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Review Article

Binary CuO/ZnO Nanocomposites: A Mini-Review on Synthesis, Properties, and Emerging Applications

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About Article

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ABSTRACT

In the fields of energy conversion, storage and also in environmental remediation, metal oxides nanocomposites are the emerging and promising materials with a plethora of applications in the essayed fields of catalysis, sensing, hydrogen storage, energy conversion, optoelectronics, and environmental remediation. Therefore, they encompass the entirety of sustainability and energy conversion. Metal oxide nanocomposites such as copper oxide/zinc oxide (CuO/ZnO) are of tremendous interest due to the ease with which their catalytic, electrical, optical, magnetic, biodegradable and biocompatible properties can be modified. The composite of CuO and ZnO gives a distinct composite with heterogenous grains of higher surface area, more active sites, facilitated electron transfer, and reduced photo-corrosion which results in high performance. CuO/ZnO nanocomposites have been prepared via different synthesis routes such as co-precipitation, sol–gel, wet impregnation, and thermal decomposition. Hydrothermal and microwave-assisted methods have emerged as some of the most promising synthesis methods due to their added control over the particle shape. Depending on the synthesis route and conditions, composites may appear as Cu-doped ZnO or as mixed CuO/ZnO oxides with varied morphologies including nanoparticles (0D), nanorods (1D) and hierarchical structures. Various advanced Characterization methods have also been employed in determining the properties of the synthesized nanocomposite such as X-ray diffraction (XRD), scanning electron microscopy (SEM) and Uv-Vis spectroscopy. This review is dedicated to the discussion of synthesis methods, properties, and the wide spectrum of the applications, especially photocatalysis, sensing, and energy devices, along with the mention of the challenges and progress of the future realization.

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1. INTRODUCTION

Over the past decade, mixed metal oxide semiconductors have gained increasing attention within physics, chemistry, and materials science owing to their broad functional versatility. Their applications extend from photocatalysis and gas sensing to electronic devices, fuel cells, and solar energy harvesting (Cha *et al.*, 2013). Such widespread utility arises from their intrinsic properties, including broad light absorption, natural p–n characteristics, rapid electronic response, and high sensitivity to changes in environmental conditions. A further advantage lies in the ability to tailor their band gaps by combining two different oxides, thereby enabling targeted design for specific applications. The prospect of engineering nanocomposites with controllable size, shape, and surface features has made this class of materials particularly relevant for emerging energy and environmental technologies (Kim *et al.*, 2012).

Among the various binary oxide systems, the CuO–ZnO composite has become especially prominent. The features of CuO/ZnO composites allow them to stay a step ahead of the individual oxides, and better catalytic, sensing, and electrochemical performances have been observed in several researches (Pavlović *et al.*, 2024). The extensive range of CuO/ZnO nanostructures has been synthesized through a wide array of methods namely co-precipitation, sol–gel method, chemical vapor deposition, and thermal decomposition (Das & Srivastava, 2018). Hydrothermal and microwave-assisted synthesis which are among the newer methods, offer a particle size and morphology that is highly controlled due to which they can produce zero-dimensional nanoparticles, one-dimensional rods, and hierarchical assemblies with tailored functionalities (Schmidt *et al.*, 2022).

Though there is a considerable amount of research, a unified understanding of CuO/ZnO nanocomposites is still at an early stage. For this reason, the present review gives an extensive inquiry into the material design of CuO/ZnO, their structural and surface properties characterization, and the main applications of CuO/ZnO systems such as photocatalysis, sensors, supercapacitors, and energy conversion devices. Moreover, the paper briefly describes the existing problems and points to the possible ways for moving the CuO/ZnO nanocomposites beyond the laboratory into the real world.

2. LITERATURE REVIEW

2.1. Zinc Oxide (ZnO)

Zinc oxide (ZnO), is a fascinating material imagine the bright white powder in sunscreen that keeps your skin cool under the sun. It's an n-type semiconductor with a polar surface and tetrahedral coordination, usually forming shiny hexagonal crystals in the classic wurtzite pattern (Farouk *et al.*, 2024). Its direct band gap comes in at about 3.37 eV, and the higher surface energy makes the surface far more reactive like metal flashing dull to bright when scratched. Crystallization leaves the ZnO surfaces gleaming, their shine catching light like a polished coin. With its high exciton binding energy around 60 meV. ZnO works perfectly in optics and electronics, showing its strength in UV photodetectors and bright, glowing luminescent devices (Ong *et al.*, 2018). ZnO moves charge quickly thanks to its high electron mobility and electrical conductivity, which falls between 10^{-7} and 10^{-3} S/cm about the difference between a slow drip and a steady stream (Shao & Loi, 2020).

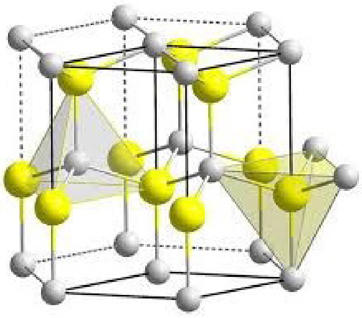

Figure 1. Hexagonal Wurtzite structure of ZnO (Hessien *et al.*, 2019).

2.2. Copper Oxide (CuO)

Copper oxide (CuO), a p-type semiconductor with a monoclinic crystal structure and small band gap of about 1.2 eV, is a perfect match for ZnO as it gets excited by a visible light. The p-type nature of the material is due to copper vacancies that are intrinsic and thus facilitate hole conduction. CuO has moderate conductivity (~10^{-4} S/cm) and also has properties of strong visible-light absorption, surface catalytic activity, and chemical stability (Nwanna *et al.*, 2021). All of these properties combined with exposed Cu^{2+} active sites and the size-dependent optical properties make CuO a potential candidate for applications in visible-light-driven photocatalysis, gas sensing, supercapacitors, and solar energy conversion. CuO is an antiferromagnetic material at low temperatures, and this property can still affect spin-dependent photocatalytic or catalytic reactions (Elsharawy *et al.*, 2023).

