and break down organic contaminants.[24]

Luevano-Hipolito et al. (2025) recorded the synthesis of g-C_3N_4/$BiVO_4$ heterojunctions using a microwave-hydrothermal method optimized using an orthogonal L9 Taguchi design. The study focused on the removal of developing pharmaceutical pollutants, specifically acetaminophen and tetracycline, from wastewater. By changing the $BiVO_4$ loading, microwave power, temperature, and reaction time, the best heterojunctions were made, which broke down 74% of acetaminophen and 87% of tetracycline. The mineralization levels reached were 21% and 35%, respectively. The enhanced photocatalytic activity was attributed to increased charge separation inside the heterojunction and the generation of reactive oxidant species that promote drug degradation, demonstrating the potential of g-C_3N_4/$BiVO_4$ systems for sustainable water purification.

Abhale et al. recorded the first green synthesis of $BiVO_4$ nanoparticles, using honey as a natural bioactive reducing and stabilizing agent. The characterisation methods (XRD, UV-Vis, FTIR, TEM, SEM, XPS, BET, EIS) confirmed the synthesis of monoclinic scheelite $BiVO_4$, which had a quasi-spherical shape and an average particle size of about 25.7 nm. FTIR studies showed that proteins were involved in making nanoparticles. The biosynthesized $BiVO_4$ nanoparticles effectively catalyzed the breakdown of metronidazole when exposed to sunlight, achieving a clearance rate of 71.04% within 40 minutes under optimum conditions. Radical scavenging studies identified the active oxidant species responsible for degradation. The study highlights the potential of green-synthesized $BiVO_4$ nanoparticles for enduring environmental remediation applications.

Al-keisy et al. (2023) synthesized g-C_3N_4/$BiVO_4$ composites utilizing a hydrothermal method with varying g-C_3N_4 loadings. XRD, SEM, and UV–Vis DRS analyses confirmed the successful formation of a heterojunction with g-C_3N_4 deposited on the $BiVO_4$ surface. The 5% g-C_3N_4/$BiVO_4$ compound showed better photocatalytic activity, breaking down about 97% of Rhodamine B and 88% of Methyl Orange after 40 minutes. The improved performance was due to increased charge carrier separation and a higher ability to adsorb. The enhanced composite removed more than 65% of paracetamol but only 15% of ciprofloxacin. This shows that it is a selective photocatalytic agent for breaking down drugs in water treatment systems.

Senasu et al. produced a green $BiVO_4$ photocatalyst using hydrothermal methods that didn't use any surfactants or organic solvents. The sample that was made had a monoclinic phase, a low band gap of 2.34 eV, and an absorption edge at 530 nm, which means it was quite reactive to visible light. The photocatalyst had a clear, truncated-bipyramidal form and a high-quality surface. It reached 83% degradation of oxytetracycline in 240 minutes when exposed to sunshine, following first-order kinetics ($k = 0.0097\ min^{-1}$). Hydroxyl radicals were identified as the principal reactive species. The catalyst showed great structural stability and could be used again up to five times, which showed how well it worked to get rid of antibiotics from wastewater.

6.5. ZnO Metal Oxides:

Zinc oxide (ZnO, bandgap ≈3.37 eV) is a long-lasting, cheap photocatalyst and sensing agent with a high exciton binding energy. ZnO composites (with g-C_3N_4, graphene, or other oxides) improve the absorption of visible light and lower recombination through heterojunctions or dopants. Recent reviews look at ways to change photocatalytic dye degradation and photoelectrochemical applications in big ways, such as doping, defect engineering, and plasmonic coupling [25].

Mohamed et al. performed an extensive assessment of the photocatalytic degradation of pharmaceutical pollutants using ZnO-based nanostructures. The study highlights the growing environmental and health risks associated with antibiotics, antidepressants, contraceptives, and anti-inflammatory drugs in wastewater, stressing their contribution to antimicrobial resistance and ecological damage. The review looks closely at how bare, doped, and composite ZnO nanoparticles can be used to break down antibiotics. It talks about the operational parameters, degradation mechanisms, and reactive species that are involved. It also talks about problems that may come up in the future, like possible toxicity issues and the need for long-lasting, effective ways to clean wastewater.

