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Physical, Chemical, and Industrial Properties of Copper Nanoparticles: A Review

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Abstract

Copper nanoparticles (CuNPs) have attracted attention as versatile nanomaterials because of their unique physical, chemical and therapeutic properties quite different to those of bulk copper. Copper at the nanoscale possesses improved surface reactivity, redox activity and tunable optical and electrical properties that enable various technological and biomedical applications. This review includes a comprehensive summary of the physical aspects of CuNPs: size- and shape-dependent properties, crystallinity, optical response and thermal/electrical conductivities. Furthermore, the chemical properties of CuNPs including oxidation property, surface chemistry, catalytic activity and mechanisms associated with ROS generation and ion release were also reviewed in detail. Special consideration is given to the therapeutic role of CuNPs, including their anti-microbial/anti-viral activities, wound-healing properties, anti-cancer effects and drug-release applications. Tendencies and challenges for toxicology, biocompatibility and translation are also explored. In general, this review describes the most recent progress in CuNP research and provides future directions for the development of safe and effective therapeutic systems using CuNPs.

Keywords: Physical, Chemical, Therapeutic Properties, Copper Nanoparticles

Introduction

Copper nanoparticles (CuNPs) have attracted immense interest in recent years because of their unique physical, chemical and biological properties, which are quite different from those of the bulk copper. As 'material system' example, it is well known that copper at the nanoscale possess higher surface to volume ratio and extrinsic properties such as shape/architecture controlled electronic structure can be tuned along with increased reactivity at surface level allowing for better performance in catalytic, optical and antimicrobial activity. These features make CuNPs as valuable candidates for various applications such as catalysis, energy conversion, environmental treatments and medical therapies (Woźniak-Budych et al., 2023).

Copper, as an antimicrobial agent, has been acknowledged since antiquity, with usage in ancient civilizations. This attribute of CuNPs has been much exacerbated with the advent of new nanotechnology, where the reduced size characteristics of CuNPs in their nanorange scale are naturally able to closely interact with surfaces and intracellular components of microorganisms (Khosravi et al., 2024). It suggested that CuNPs possess the broad-spectrum antimicrobial activity against Gram-positive and Gram-negative bacteria, fungi, and viruses. It has been suggested that the action is partly due to the disruption of membrane and formation reactive oxygen species (ROS), protein denaturation, and release of Cu^{2+} ions which would hamper bacterial metabolism (Pricop et al., 2025).

Chemically, copper nanoparticles are unique in their multiple oxidation states (Cu^0, Cu^+, and Cu^{2+}) leading to a number of redox reactions. Such chemical flexibility has rendered the CuNPs as efficient catalysts, suitable for chemical synthesis, environmental detoxification and energy related processes (e.g., CO_2 reduction and electrocatalysis). The physicochemical attributes of CuNPs, such as size, shape, crystallinity and surface chemistry can be precisely adjusted at the time of their synthesis that in turn enables modification of their activity towards specific applications (Aggarwal et al., 2025).

In biological field, the therapeutic properties of CuNPs have attracted much interest. Copper nanoparticles have been promising for different applications such as antimicrobial coating, wound healing application (as an antimicrobial and to promote growth or differentiation of the wound), anticancer therapeutic, and drug delivery system. Due to their ability to induce angiogenesis and collagen generation, the possibility of using MSCs for tissue regeneration as well as chronic wound care is promising (Sandoval et al., 2022). In addition, CuNPs have indicated preferential cytotoxicity against cancer cells due to oxidative stress and mitochondrial damage indicating their potential use for anticancer applications (Khosravi et al., 2024).

Nevertheless, challenges with respect to toxicity and biocompatibility persist. The cytotoxicity in health mammalian cells induced by these effects could be the same mechanisms that mediated the antibacterial and anticancer characteristic. It is reported that factors of CuNP toxicity include particle size, concentration, surface functionalization of the nanoparticles, exposure time and biological contexts. In this context, a growing number of recent researches highlights the optimal dose, surface functionalization and biocompatible synthesis strategies in order to minimize toxicity symptoms and at the same time ensure therapeutic effectiveness (Ramos-Zúñiga et al., 2023).

The synthe-sis route greatly influences the physical, and chemical properties of CuNPs. Classical chemical reduction processes are common owing to their cheap reaction conditions and feasible scale-up but involve often toxic reagents and produce frequently less stable nanoparticles (Pricop et al., 2025). Conversely, green and biogenic approaches - employing plant extracts, bacteria, fungi - have gained the limelight as green options. These strategies can not only decrease the environmental impact, but also improve particle stability and biocompatibility, being key aspects for any medical/nanotechnological application (El-Sayed et al., 2025).