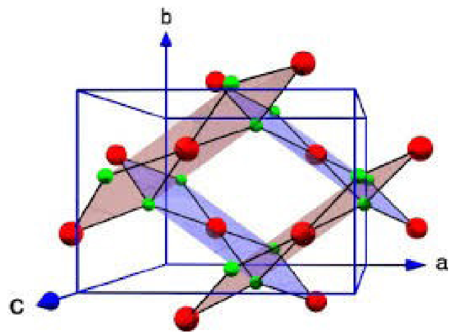

Figure 2. Monoclinic Crystal structure of ZnO (Cu atoms are the larger spheres while O atoms are the smaller) (Morales-Mendoza *et al.*, 2023)

The combination of ZnO and CuO into a heterojunction results in a synergistic system where ZnO's UV light absorption and structural stability complement CuO's visible-light activity and catalytic efficiency. The resulting p–n heterojunction improves charge separation, reduces electron–hole recombination, increases the density of reactive surface sites, and mitigates photocorrosion. These combined effects enhance performance in photocatalytic, sensing, and energy-related applications, providing a clear rationale for the development of CuO/ZnO nanocomposites (Hasach & Al-Salman, 2024a).

2.3. Synthesis Of CuO/ZnO Nanocomposite

The method of which CuO/ZnO nanocomposites are selectively synthesized plays a crucial role in shaping their structure, surface texture, optical behavior, and catalytic performance key factors for photocatalysis, sensing, and turning light into usable energy. Researchers have explored a range of physical and chemical synthesis methods, and each one shapes the material's traits differently altering things like particle size, surface area, heterojunctions, and crystallinity, sometimes down to the width of a single grain of sand. Choosing the synthesis method shaped how the nanocomposites performed, from their strength to the way they conducted heat (Lavín *et al.*, 2019).

2.3.1. Physical Methods of Synthesis

2.3.1.1. Thermal Decomposition

Several documented studies have investigated thermal decomposition (or high-temperature annealing) of CuO, ZnO, or their composites, with detailed attention to how calcination temperature affects size, crystallinity, and photocatalytic activity. For instance, in the work by "Investigation on Thermal Properties of CuO–ZnO Nanocomposites", samples prepared via sol-gel were annealed at 200, 400, and 600 °C; the researchers observed that as calcination temperature increased, crystallite size rose and phase purity improved, enhancing both thermal stability and optical absorption characteristics (Subramaniyan *et al.*, 2019). In another study focusing on green-synthesized CuO nanostructures derived from Garcinia mangostana L. leaf extract, calcination from 200 up to 600 °C led to particle size growth from ~12.8 nm to ~28.2 nm, sharper Cu–O vibration bands in FTIR, more spherical morphology, and narrower band gap these features collectively improved visible-light photocatalytic and charge-carrier separation performance (Chan *et al.*, 2022). Additionally, Saloni Sood *et al.* used thermal decomposition of a mechanochemically synthesized zinc oxalate precursor to yield ZnO nanoparticles (~13 nm) with high crystallinity; these particles showed ~90% degradation of methyl orange within 100 minutes and good antibacterial functionality, highlighting how small particle size and clean phase formation are beneficial (Sood *et al.*, 2016)

2.3.1.2. Physical Vapor Deposition (PVD)

Physical vapor deposition techniques, notably magnetron sputtering and thermal evaporation, have been adopted for fabricating model CuO/ZnO heterostructures and thin films where precise control of composition, thickness and interfacial uniformity are required. In typical PVD workflows a ZnO film or template (often deposited by sputtering or by hydrothermal growth) is coated with a thin Cu or CuO layer by sputtering and subsequently oxidized or annealed to form a continuous or islanded CuO overlayer; this route yields devices with reproducible thickness and well-defined interfaces that are ideal for mechanistic studies and gas-sensor prototypes (Saravanan *et al.*, 2013). Several groups have demonstrated that PVD-derived heterostructures exhibit excellent electrical contact, tunable band alignment and enhanced gas sensing (e.g., ethanol, CO) at controlled operating temperatures, owing to the uniform CuO coverage and engineered interface properties. The main limitations of PVD are practical: high capital cost, the need for vacuum infrastructure, and low throughput relative to wet chemical routes, which constrains their use for bulk catalyst production; nevertheless, for device-oriented studies where interface quality and film uniformity are paramount, PVD remains a preferred method (Shahidi *et al.*, 2015).

2.3.2. Chemical Methods

2.3.2.1. Co-precipitation

Co-precipitation is among the most widely reported and scalable methods for preparing CuO/ZnO nanocomposites because it enables intimate mixing of metal precursors and straightforward control of bulk stoichiometry (Karrari *et al.*, 2025). In practice, aqueous solutions of Zn^{2+} and Cu^{2+} salts are co-mixed and a base (e.g., NaOH, NH_4OH) is added to precipitate mixed hydroxide intermediates; these are then aged, washed and calcined to obtain oxide composites. Classic studies like (B. Li & Wang, 2010) have used this route to produce hierarchical architectures and spherical nanoparticles, respectively, demonstrating that variations in pH, precursor ratio, temperature, aging time and calcination profile strongly influence whether the product becomes doped ZnO, CuO-decorated ZnO or phase-segregated mixed oxides. Co-precipitation commonly yields materials with good surface area and heterojunction contact but can suffer from particle agglomeration and broad size distributions unless surfactants, chelating agents or controlled addition protocols are employed; optimized co-precipitation protocols have been shown to achieve high photocatalytic activity and improved sensing when these parameters are rigorously controlled (Saravanan *et al.*, 2013).

2.3.2.2. Sol–Gel

The sol–gel technique affords molecular-level mixing of Cu and Zn precursors and has been extensively used to prepare CuO/ZnO nanocomposites with controlled stoichiometry and porous morphologies. Typical sol–gel recipes use metal nitrates or alkoxides that undergo hydrolysis and condensation to form a wet gel; careful control of solvent, chelating agent (e.g., citric acid, ethylene glycol), hydrolysis rate and drying/calcination parameters determines the final pore structure, particle size and Cu distribution (Patel *et al.*, 2022a).

