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Biomedical and Human Health Applications of ZnO, CuO, and Cu2O Oxide Nanomaterials: A Literature Review

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ABSTRACT: Zinc oxide (ZnO), copper(II) oxide (CuO), and copper(I) oxide (Cu2O) are among the most extensively studied metal oxide semiconductor materials, with applications spanning electronics, sensing, and photovoltaics. Beyond these established technological domains, a substantial and rapidly growing body of literature has documented significant human health-related applications of these same oxide materials, spanning antimicrobial therapy, wound healing, drug delivery, cancer theranostics, and biosensing. This review synthesizes recent literature on the biomedical applications of ZnO, CuO, and Cu2O nanomaterials, with particular attention to the relationship between material synthesis approach, resulting structural and optical properties, such as band gap and crystallite morphology, and documented biological activity. The materials examined share fabrication and characterization methodologies, including magnetron and ion-plasma deposition, controlled oxygen partial pressure processing for phase selection, and structural characterization via X-ray diffraction and electron microscopy, with techniques applied in materials physics research on these oxides for electronic and sensor applications. The review addresses three principal health-related application domains: antimicrobial and wound-healing activity, attributed primarily to reactive oxygen species generation and metal ion release upon cellular internalization; drug delivery and cancer theranostic applications, exploiting the tunable band gap and photoluminescent properties of ZnO-based nanostructures; and biosensing applications leveraging the high electron mobility and biocompatibility of ZnO nanostructures. The reviewed literature indicates that the same structural and electronic properties that determine these materials' performance in conventional electronic and photovoltaic applications, namely controlled band gap, crystallite size, and defect density, are directly implicated in determining their biological activity and biomedical performance, suggesting substantial translational relevance between materials physics research on these oxides and their biomedical application development.

INTRODUCTION

Zinc oxide (ZnO), copper(II) oxide (CuO), and copper(I) oxide (Cu_2O) are wide- and moderate-band-gap metal oxide semiconductors that have been extensively investigated for applications in electronics, optoelectronics, and photovoltaic devices, with well-established fabrication routes including magnetron and ion-plasma sputtering, sol-gel synthesis, and hydrothermal growth, and with material properties, including phase composition, crystallite size, and band gap, systematically tunable through control of deposition parameters such as substrate temperature and oxygen partial pressure. Materials physics research on these oxides has extensively characterized their structural, optical, and electrical properties using techniques including X-ray diffraction, scanning electron microscopy, atomic force microscopy, and UV-visible spectroscopy, establishing detailed structure-property relationships relevant to electronic device performance.

In parallel with this materials physics research tradition, a substantial and independently developing body of literature has documented that the same ZnO, CuO, and Cu_2O oxide materials possess significant biological activity relevant to human health, including antimicrobial, wound-healing, drug-delivery, and biosensing applications. This review synthesizes recent literature, published predominantly between 2023 and 2026, on the biomedical applications of these oxide nanomaterials, with particular attention to how the structural and optical properties characterized in materials physics research, such as band gap, crystallite size, and defect density, relate to the documented biological activity underlying these health applications. The review addresses three principal application domains identified as recurring foci in this literature: antimicrobial and wound-healing activity; drug delivery and cancer theranostic applications; and biosensing applications.

ANTIMICROBIAL AND WOUND-HEALING APPLICATIONS

Antimicrobial resistance has emerged as a major driver of interest in metal oxide nanomaterials as alternative antibacterial agents, with chronic wound infections representing a particularly significant clinical burden given their increasing incidence in aging populations and their growing resistance to conventional antibiotic treatment. A comprehensive review of antimicrobial nano-zinc oxide biocomposites for wound-healing applications documented that ZnO nanostructures, when incorporated into wound dressing biomacromolecule composites, provide sustained antimicrobial activity while supporting the tissue regeneration processes required for effective wound closure, positioning nanostructured ZnO as a promising response to the dual clinical challenges of infection control and antimicrobial resistance in chronic wound management (Pino et al., 2023).

The antimicrobial mechanism underlying these applications has been documented to involve both direct metal ion toxicity and reactive oxygen species (ROS) generation: released Zn^{2+} and Cu^{2+} ions accumulate on negatively charged microbial cell membranes through electrostatic attraction, disrupting membrane integrity and permeability, while doping-induced lattice defects and oxygen vacancies, structural features directly characterized through the X-ray diffraction and electron microscopy techniques standard in materials physics research on these oxides, enhance ROS generation following cellular internalization, ultimately causing protein destruction and cell death in target microorganisms (Pino et al., 2023). A comprehensive review of CuO nanoparticle synthesis, biomedical applications, and toxicity similarly identified antibacterial, antioxidant, antiparasitic, antidiabetic, and antiviral activity among the documented biological properties of CuO nanoparticles, while emphasizing that the specific synthesis technique employed, whether physical, chemical, or biological, substantially determines the resulting physicochemical and biological properties and therefore the suitability of a given CuO nanoparticle preparation for a specific biomedical application (Naz et al., 2023).