Recent developments in copper nanotechnology have broadened the range of possible applications for CuNP. CuNPs embedded in nanocomposites, polymer matrices, and biomedical coatings created multi-functional materials having durable antimicrobial nature and the controllable release of ions. While antibiotic resistance and chronic infections remain global health problems, nanomaterials based on copper are a potentially complementary or alternative solution (Aggarwal et al., 2025).

This review deals with copper nanomaterials as an exciting new class of materials harboring combined physical-chemical-medical properties. Further cross-disciplinary research is necessary for a complete description of their behavior, to maximize their performance and safety. This review attempts to provide a complete summary of the progresses in the research on CuNPs, especially involved after 2015.and discuss their prospects and limitations in medical and therapeutic uses.

Physical Properties of Copper Nanoparticles

Copper nanoparticles (Cu NPs) possession a number of special physical properties due to small size and high surface atom ratio. The physical properties of copper at the nanoscale When copper is fabricated at the nanometer scale, its physical behaviour changes significantly with respect to bulk owing to quantum size effects, surface plasmon interactions and stronger surface energy1. These properties play a crucial role in the performance of CuNPs in various applications such as catalysis, electronics and sensing devices, biomedical systems (Woźniak-Budych et al., 2023).

The particle size is one of the most important physical parameters since it varies usually from 1 nm to 100 nm in copper nanoparticles. The larger surface-to-volume increases tremendously, and so does the reactivity at surfaces and electronic state. The melting point, the electrical and optical absorption properties of nanoparticles are also observed to be affected by the size reduction. It has been reported that the melting temperature of CuNPs is lower than its bulk counterpart, owing to the unstable surface atoms and a weakened interatomic bonding associated with nanoparticle size. This size-dependent behavior is of interest especially in the context of thermal processing, sintering and conductive ink use (Khosravi et al., 2024).

Particle shape is also an important physical parameter affecting the activity of CuNPs. Copper nanoparticles can be prepared in different shapes such as spherical, cubic, rod type and plat-type structures. Surface energy dispersion, crystallographic facets and interaction with surrounding media are influenced by morphology. For instance, spherical CuNPs are typically isotropic with respect to their physical properties; however, anisotropic shapes (e.g., nanorods and nanoplates) have directionally dependent optical and electrical properties. Thus, control on morphology of nanoparticles is crucial to improve the performance in optoelectronic and catalytic fields (Aggarwal et al., 2025).

The physical properties of copper nanoparticles are also depended upon the crystallographic structure. The majority of CuNPs adopt a fcc structure, which has also been observed in bulk copper but with increased lattice distortions and presence of defects at N scale. Such structural defects can impact mechanical strength, electron transport and thermal conductance. X-ray diffraction and electron microscopy analysis indicates that smaller CuNPs frequently experience lattice distortion leading to altered physical and electrical characteristics when compared with their bulk analogue (Woźniak-Budych et al., 2023).

Copper nanoparticles also exhibit exceptional optical characteristics, especially related to the surface plasmon resonance (SPR). SPR is due to the collective oscillation of conduction electrons that occurs on the surface of a nanoparticle when it absorbs light. Although copper has weaker plasmonic activity compared to noble metals like gold or silver, CuNPs have a peculiar absorption band in the visible range which is positioned between 560 and 600 nm and can differ with particle size, shape, and external medium. These optical properties render CuNPs promising for utilization in sensors, imaging and photothermal therapies (Khosravi et al., 2024).

Electrical is another key physical property of copper nanoparticle, especially for printed electronics and conductive films. Bulk copper possesses high electrical conductivity, which CuNPs usually lack primarily as a result of electron scattering at grain boundaries, surface oxidation and interparticle contact resistance. However, breakthroughs in sintering technology and surface modification have allowed CuNPs-based inks to achieve conductivities close to bulk copper, providing an inexpensive option compared to silver-based systems (Aggarwal et al., 2025).

Heat conduction and thermal stability of CuNPs are also size limited. CuNPs have a lower heat transfer efficiency than bulk copper because the phonon is scattered by the nanoparticle boundary despite an enhanced thermal conductivity over host polymer. Nevertheless, their high surface area is exploited to promote heat dissipation for instance in nanofluids and composite materials where CuNPs enhance thermal management systems (Pricop et al., 2025).