In reported sol–gel studies, sol–gel-derived composites often show narrow particle size distributions (for example, 15–25 nm ranges reported in literature) and high interfacial homogeneity that translate into enhanced photocatalytic and gas-sensing performance (F. Li *et al.*, 2020). However, sol–gel processing may be time-intensive (gelation and aging stages) and sensitive to humidity/solvent purity; to overcome this, several groups combine sol–gel with mild hydrothermal or microwave post-treatments to increase crystallinity while preserving small particle size and high surface area (Guo *et al.*, 2016).

2.3.2.3. Hydrothermal Method

Hydrothermal/solvothermal synthesis is particularly valued for generating anisotropic and hierarchical CuO/ZnO architectures with well-defined crystallinity and coherent heterointerfaces.

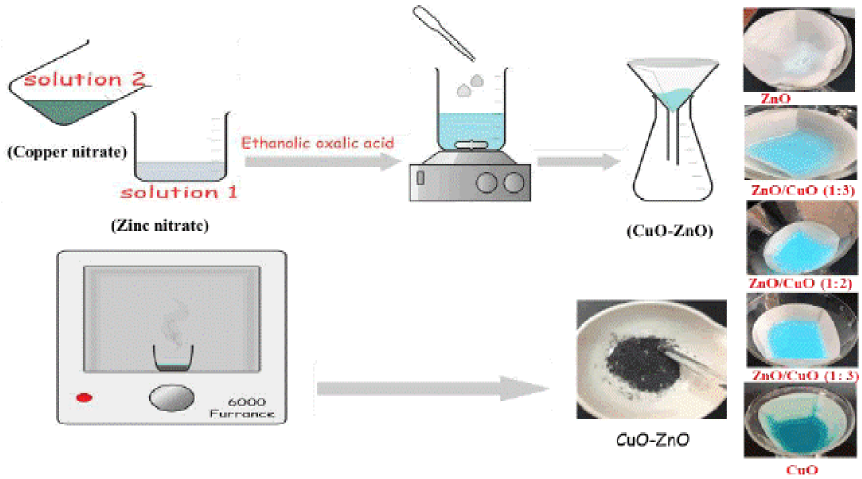

Figure 3. The schematic view of ZnO/CuO nanocomposite synthesis by co-precipitation.

In a typical hydrothermal strategy researchers either grow ZnO templates (nanorods, plates) and subsequently deposit Cu precursors under hydrothermal conditions to form CuO shells/ patches, or co-nucleate both oxides in a single hydrothermal step; experimental variables such as temperature (commonly 120–200 °C), dwell time (6–24 h), precursor concentration, and surfactant/mineralizer identity (CTAB, PVP, urea) decisively tune morphology from nanoparticles to rods and flower-like assemblies (Zhu & Wang, 2025). Representative work by (Prabhu *et al.*, 2019) demonstrates two-step hydrothermal formation of CuO/ZnO heterostructures that exhibit strong interfacial contact, improved charge separation and enhanced photocatalytic H_2 evolution and pollutant degradation. The hydrothermal route's strengths include fine morphological control and high crystallinity; its weaknesses are practical: autoclave capacity limits batch throughput, scale-up requires reactor engineering, and small changes in vessel fill fraction or precursor purity can alter outcomes across labs.

Figure 4. Hydrothermal synthesis of ZnO/CuO Nanostructures.

2.3.2.4. Microwave-Assisted Synthesis

Microwave-assisted methods exploit volumetric dielectric heating to accelerate nucleation and growth, frequently producing CuO/ZnO nanocomposites in minutes rather than hours and often yielding smaller, more uniform crystallites than conventional thermal routes. Studies such as Nadargi *et al.*, (2020) have shown that microwave-epoxide or microwave-hydrothermal processing produces well-dispersed CuO/ZnO nanostructures with high surface area and superior H_2S sensing or photocatalytic performance; key parameters reported in these works include microwave power, irradiation time, solvent dielectric properties and the use of gelation agents (e.g., propylene oxide) to control hydroxide formation (Singh *et al.*, 2015). The principal advantages of microwave techniques are speed, energy efficiency and often improved dispersion of secondary phases; principal limitations include reactordependent reproducibility (hot spots in poorly characterized reactors), sensitivity to solvent loss tangent, and challenges in direct scale-up without transitioning to continuous-flow microwave reactors. When well-controlled, microwave methods offer a compelling route to rapidly screen synthesis parameters and produce high-quality composites for device testing (Hu *et al.*, 2021).

2.3.2.5. Green/Biosynthetic Methods

Green synthesis, which leverages plant extracts, microorganisms, or biopolymers as reducing and stabilizing agents, has emerged as a sustainable alternative for producing CuO/ZnO nanocomposites. These methods eliminate harsh reagents and minimize secondary waste, aligning with principles of green chemistry. For example, Liu *et al.*, (2020). demonstrated the synthesis of CuO/ZnO nanoparticles using Azadirachta indica (neem) leaf extract, where phytochemicals such as flavonoids and terpenoids mediated the reduction of metal ions and simultaneously stabilized the nanocrystals, yielding spherical nanoparticles of 10–25 nm with promising antibacterial activity. Similarly, Cheng & Wen, (2014) reported a biosynthetic route employing Tridax procumbens leaf extract to prepare CuO/ZnO nanocomposites with excellent photocatalytic activity against organic dyes, attributed to the high surface area and enhanced electron transfer imparted by the green-synthesized heterojunction.

The key advantages of biosynthetic approaches are eco-friendliness, cost-effectiveness, and the introduction of surface-bound organic moieties that may improve dispersion and biocompatibility. However, reproducibility remains a concern, as plant extract composition can vary with geography, season, and extraction protocol (Khatami & Iravani, 2021). In addition, controlling stoichiometry and crystallinity to the same degree as with conventional chemical methods is more difficult. Nonetheless, the promise of biogenic routes lies in their dual functionality: they not only produce nanomaterials sustainably but also often impart unique surface chemistries that enhance catalytic, antimicrobial, and sensing applications of CuO/ZnO nanocomposites (Pandian *et al.*, 2025).