ANTICANCER AND ANTIOXIDANT APPLICATIONS

Beyond antimicrobial activity, CuO nanoparticles have been increasingly investigated for anticancer applications, exploiting the same reactive-oxygen-species-generating mechanism responsible for their antimicrobial activity to induce cytotoxicity selectively in cancer cells. Biosynthesized CuO nanoparticles produced using Camellia sinensis (tea) plant extract as a green reducing agent were evaluated against human colon (HT-29) and breast (MCF-7) cancer cell lines, with flow cytometry and apoptosis assays indicating that the nanoparticles induced cell cycle arrest and apoptosis, with reactive oxygen species generation, caspase activation, and DNA damage identified as the principal mechanisms underlying the observed cytotoxicity, alongside moderate selectivity favoring cancer cells over normal cells (Letchumanan et al., 2025). The comprehensive review of CuO nanoparticle biomedical applications noted above further situates such anticancer findings within a broader documented profile of antioxidant activity for CuO nanoparticles, suggesting that the reactive oxygen species mechanism central to CuO's antimicrobial and anticancer efficacy must be carefully balanced against oxidative stress-related toxicity concerns relevant to healthy tissue exposure (Naz et al., 2023).

DRUG DELIVERY AND CANCER THERANOSTIC APPLICATIONS

Beyond antimicrobial applications, ZnO-based nanostructures, particularly in quantum dot form, have been extensively investigated for drug delivery and theranostic applications, combining therapeutic and diagnostic function within a single nanomaterial platform. A review of ZnO nanostructures for drug delivery and theranostic applications documented that ZnO semiconductor quantum dots possess favorable luminescent properties supporting bio-imaging applications, combined with low cost, low toxicity, and biocompatibility, alongside an ability to generate destructive reactive oxygen species, high catalytic efficiency, and strong adsorption capability, collectively positioning ZnO-based nanoplatforms as promising candidates for combined therapeutic and diagnostic function across diseases including bacterial infection and cancer (Martínez-Carmona et al., 2018).

More recent work has extended this drug-delivery application domain to copper-zinc mixed oxide systems specifically: a chitosan-anchored Cu2O/ZnO nanocomposite, synthesized via a green route using plant-derived reducing and stabilizing agents and structurally confirmed by X-ray diffraction to contain crystalline Cu2O and ZnO phases, was documented to achieve efficient cisplatin drug encapsulation with sustained, pH-responsive release, alongside concentration-dependent cytotoxicity against A375 melanoma cancer cells, illustrating synergistic drug-delivery, antineoplastic, and wound-repair functionality within a single biocompatible platform (Nayak et al., 2026). This finding illustrates that the Cu2O phase specifically, alongside the more extensively studied ZnO phase, contributes documented biomedical functionality relevant to cancer treatment applications beyond the antimicrobial and wound-healing domains discussed above. This body of research suggests that the phase-selective synthesis control achievable through parameters such as oxygen partial pressure, well established in materials physics research on ZnO, CuO, and Cu2O for electronic applications, may carry direct translational relevance for tuning the specific biomedical functionality, whether predominantly antimicrobial, drug-delivery, or theranostic, of these oxide nanomaterials for targeted health applications.

BIOSENSING APPLICATIONS

A further significant health-related application domain for these oxide nanomaterials concerns biosensing, leveraging their electronic and structural properties for the detection of biologically relevant molecules and analytes. A review of zinc oxide nanostructures in biosensor applications documented that ZnO's superior electron mobility enables effective electron transfer between a biological receptor and an electronic transducer, enhancing detection sensitivity and reducing detection limits relative to alternative sensing materials, while ZnO's biocompatibility and non-toxicity further support its suitability for in vivo biosensing applications by reducing the likelihood of adverse biological responses to the implanted or applied sensing material (Maafa, 2025). The same review documented that varied ZnO nanostructure morphologies, including nanorods, nanotubes, and nanowires, prepared via synthesis techniques such as sol-gel processing, sputtering, and chemical vapor deposition, have each been successfully employed in biosensor development, underscoring that the morphological control achievable through established ZnO synthesis routes carries direct relevance for biosensor performance optimization (Maafa, 2025).