El-Kemary et al. recorded the creation of very small ZnO nanoparticles (~2.1 nm) using a chemical precipitation method. The structural and morphological characterization (XRD, FT-IR, SEM, TEM) confirmed the synthesis of nanostructured ZnO, whereas UV–Vis examination indicated a pronounced absorption edge at around 334 nm, corresponding to a band gap of approximately 3.7 eV. Photoluminescence studies revealed near-band-edge ultraviolet emission and green emission attributed to defect states. The photocatalytic efficiency was evaluated for the degradation of ciprofloxacin under UV irradiation at different pH levels.

The process showed pseudo-first-order kinetics, with a degradation efficiency of about 50% at pH 10 after 60 minutes. This shows that ZnO nanoparticles work better as photocatalysts when the pH is higher.

Sabouni and Gomaa investigated the UV-assisted photocatalytic degradation of progesterone (PGS), ibuprofen (IBU), and naproxen (NAP) employing ZnO as the catalyst. The effects of catalyst loading and initial pollutant concentration were examined in a batch reactor, while scalability was evaluated using a submerged membrane photocatalytic reactor. ZnO had degradation rates of 92.3% (PGS), 94.5% (IBU), and 98.7% (NAP) under varied situations. The degradation showed pseudo-first-order dynamics. The membrane reactor effectively eliminated pollutants, exhibiting increased degradation rates at higher membrane oscillation frequencies, indicating its suitability for extensive wastewater treatment applications.

Isa et al. produced biogenic ZnO nanoparticles by a precipitation technique, employing pullulan as a stabilizing biomaterial. Pullulan significantly reduced the particle size from 110.86 nm (without pullulan) to 58.13 nm, with surface areas ranging from 14.84 to 19.99 $m^2\ g^{-1}$. The photocatalytic effectiveness was evaluated for the degradation of amoxicillin (AMX) and paracetamol (PCT). Under perfect conditions (30 ppm drug concentration, pH 9 for AMX, pH 5 for PCT, and 50 mg catalyst), the optimized ZnO nanoparticles (0.67 M zinc salt in 50 g/L pullulan) broke down 85.7% of AMX and got rid of 96.8% of PCT. The study demonstrates that biogenic ZnO nanoparticles serve as efficient photocatalysts for the remediation of pharmaceutical wastewater.

6.6. Cadmium Molybdate ($CdMoO_4$) Metal Oxides:

Cadmium molybdate is a form of ternary molybdate semiconductor called scheelite. Its band gap is usually between 3.2 and 3.6 eV. $CdMoO_4$ has great crystallinity, good thermal stability, and strong photoluminescent characteristics, which make it a good choice for photocatalytic and luminescence applications . $CdMoO_4$ is mostly UV-active and has a quick electron-hole recombination, which limits its ability to work as a photocatalyst under visible light, just like $ZnWO_4$ [26].

Chen et al. reported the fabrication of a novel $CdMoO_4$/CdO S-scheme heterojunction by a simple precipitation-calcination method to enhance photocatalytic performance. Even though it had a small band gap, pure CdO didn't do any photocatalytic hydrogen evolution (PHE). When combined with $CdMoO_4$, the composite showed great performance in visible light. The optimized $CdMoO_4$/CdO (3:4) ratio attained a hydrogen evolution rate of 7029 $\mu mol\ g^{-1}\ h^{-1}$. The heterostructure showed amazing degradation rates for antibiotics and dyes, such as tetracycline hydrochloride (96.33%), oxytetracycline (95.38%), norfloxacin (88.48%), reactive red 2 (95.93%), and levofloxacin (77.30%) after 90 minutes of exposure to visible light. The heightened activity was attributed to the formation of an S-scheme heterojunction, which enhanced charge carrier separation while maintaining strong redox capacity. This study highlights the potential of CdO-based S-scheme composites for simultaneous hydrogen production and pollutant degradation.