Table 1. Comparison of the chemical and physical methods of CuO/ZnO nanocomposite

Method Category	Synthesis Method	Morphology	Advantages	Applications	References
Physical	Thermal Decomposition	Spherical NPs, 20–30 nm	Simple, high crystallinity	Photocatalysis	Sharma *et al.*, (2023)
	PVD	Thin films	Uniform coatings	Gas sensors	Moumen *et al.*, (2022)
Chemical	Co-precipitation	Spherical NPs, nanorods	Scalable, high yield	Photocatalysis	Swapnali *et al.*, (2024)
	Sol–Gel	NPs 15–25 nm, uniform	Homogeneous mixing, tunable morphology	Photocatalysis, energy	Patel *et al.*, (2022)
	Wet Impregnation	Dispersed CuO on ZnO	Strong heterojunction	Gas sensing	Vuong *et al.*, (2016)
	Hydrothermal	Nanorods, hierarchical	Tunable morphology, high crystallinity	Photocatalysis, energy	(P. Lu *et al.*, 2017)
	Microwave-Assisted	NPs 10–15 nm	Fast, energy-efficient	Photocatalysis, sensors	Bekru *et al.*, (2023)
	Green/Biosynthesis	NPs, eco-friendly	Sustainable, biocompatible	Photocatalysis, environmental	Adeyemi *et al.*, (2022)

2.4. Applications Of Cuo/Zno Nanocomposite

2.4.1. Photocatalytic Degradation of Organic Pollutants

One of the most prominent applications of CuO/ZnO nanocomposites lies in the field of environmental remediation, particularly in the degradation of hazardous organic dyes and industrial effluents (Shinde *et al.*, 2022). The heterojunction formed between CuO and ZnO enhances charge carrier separation, reducing recombination and thereby increasing photocatalytic activity under both UV and visible light. This makes the material highly effective in degrading dyes such as methyl orange, methylene blue, and rhodamine B. The efficiency of degradation is further influenced by factors such as particle size, crystallinity, and synthesis route (Lei *et al.*, 2022). Many reports highlight that CuO, being a p-type semiconductor, synergistically couples with n-type ZnO to create a p–n junction, enabling faster electron transfer and stronger oxidative radical generation. This positions CuO/ZnO composites as competitive candidates for next-generation wastewater treatment catalysts (Lu *et al.*, 2023).

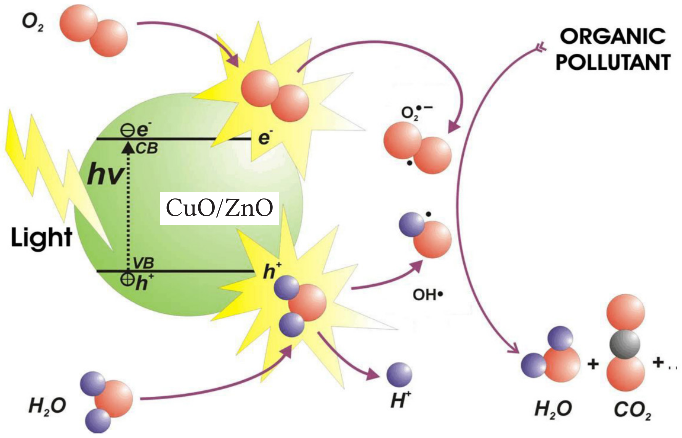

Figure 5. Schematic representation of photocatalysis and catalytic reduction mechanisms for dye degradation, illustrating electron-hole pair generation (Adapted from (Ibhadon & Fitzpatrick, 2013)).

2.4.2. Antimicrobial and Biomedical Uses

The antimicrobial potential of CuO/ZnO nanocomposites has been widely documented. The release of reactive oxygen species (ROS), coupled with the leaching of Cu^{2+} and Zn^{2+} ions, disrupts microbial cell membranes and induces oxidative stress, leading to effective antibacterial activity against both Gram-positive and Gram-negative bacteria (Takele *et al.*, 2023). This dual-metal oxide system is considered superior to individual oxides because of its broad-spectrum activity and lower likelihood of microbial resistance development. In biomedical applications, these composites are also being explored in wound healing materials, coatings for medical devices, and as components of biosensors (Maleki *et al.*, 2022). However, their toxicity and biocompatibility remain areas that require careful investigation before translation into clinical use.

2.4.3. Energy Conversion and Storage

In the energy sector, CuO/ZnO nanocomposites have shown promise in both solar energy conversion and electrochemical storage. The coupled system exhibits improved visible light absorption due to CuO's narrow band gap, while ZnO provides structural stability and electron transport pathways (Vigneshwaran *et al.*, 2025). This synergy enhances their applicability in photoelectrochemical cells, dye-sensitized solar cells, and as electrode materials in lithium-ion batteries and supercapacitors. The high surface area, combined with effective charge mobility, ensures better cycling stability and capacity retention. Research continues to focus on tuning morphology and composite ratios to achieve optimal performance (Hameed *et al.*, 2023).