Surface properties, including specific surface area, surface roughness, and side group charge also determine the physical behaviour of CuNPs. A high specific surface area could enhance adsorption capacity and interaction with bio- or chemistries, whereas the surface charge will affect colloidal stability and dispersion behavior in biological and aqueous matrix. These properties are of particular significance in biomedical and therapeutic applications, where aggregation and instability can promote toxicity or reduce efficacy (Sandoval et al., 2022).

Chemical Properties of Copper Nanoparticles

The chemical properties of copper nanoparticles (CuNPs) are the essential for their activities different from bulk copper. Copper has higher chemical activity, redox reactivity, and interaction with the surrounding chemicals than bulk materials at the nanoscale attributed to high surface energy and plenty of low-coordination surface atoms. The aforementioned properties have made CuNPs to be used widely in catalysis, sensing, environmental applications and biomedical systems (Nasrollahzadeh et al., 2019).

One of the key chemical characteristics of copper nanoparticles is their ability to be present as Cu in a different oxidation state, primarily, + and ². This redox flexibility makes the CuNPs suitable for use in a number of redox reactions. In contrast to noble metal nanoparticles, copper is prone to surface oxidation in the presence of air or aqueous solution and it forms a layer of either Cu_2O or CuO on its surface. Although the surface oxidation may affect electrical conductivity, it can also improve catalytic and antimicrobial activity due to switching electron transfer and ion release (de Almeida et al., 2025).

The surface chemistry of the CuNPs is important in terms of their chemical stability and reactivity. Naked copper NPs are thermodynamically unstable with a high tendency for agglomeration and oxidation. The use of substantive materials, such as polymers, surfactants, ligands or biomolecules has often been used to overcome this drawback. Surface modifiers affect charge distribution, steric repulsion, and the chemical acquisition of attacker's sites to control particle dispersion and reactivity (Khan et al., 2019). Functionalization of CuNPs will also make it possible to adapt them for use in various chemical environments, such as aqueous, biological or organic. Copper nanoparticles have strong catalytic activities, one of the most widely investigated chemical properties. It is the high surface atom density and unsaturated coordination sites which give them their catalytic efficiency. CuNPs have been reported to be active in a variety of catalytic applications like carbon–carbon coupling, hydrogenation, oxidation of organic pollutants and reduction of nitro compounds (Nasrollahzadeh et al., 2019). In environmental chemistry, CuNPs are efficient catalysts for dye, phenol and pesticide degradation offering wastewater processing and reducing contamination of the environment (Usman et al., 2013).

One other chemical property of CuNPs is their potential ability to produce ROS through redox cycling between the Cu^{+} and Cu^{2+} states. This property is important, especially for biological and antimicrobial applications. ROS generation can lead to oxidative stress in microbial cells resulting lipid peroxidation, protein oxidation and DNA lesions. From a chemical point of view, it is associated with fenton-like reactions which were catalyzed by cupper ions from the nanoparticle surface. Although it is beneficial for antimicrobial and antitumor purposes, excessive ROS generation can cause cytotoxicity too, which highlights the necessity of chemical manipulation and surface modification .(de Almeida et al., 2025)

These copper nanoparticles are chemically characterized by their solubility and ion release behavior. CuNPs release Cu^{2+} ions in aqueous and physiological media, which have an effect on their biological properties and chemical reactivity. The ion release was found to be influenced by the size of particles, surface oxidation state, pH and presence of chelating agents (Usman et al., 2013). AgNPs with smaller size have greater dissolution rate because of larger surface energy, hence enhancing the role of size in chemical behavior.

Chemical interaction with biomolecules such as proteins, enzymes and nucleic acids by CuNPs is well-documented too. These are mediated by electrostatic interactions, coordination bonding and redox mechanisms. Thiol, amine, and imidazole groups exhibit very high affinity towards Cu; the above reasoning led to strong binding and saturation. These interactions are used in biosensing and therapeutics platforms, however may impact the protein conformation and enzymatic activity status leading to efficacy or toxicity (Khan et al., 2019).

From the thermodynamic point of view, copper nanoparticles have a high surface free energy which promotes chemical adsorption and catalytic reaction. From this property hinges his use as a heterogeneous catalyst in composite materials. However, high surface energy is also favorable for aggregation and easy to degrade chemically, demanding stability of the structure against these problem under synthesis and application (Nasrollahzadeh et al., 2019).