Wen et al. documented the development of an Ag/AgCl–$CdMoO_4$ plasmonic heterojunction to enhance the visible-light photocatalytic efficacy of $CdMoO_4$. Pure $CdMoO_4$ exhibits commendable UV activity but is hindered by inadequate visible-light absorption and swift charge recombination. To overcome these limitations, three-dimensional $CdMoO_4$ microspheres (2–3 μm) were synthesized via a hydrothermal method and subsequently decorated with Ag/AgCl nanoparticles through in situ coprecipitation followed by photoreduction. The adjusted Ag/AgCl–$CdMoO_4$ hybrid demonstrated a markedly improved visible-light-induced degradation of doxycycline, attaining 46.65% mineralization in 60 minutes. The increased photocatalytic activity was due to the surface plasmon resonance (SPR) effect of Ag, which allowed light to be absorbed in the visible spectrum, and the formation of a heterojunction that helped separate charge carriers. This study demonstrates that plasmonic modification is an effective method to improve the visible-light efficacy of $CdMoO_4$-based photocatalysts.

Lahootifar et al. reported the synthesis of a ternary CdS/$CdMoO_4$/g-C_3N_4 nanocomposite by a one-pot hydrothermal method for efficient visible-light-mediated water purification. CdS and $CdMoO_4$ nanoparticles were evenly attached to g-C_3N_4 nanoplates. A thorough assessment showed that the heterostructure was successfully made, which improved the surface and optical properties.
The modified ternary composite showed much better photocatalytic activity for tetracycline, Congo red, methylene blue, methyl orange, and malachite green. Its activities were 41.6, 29.0, 16.1, 27.4, and 38.2 times larger than those of pure g-C_3N_4, respectively. The improved performance was due to more charge carriers being created, better separation and transfer of photogenerated charges, and a larger surface area. Radical trapping experiments showed that holes (h^+) and superoxide radicals ($\bullet O_2^-$) were the main things that caused the

deterioration to happen. This study highlights the effectiveness of ternary heterojunction engineering in enhancing photocatalytic water treatment.

Zhen et al. recorded the creation of $CdMoO_4$ hollow microspheres by a simple water-based method at room temperature. The microspheres were about 5 µm in diameter and had a hollow interior that was 1–1.5 µm wide. They were made up of well-aligned nanorods that were 80 to 120 nm in diameter and up to 2 µm long, giving them a unique hierarchical structure.

The hollow $CdMoO_4$ microspheres were very good in breaking down Rhodamine B when exposed to UV light. The better performance was due to its hollow design, which helps it gather more light and transmit mass more efficiently. They also looked into their photoluminescence properties, which gave them further information about how charge carriers behave.

6.7. Zinc Tungstate ($ZnWO_4$) Metal Oxides:

Zinc tungstate ($ZnWO_4$) is an n-type semiconductor that belongs to the wolframite family and has a monoclinic crystal structure. It has attracted considerable attention due to its remarkable physicochemical stability, visible-light photocatalytic effectiveness, luminescent properties, and proficiency in radiation detection. The material has a wide band gap of 3.6–3.9 eV, which means it mostly reacts to UV light. However, band-gap engineering and composite synthesis could make it work in the visible spectrum as well [27-28].

Parasuraman et al. documented the synthesis of a ternary $ZnWO_4/CoWO_4/g\text{-}C_3N_4$ nanocomposite by a straightforward one-step wet impregnation technique for improved environmental and antibacterial applications. We evenly attached $ZnWO_4$ and $CoWO_4$ nanoparticles to $g\text{-}C_3N_4$ nanosheets, which created many active sites and improved charge transfer at the interface. The ternary system exhibited superior visible-light photocatalytic performance compared to pristine $g\text{-}C_3N_4$, $ZnWO_4$, $CoWO_4$, and the binary $ZnWO_4/CoWO_4$ composite, achieving 94.6% degradation of methylene blue within 120 minutes. The combination exhibited significant antibacterial activity against Staphylococcus aureus and Escherichia coli. Mechanistic studies, including radical trapping tests, confirmed the primary involvement of •OH radicals, while increased activity was attributed to efficient charge transfer, synergistic interactions, and improved stability of the heterostructure.