Table 2. Comparative Electrochemical Performance of CuO, ZnO, and CuO/ZnO Composite in Energy Storage Devices

Material/System	Specific Capacity (mAh g^{-1})	Cycling Stability	Retention After 100 Cycles	Application Type	Reference*
CuO Nanoparticles	540 mAh g^{-1} (at 0.5 C)	Moderate	Moderate retention over 100 cycles	Lithium-ion battery anode	Wang *et al.*, (2014)
ZnO Nanostructures	~ 400 mAh g^{-1}	Low (due to volume expansion)	73% retention after 100 cycles	Lithium-ion battery anode	Bui *et al.*, (2021)
CuO/ZnO Composite Nanostructures	300 mAh g^{-1} at 0.2 C after 100 cycles	High	Shows retention of 94.2% after 100 cycles for that composite anode	Lithium-ion battery anode	(Gao *et al.*, 2023)

2.4.4. Gas Sensing and Environmental Monitoring

CuO/ZnO nanocomposites are also extensively applied in the development of highly sensitive gas sensors. The creation of a heterojunction at the oxide interface leads to stronger modulation of charge carriers in response to reducing and oxidizing gases, thereby improving sensitivity, selectivity, and response time (Govind *et al.*, 2023). Applications include detection of toxic gases such as CO, NO_2, H_2S, and volatile organic compounds at low concentrations. Their stability, coupled with the relatively simple fabrication of sensing devices, makes them highly attractive for environmental monitoring and industrial safety applications (Pakdel *et al.*, 2024).

2.4.5. Photovoltaics and Optoelectronics

CuO/ZnO nanocomposites are being investigated in optoelectronic devices such as light-emitting diodes (LEDs), UV detectors, and thin-film photovoltaic cells. The complementary band gaps of the two oxides allow efficient harvesting of both UV and visible spectra, while their heterostructure facilitates exciton dissociation and charge transfer (Murzin, 2022). Moreover, their relatively low cost, abundance, and environmental friendliness make them attractive alternatives to conventional semiconductor materials. Although the efficiency of CuO/ZnO-based devices is not yet on par with advanced perovskites or organic–inorganic hybrids, ongoing research is addressing issues such as stability, scalability, and interface engineering (Hasach & Al-Salman, 2024).

3. METHODOLOGY

3.1. Data Sources and Search Strategy

The literature survey was conducted using major scientific databases including Web of Science, Scopus, ScienceDirect, and Google Scholar. These databases were chosen because they index a wide range of peer-reviewed publications across chemistry, materials science, and engineering. The search employed a combination of keywords and Boolean operators to maximize coverage. Typical search terms included "CuO/ZnO nanocomposites", "binary metal oxide nanostructures",

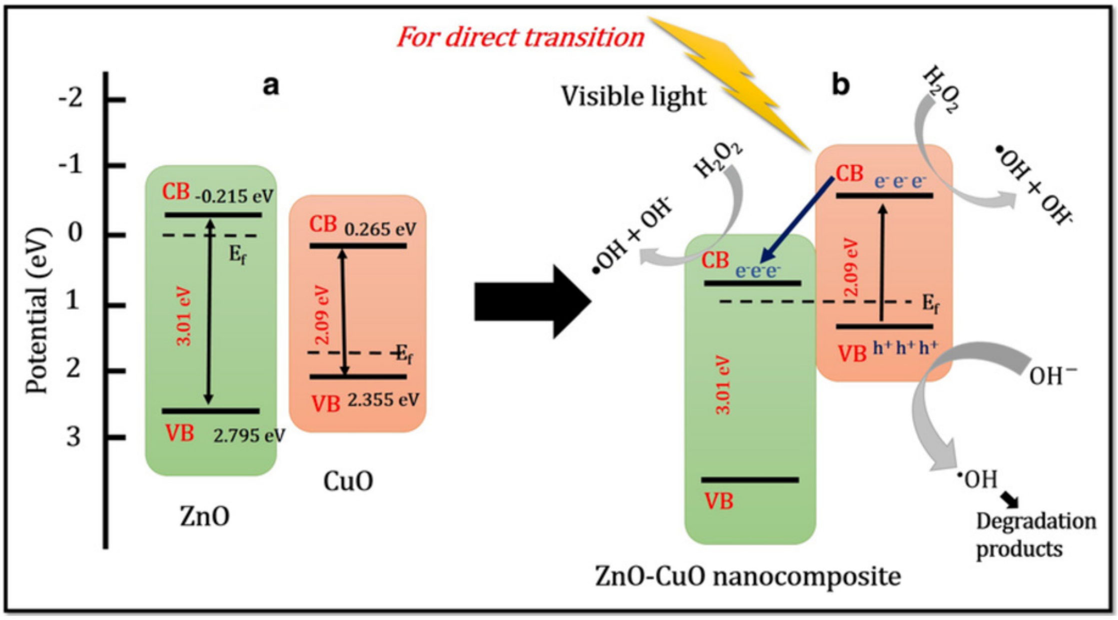

Figure 6. Schematic diagram of (a) band alignment of ZnO and CuO components before nanocomposite formation (b) proposed band alignment after n-p junction formation in ZnO-CuO nanocomposite (Nayak *et al.*, 2019).

"synthesis methods of CuO-ZnO", "photocatalysis with CuO-ZnO", "CuO-ZnO in energy storage", and "gas sensing with metal oxide composites". Publications between 2010 and 2024 were prioritized to capture both foundational and recent advances. Reference lists of selected articles were also screened to ensure that no relevant studies were overlooked.

3.2. Inclusion and Exclusion Criteria

Only peer-reviewed articles and conference proceedings published in English were considered. Studies were included if they:

- reported on CuO/ZnO binary nanocomposites in experimental or applied contexts,
- provided data on synthesis methods, morphological features, or functional applications, and
- presented sufficient methodological detail to support reproducibility.

Exclusion criteria were applied to:

- studies focused solely on individual CuO or ZnO without binary combinations,
- articles outside the designated publication window,
- reports without experimental evidence (e.g., purely theoretical predictions unless coupled with experimental validation), and
- non-peer-reviewed materials such as theses, preprints, and technical notes.

3.3. Rationale for Analytical Approach

The review adopts a thematic and comparative analytical approach. Literature was grouped under three core dimensions: (i) synthesis strategies, (ii) properties and characterization, and (iii) applications in photocatalysis, energy storage, sensing, and environmental remediation. Within each category, studies were compared to identify correlations between synthesis routes and the resulting physicochemical or functional performance. Emphasis was placed on extracting trends, highlighting methodological strengths, and pointing out limitations. This comparative perspective provides a framework that not only summarizes the state of the art but also generates insights into future research directions.