This electron-transport-dependent sensing mechanism connects directly to the electrical characterization methodologies, including measurement of carrier concentration, electrical resistance, and frequency-dependent electrical response, that are standard in materials physics research on ZnO, CuO, and Cu2O thin films and heterostructures for conventional electronic and radiation-sensing applications, suggesting that structural and electrical characterization data generated in such materials physics research may carry direct relevance for anticipating and optimizing the performance of these same materials when adapted for biosensing applications in health diagnostic contexts.

Complementing oxide-based electronic biosensing approaches, piezoelectric quartz crystal substrates constitute a further well-established biosensor transduction platform in health diagnostics, most notably in the quartz crystal microbalance (QCM), which detects biomolecular binding events through minute mass-induced shifts in the crystal's resonant oscillation frequency. Research on the controlled growth of synthetic piezoelectric quartz, including the identification of optimal growth-solution and seed-crystal conditions for obtaining high structural quality quartz suitable for precision oscillator and sensor applications, remains directly relevant to the fabrication of such piezoelectric sensing platforms (Mustafakulov et al., 2025). Integration of oxide semiconductor thin films, including ZnO, CuO, and Cu2O, onto piezoelectric quartz substrates further offers a route toward hybrid biosensor architectures combining the mass-sensitive transduction of the quartz substrate with the electronic and biochemical surface functionality of the oxide semiconductor layer, an integration approach documented in materials physics research on oxide-quartz heterostructures for sensor applications more broadly.

DISCUSSION

The literature reviewed here indicates substantial convergence between the structural and electronic properties of ZnO, CuO, and Cu2O oxide materials that are the central object of study in materials physics research on these oxides for electronic and sensor applications, and the biological mechanisms underlying their documented antimicrobial, drug-delivery, and biosensing applications in the biomedical literature. In particular, the dependence of antimicrobial activity on lattice defects, oxygen vacancies, and dopant-induced band gap modification, structural features directly characterized through X-ray diffraction, electron microscopy, and optical spectroscopy in materials physics studies of these oxides, suggests that materials characterization data generated for electronic or sensor-oriented purposes may carry direct, currently underexploited relevance for anticipating and optimizing the biomedical performance of the same or closely related oxide formulations.

This convergence carries a specific implication for research at the intersection of materials physics and biomedical nanomaterials: synthesis parameters established for controlling phase selection and structural properties in electronic-application contexts, such as oxygen partial pressure control for selecting between Cu2O and CuO phases, may be directly transferable to, and indeed already implicitly exploited within, the synthesis protocols documented in the biomedical literature reviewed here, even where the two research traditions have developed with limited explicit cross-referencing to date. The observation that Cu2O specifically, rather than only the more extensively studied ZnO and CuO phases, has been documented to contribute distinct anticancer and drug-delivery functionality within composite nanomaterial systems further suggests that the phase-selective synthesis control central to materials physics research on these copper oxides carries direct relevance for the deliberate biomedical functionalization of copper-zinc oxide nanomaterial systems.

Limitations of the reviewed literature include the predominance of in vitro rather than in vivo or clinical evidence across the antimicrobial, drug-delivery, and biosensing application domains reviewed, meaning that translation of the documented laboratory-scale biological activity into validated clinical applications remains at a comparatively early stage; and the documented existence of dose-, exposure-time-, and nanoparticle-shape-dependent toxicity concerns associated with ZnO nanoparticles specifically, which underscore that the same reactive-oxygen-species-generating mechanism responsible for documented antimicrobial and anticancer efficacy also necessitates careful dose optimization and toxicological characterization prior to clinical translation.

CONCLUSION

This review of recent literature on the biomedical applications of ZnO, CuO, and Cu2O oxide nanomaterials indicates substantial and mechanistically grounded evidence for antimicrobial, wound-healing, drug-delivery, cancer theranostic, and biosensing applications of these materials, with the underlying biological activity closely tied to structural and electronic properties, including band gap, crystallite size, and defect density, that are also the central focus of materials physics research on these same oxides for conventional electronic and sensor applications. This convergence suggests considerable, currently underexploited translational potential between materials physics characterization approaches for ZnO, CuO, and Cu2O thin films and heterostructures and the deliberate biomedical functionalization of these materials, representing a promising direction for interdisciplinary research bridging materials physics and biomedical nanomaterials science.

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