Xu et al. investigated $ZnWO_4$ nanoparticles as an innovative sonocatalyst for the degradation of meloxicam (MEL) under ultrasonic irradiation. $ZnWO_4$ was synthesized via a hydrothermal method at several pH levels (5–9), yielding similar crystal structures but varied morphologies, including nanosheets, nanorods, and nanomicrospheres. $ZnWO_4$ produced at pH 6 was the best at sonocatalysis, breaking down 75.7% of MEL. The higher activity was due to its nanomicrosphere shape, small particle size (40–60 nm), and large surface area (27.068 $m^2\ g^{-1}$), which give it many active sites for making reactive oxygen species (ROS). The best degradation happened at 10 mg/L MEL, with a catalyst dose of 20 mg, an irradiation time of 120 minutes, and an ultrasonic power of 0.278 W/cm^2. Radical scavenging assays confirmed the involvement of •OH and $^1O_2$ species. The study demonstrated that $ZnWO_4$ serves as an efficient sonocatalyst for the removal of organic contaminants in aqueous settings.

Santana et al. recorded the creation of $p\text{-}BiOBr/n\text{-}ZnWO_4$ heterostructures using a combined hydrothermal–precipitation method to enhance the photocatalytic breakdown of Rhodamine B (RhB) and ciprofloxacin (CIP). Structural analyses confirmed a hybrid tetragonal/monoclinic phase, characterized by the attachment of $n\text{-}ZnWO_4$ nanocrystals to flower-like p-BiOBr microstructures. XPS verified the presence of Bi, O, Br, Zn, and W components in the composite.The $p\text{-}BiOBr/n\text{-}ZnWO_4$ heterojunction showed that it could absorb more visible light and had a lower photoluminescence intensity, which meant that it was better at separating charges. $p\text{-}BiOBr/n\text{-}ZnWO_4$-2.5% was the most active combination, breaking down 99.4% of RhB in 25 minutes and 58.2% of CIP in 170 minutes. The better performance was due to its larger surface area (SBET = 13 $m^2\ g^{-1}$), the right pore sizes, and the fact that charge could move between the two surfaces easily. Scavenger studies indicated that •OH and $•O_2^-$ radicals were the most reactive oxygen species involved in the degradation process.

Jeyaprakash et al. investigated the sonophotocatalytic degradation of tetracycline (TC) using a $Cu\text{-}BTC/ZnWO_4$ S-scheme heterojunction fabricated via an ultrasound-assisted hydrothermal method. The combination of Cu-BTC MOF with $ZnWO_4$ significantly enhanced catalytic performance, achieving complete tetracycline removal within 60 minutes under simultaneous visible light and ultrasonic irradiation.

The $Cu\text{-}BTC/ZnWO_4$ heterojunction exhibited superior sonophotocatalytic effectiveness compared to individual photocatalytic or sonocatalytic techniques, achieving a synergy index of roughly 0.70. The heightened activity was attributed to the formation of an S-scheme heterojunction, which facilitated effective charge separation through intrinsic electric fields and band bending. Electrons in Cu-BTC and holes in $ZnWO_4$ participated in redox processes, generating reactive radicals that promoted TC breakdown. This study highlights the effectiveness of MOF-based S-scheme systems in eliminating persistent pollutants.

7. Conclusion

Nanocomposites are a new type of multifunctional material that have better physicochemical properties because of nanoscale dispersion and strong interactions between the matrix and filler. Their larger surface area, stronger mechanical strength, better thermal stability, higher charge transfer efficiency, and better catalytic activity make a lot of development possible in environmental and biological applications. Their ability to break down photocatalytic dyes, get rid of pharmaceutical pollutants using advanced oxidation processes, and kill germs by controlling the generation of reactive oxygen species shows how versatile they are. Despite improvements in synthesis methods and building design, problems with scalability, cost-effectiveness, environmental safety, and long-term production remain. To use nanocomposite technology in large-scale, practical ways, we need to find new, sustainable ways to make things and improve structural design that get around these limits.

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