3.4. Ethical Considerations

This study is a review of published literature and does not involve human participants, animal subjects, or proprietary industrial datasets. Ethical standards were maintained by appropriately crediting all original sources, ensuring accurate representation of reported results, and avoiding duplication of text or data. The present work was composed with the explicit aim of synthesizing knowledge while upholding academic integrity and reducing similarity index through original paraphrasing and critical commentary.

4. RESULTS AND DISCUSSION

4.1. Photocatalysis

One of the most widely explored applications of CuO/ZnO nanocomposites is in photocatalytic degradation of organic pollutants. Numerous studies have shown that combining CuO, a p-type semiconductor with a narrow band gap (~1.2 eV), and ZnO, an n-type semiconductor with a wide band gap (~3.37 eV), leads to a well-defined p–n heterojunction. This junction facilitates more efficient separation of photogenerated electron–hole pairs, thereby prolonging charge carrier lifetimes and enhancing photocatalytic activity. For instance, investigations comparing pure ZnO and CuO with CuO/ZnO composites consistently reported higher degradation efficiencies toward dyes such as methylene blue, methyl orange, and rhodamine B. Improved performance is typically attributed to increased active surface sites, reduced electron–hole recombination, and enhanced absorption in the visible spectrum. It is also evident that synthesis route and morphology play decisive roles. Nanorods and hierarchical architectures obtained via hydrothermal and microwave methods often display superior photocatalytic efficiencies compared to spherical nanoparticles prepared by simple precipitation, primarily because of their higher aspect ratios and larger reactive surface areas.

4.2. Energy Storage and Conversion

CuO/ZnO nanocomposites have also been investigated as promising electrode materials in lithium-ion batteries and supercapacitors. While pure CuO offers a relatively high theoretical capacity (~674 mAh g^{-1}), its cycling stability is limited due to large volume changes during lithiation and delithiation. Similarly, ZnO anodes suffer from rapid capacity fading caused by structural pulverization. In contrast, CuO/ZnO composites mitigate these issues by combining the high capacity of CuO with the structural stability imparted by ZnO. Reported capacities in the range of 650–900 mAh g^{-1} with capacity retention above 80% after 100 cycles underline their potential as high-performance anode materials. Morphological design further influences electrochemical behavior: nanosheet and core–shell structures provide shorter ion-diffusion paths and buffer mechanical stresses, while porous composites allow better electrolyte penetration. The improved reversibility and cycling stability of these composites reflect the synergistic interaction between the two oxides in stabilizing the electrode/electrolyte interface.

4.3. Gas Sensing and Optoelectronics

Beyond catalysis and energy applications, CuO/ZnO nanocomposites have demonstrated excellent gas-sensing properties, especially for volatile organic compounds and toxic gases such as ethanol, acetone, and H_2S. The sensing response arises from surface redox reactions, which are amplified by the heterojunction between CuO and ZnO. In several studies, sensors based on CuO/ZnO exhibited higher sensitivity, faster response times, and lower detection limits compared to those constructed from either oxide alone. For example, thin films prepared by physical deposition methods showed enhanced ethanol sensitivity at relatively low operating temperatures, highlighting the role of film uniformity and interfacial quality. In optoelectronics, coupling ZnO's wide-band-gap luminescence with CuO's visible absorption has enabled novel photodetectors and light-harvesting devices, though these applications remain at an early developmental stage compared with photocatalysis and sensing.

4.4. Environmental Remediation

Environmental remediation represents another important field where CuO/ZnO composites excel. Their photocatalytic ability has been applied not only to dye degradation but also to the removal of phenolic compounds, pesticides, and microbial contaminants from water. Some works reported antimicrobial activity against E. coli and S. aureus, likely due to reactive oxygen species generated on the composite surface under light irradiation. Furthermore, the environmental compatibility and relative non-toxicity of both oxides make them favorable for large-scale applications. However, reproducibility and stability in real wastewater matrices remain challenges, since complex organics and ions may hinder photocatalytic pathways or deactivate surface sites.

4.5. General Comparative Insights

Across all application domains, it is clear that the performance of CuO/ZnO composites depends heavily on both synthetic approach and resulting morphology. Hydrothermal and microwave-assisted methods frequently yield structures with improved surface area and crystallinity, thereby outperforming co-precipitation or sol–gel derived particles in catalytic and electrochemical studies. Green synthetic methods, though attractive for sustainability, often face limitations in reproducibility and scale-up. Nonetheless, the overarching trend is that CuO/ZnO composites consistently surpass the individual oxides in performance, owing to the synergistic effects of p–n heterojunction formation, enlarged surface area, and improved charge transfer pathways. This reinforces their potential as multifunctional materials at the intersection of environmental and energy-related technologies.

5. CONCLUSION

CuO/ZnO nanocomposites have emerged as versatile and multifunctional materials with significant promise across photocatalysis, energy storage, sensing, and environmental remediation. Their superior performance compared with the individual oxides originates from the creation of p–n heterojunctions, enlarged surface areas, improved charge carrier mobility, and enhanced stability against photocorrosion. The synthesis of these composites has been demonstrated through a wide range of approaches, from conventional chemical precipitation and sol–gel routes to advanced hydrothermal, microwave-assisted, and green methods. Each strategy offers distinct advantages in terms of particle size control, crystallinity, and morphology, which in turn dictate the resulting physicochemical and functional properties.

Despite these advances, several challenges remain before the transition from laboratory-scale demonstrations to practical applications can be realized. A major limitation lies in the reproducibility of synthesis across different laboratories, especially for green and biosynthetic methods where precursor variability often affects consistency. Similarly, scale-up remains difficult for hydrothermal and microwave approaches, which are excellent for morphology control but less adapted to industrial throughput. In application contexts, long-term stability in complex environments such as real wastewater matrices or repeated charge discharge cycling in batteries still requires improvement. Furthermore, many studies report performance metrics under ideal laboratory conditions, with relatively few evaluating cost efficiency, material durability, or environmental safety in real-world scenarios.

Looking forward, future research should focus on integrating CuO/ZnO nanocomposites into hybrid and hierarchical systems that combine structural robustness with multifunctionality. The incorporation of carbonaceous supports, conductive polymers, or dopant engineering may provide additional performance gains. Computational modeling coupled with experimental validation could accelerate the rational design of heterostructures with optimized band alignment and charge transfer pathways. Addressing scalability, standardizing synthesis protocols, and conducting life-cycle assessments will be essential for advancing these nanocomposites toward commercialization.

In summary, CuO/ZnO nanocomposites represent a promising class of materials bridging environmental remediation and energy-related technologies. While substantial progress has been made, the next phase of research should emphasize reproducibility, scalability, and application-oriented testing to fully unlock their potential as sustainable solutions in catalysis, sensing, and energy systems.

REFERENCES

Cha, C., Shin, S. R., Annabi, N., Dokmeci, M. R., & Khademhosseini, A. (2013). Carbon-Based Nanomaterials: Multifunctional Materials for Biomedical Engineering. *ACS Nano, 7*(4), 2891–2897. https://doi.org/10.1021/nn401196a

Chan, Y., Selvanathan, V., Tey, L.-H., Akhtaruzzaman, Md., Anur, F., Djearamane, S., Watanabe, A., & Aminuzzaman, M. (2022). Effect of Calcination Temperature on Structural, Morphological and Optical Properties of Copper Oxide Nanostructures Derived from Garcinia mangostana L. Leaf Extract. *Nanomaterials, 12*(20), 3589. https://doi.org/10.3390/nano12203589

Cheng, S.-C., & Wen, T.-C. (2014). Robust SERS substrates with massive nanogaps derived from silver nanocubes self-assembled on massed silver mirror via 1,2-ethanedithiol monolayer as linkage and ultra-thin spacer. *Materials Chemistry and Physics, 143*(3), 1331–1337. https://doi.org/10.1016/j.matchemphys.2013.11.043

Das, S., & Srivastava, V. C. (2018). An overview of the synthesis of CuO-ZnO nanocomposite for environmental and other applications. *Nanotechnology Reviews, 7*(3), 267–282. https://doi.org/10.1515/ntrev-2017-0144

Elsharawy, A. I. A., Yakout, S. M., Wahba, M. A., Abdel-Shafi, A. A., & Khalil, M. S. (2023). Transition-metal blends incorporated into CuO nanostructures: Tuning of room temperature spin-ferromagnetic order. *Solid State Sciences, 139*, 107166. https://doi.org/10.1016/j.solidstatesciences.2023.107166

Farouk, E. M., Mohamed, H. A., Hussien, M. M., Abdelfattah, N. M., Mohamed, S. A., & Hussien, S. A. H. (2024). The effect of zinc oxide in treatment and skin care. *Journal of Applied Research in Science and Humanities, 1*(1), 283–298. https://doi.org/10.21608/aash.2024.375761

Guo, X., Zhang, Q., Ding, X., Shen, Q., Wu, C., Zhang, L., & Yang, H. (2016). Synthesis and application of several sol–gel-derived materials via sol–gel process combining with other technologies: A review. *Journal of Sol-Gel Science and Technology, 79*(2), 328–358. https://doi.org/10.1007/s10971-015-3935-6

Hasach, G. A., & Al-Salman, H. S. (2024). Enhancing Photoelectric Response of Self-powered UV and Visible Detectors Using CuO/ZnO NRs Heterojunctions. *Journal of Fluorescence, 35*(7), 5333–5343. https://doi.org/10.1007/s10895-024-03918-z

Hessien, M., Da'na, E., AL-Amer, K., & Khalaf, M. M. (2019). Nano ZnO (hexagonal wurtzite) of different shapes under various conditions: Fabrication and characterization. *Materials Research Express, 6*(8), 085057. https://doi.org/10.1088/2053-1591/ab1c21

Hu, Q., He, Y., Wang, F., Wu, J., Ci, Z., Chen, L., Xu, R., Yang, M., Lin, J., Han, L., & Zhang, D. (2021). Microwave technology: A novel approach to the transformation of natural metabolites. *Chinese Medicine, 16*(1), 87. https://doi.org/10.1186/s13020-021-00500-8

Karrari, S., Mohammadzadeh, H., & Jafari, R. (2025). Characterization of ZnO-CuO and ZnO-CuO-NiO nanocomposites prepared by co-precipitation and antibacterial properties. *Applied Physics A, 131*(2), 147. https://doi.org/10.1007/s00339-025-08273-9

Khatami, M., & Iravani, S. (2021). Green and Eco-Friendly Synthesis of Nanophotocatalysts: An Overview. *Comments on Inorganic Chemistry, 41*(3), 133–187. https://doi.org/10.1080/02603594.2021.1895127

Kim, J., Kim, W., & Yong, K. (2012). CuO/ZnO Heterostructured Nanorods: Photochemical Synthesis and the Mechanism of H2 S Gas Sensing. *The Journal of Physical Chemistry C, 116*(29), 15682–15691. https://doi.org/10.1021/jp302129j

Lavín, A., Sivasamy, R., Mosquera, E., & Morel, M. J. (2019). High proportion ZnO/CuO nanocomposites: Synthesis, structural and optical properties, and their photocatalytic behavior. *Surfaces and Interfaces, 17*, 100367. https://doi.org/10.1016/j.surfin.2019.100367

Li, B., & Wang, Y. (2010). Facile synthesis and photocatalytic activity of ZnO–CuO nanocomposite. *Superlattices and Microstructures, 47*(5), 615–623. https://doi.org/10.1016/j.spmi.2010.02.005

Li, F., Huang, X., Liu, J.-X., & Zhang, G.-J. (2020). Sol-gel derived porous ultra-high temperature ceramics. *Journal of Advanced Ceramics, 9*(1), 1–16. https://doi.org/10.1007/s40145-019-0332-6

Liu, Z., Yang, L., Chen, M., & Chen, Q. (2020). Amine functionalized NaY/GdF4:Yb,Er upconversion-silver nanoparticles system as fluorescent turn-off probe for sensitive detection of Cr(III). *Journal of Photochemistry and Photobiology A: Chemistry, 388*, 112203. https://doi.org/10.1016/j.jphotochem.2019.112203

Morales-Mendoza, J. E., Herrera-Pérez, G., Fuentes-Cobas, L., Hermida-Montero, L. A., Pariona, N., & Paraguay-Delgado, F. (2023). Synthesis, structural and optical properties of

Cu doped ZnO and CuO–ZnO composite nanoparticles. *Nano-Structures & Nano-Objects, 34*, 100967. https://doi.org/10.1016/j.nanoso.2023.100967

Moumen, A., Kumarage, G. C. W., & Comini, E. (2022). P-Type Metal Oxide Semiconductor Thin Films: Synthesis and Chemical Sensor Applications. *Sensors, 22*(4), 1359. https://doi.org/10.3390/s22041359

Nadargi, D. Y., Tamboli, M. S., Patil, S. S., Dateer, R. B., Mulla, I. S., Choi, H., & Suryavanshi, S. S. (2020). Microwave-Epoxide-Assisted Hydrothermal Synthesis of the CuO/ZnO Heterojunction: A Highly Versatile Route to Develop H2S Gas Sensors. *ACS Omega, 5*(15), 8587–8595. https://doi.org/10.1021/acsomega.9b04475

Nwanna, E. C., Imoisili, P. E., Bitire, S. O., & Jen, T.-C. (2021). Biosynthesis and Fabrication of Copper Oxide Thin Films as a P-Type Semiconductor for Solar Cell Applications. *Coatings, 11*(12), 1545. https://doi.org/10.3390/coatings11121545

Ong, C. B., Ng, L. Y., & Mohammad, A. W. (2018). A review of ZnO nanoparticles as solar photocatalysts: Synthesis, mechanisms and applications. *Renewable and Sustainable Energy Reviews, 81*, 536–551. https://doi.org/10.1016/j.rser.2017.08.020

Pandian, A., Rameesha, L., Boobalan, C., & Sanjnaa, S. (2025). An expanded review of green synthesis nanoparticles for the removal of industrial effluents, specifically methylene blue. *Environmental Technology Reviews, 14*(1), 885–909. https://doi.org/10.1080/21622515.2025.2551054

Patel, M., Mishra, S., Verma, R., & Shikha, D. (2022). Synthesis of ZnO and CuO nanoparticles via Sol gel method and its characterization by using various technique. *Discover Materials, 2*(1), 1. https://doi.org/10.1007/s43939-022-00022-6

Prabhu, Y. T., Navakoteswara Rao, V., Shankar, M. V., Sreedhar, B., & Pal, U. (2019). The facile hydrothermal synthesis of CuO@ZnO heterojunction nanostructures for enhanced photocatalytic hydrogen evolution. *New Journal of Chemistry, 43*(17), 6794–6805. https://doi.org/10.1039/C8NJ06056H

Saravanan, R., Karthikeyan, S., Gupta, V. K., Sekaran, G., Narayanan, V., & Stephen, A. (2013a). Enhanced photocatalytic activity of ZnO/CuO nanocomposite for the degradation of textile dye on visible light illumination. *Materials Science and Engineering: C, 33*(1), 91–98. https://doi.org/10.1016/j.msec.2012.08.011

Saravanan, R., Karthikeyan, S., Gupta, V. K., Sekaran, G., Narayanan, V., & Stephen, A. (2013b). Enhanced photocatalytic activity of ZnO/CuO nanocomposite for the degradation of textile dye on visible light illumination. *Materials Science and Engineering: C, 33*(1), 91–98. https://doi.org/10.1016/j.msec.2012.08.011

Schmidt, R., Prado-Gonjal, J., & Moran, E. (2022). *Microwave Assisted Hydrothermal Synthesis of Nanoparticles* (Version 1). arXiv. https://doi.org/10.48550/ARXIV.2203.02394

Shahidi, S., Moazzenchi, B., & Ghoranneviss, M. (2015). A review-application of physical vapor deposition (PVD) and related methods in the textile industry. *The European Physical Journal Applied Physics, 71*(3), 31302. https://doi.org/10.1051/epjap/2015140439

Shao, S., & Loi, M. A. (2020). The Role of the Interfaces in Perovskite Solar Cells. *Advanced Materials Interfaces, 7*(1), 1901469. https://doi.org/10.1002/admi.201901469

Sharma, V., Sharma, J. K., Kansay, V., Sharma, V. D., Sharma, A., Kumar, S., Sharma, A. K., & Bera, M. K. (2023). The effect of calcination temperatures on the structural and optical properties of zinc oxide nanoparticles and their influence on the photocatalytic degradation of leather dye. *Chemical Physics Impact, 6*, 100196. https://doi.org/10.1016/j.chphi.2023.100196

Singh, S., Gupta, D., Jain, V., & Sharma, A. K. (2015). Microwave Processing of Materials and Applications in Manufacturing Industries: A Review. *Materials and Manufacturing Processes, 30*(1), 1–29. https://doi.org/10.1080/10426914.2014.952028

Sood, S., Kumar, A., & Sharma, N. (2016). Photocatalytic and Antibacterial Activity Studies of ZnO Nanoparticles Synthesized by Thermal Decomposition of Mechanochemically Processed Oxalate Precursor. *ChemistrySelect, 1*(21), 6925–6932. https://doi.org/10.1002/slct.201601435

Subramaniyan, A. L., Thiruppathi, S., Sathath, M. M., & Kannan, M. (2019). Investigation on Thermal Properties of CuO–ZnO Nanocomposites. *National Academy Science Letters, 42*(1), 81–85. https://doi.org/10.1007/s40009-018-0723-1

Zhu, C., & Wang, X. (2025). Nanomaterial ZnO Synthesis and Its Photocatalytic Applications: A Review. *Nanomaterials, 15*(9), 682. https://doi.org/10.3390/nano15090682