Therapeutic Properties of Copper Nanoparticles

Copper nanoparticles (CuNPs) have been emerging as an active area of biomedical research owing to multiple therapeutic activities involving several nanosized effects, their redox capability and controlled regulation of ion release. In contrast to bulk copper, CuNPs possess the ability of improved biological interactions, which may be utilised for antimicrobial activity, wound-healing promotion, anticancer effect and as functional materials in drug carriers. All these features make CuNPs attractive multifunctional therapeutics for use in contemporary medicine (Woźniak-Budych et al., 2023).

The therapeutic application of CuNPs which has been most widely investigated is their antimicrobial activity. Copper nanoparticles show a multifunctional spectrum of activity towards other micro-organisms, including Gram-positive and -negative bacteria, fungi and viruses. Their antimicrobial action is multi-target and consists of impairment of the microbial cell membrane, production of ROS, protein oxidation, with release of Cu^{2+} ions which alter key metabolic route. Crucially, CuNPs have been proven to be effective against antibiotic-resistant strains, suggesting that these nanoparticles could be used as an alternative or adjunct antimicrobial strategy in the face of the rising challenge of antimicrobial resistance (Vinayagam et al., 2020).

Antiviral activities of CuNPs have also attracted interest, especially with the advent of viral pandemics. Research has shown that copper nanoparticles have the potential to kill viruses by damaging their envelopes, disrupting the structures of viral capsid proteins and oxidizing the genetic material of viruses (Sportelli et al., 2020). This offers a strong rationale for the inclusion of CuNPs in antiviral coatings, personal protective equipment and medical device surfaces to mitigate viral transmission within healthcare environments.

Wound healing and tissue regeneration are another major therapeutic use of CuNPs. Copper is an important element in angiogenesis, collagen synthesis and extracellular matrix turnover. At the cellular level, copper can further promote these biological activities through sustained release of copper ions by CuNPs and cells migration and proliferation induction. Findings in vivo and in vitro have shown that CuNPs speed up wound healing, increase neovascularization as well as decrease the microbial burden at wounds site. These properties are especially useful for treatment of chronic wounds, burns or diabetic ulcers (Borkow & Gabbay, 2009; Sandoval et al., 2022).

Copper nanoparticles have also emerged as a good anticancer agent and this is mainly due to the selective generation of oxidative stress in cancer cells. ROS damage is more harmful to the cancer cell because of their different redox status and increased rate of metabolism. This vulnerability is exploited by CuNPs which cause the formation of intracellular ROS and subsequently result in mitochondrial damage, DNA modifications, and apoptosis of cancer cells. Moreover, it can disrupt angiogenic process as well as signaling in the tumor microenvironment cell affecting growth of tumors. These features indicated that CuNPs could be promising candidates for cancer treatment, alone or in combination with antineoplastic drugs (Laha et al., 2014).

The immunomodulatory and anti-inflammatory activities of CuNPs also help their therapeutic potential. Copper is a vital trace element regulating immunity and antioxidant capacity. Regulated exposure with CuNPs has demonstrated an anti-inflammatory effect by altering the cytokine production and minimizing oxidative stress during some pathological states. These effects may be favourable in inflammatory conditions, provided the not only injected but also accumulated dose is carefully managed (Crisan et al., 2020).

For drug delivery, CuNPs are being investigated as vehicles for therapeutic agents. Large surface area for adsorption or conjugation of drug, Bmolecule and targeting ligand. In addition, the redox-sensitive property of CuNPs allows for therapy on demand in response to specific biological stimuli, such as acidic tumor cells or oxidative stress. These features facilitate drug stability, bioavailability and site-specific delivery to minimize the systemic side effects (Chen et al., 2020).

Biocompatibility and toxicity are main concerns despite being promising for treatments. The processes of ROS creation and ion discharge (characteristic for radiotherapy) contribute to anticancer activity, but can cause nonspecific destruction in adjacent healthy tissues when left unregulated. Research has shown that the toxicity of CuNPs to be dosage-dependent as well as modified by NP size and surface chemistry, exposure time. Therefore, these days the studies are focused on surface functionalization, synthetic design and delivery target to enhance therapeutic effect and reduce side effect (Crisan et al., 2020).

Biocompatible and green synthetic approaches have recently been developed to improve the therapeutic application of CuNPs. Thus, the nanoparticles produced with plant extracts or biological agents are highly cytocompatible and less toxic than their chemically synthesized equivalents. These findings facilitate the integration of CuNPs in clinical and pharmaceutical formulations (Vinayagam et al., 2022).

Conclusion

It is on the basis of optical density that both theoretical and applied optics develop. Ideally, therefore, this review should make evident the great strides that have been made in the field while bringing out gaps of knowledge that exist and need to be filled. Closing these gaps will provide a better understanding of optical density and its applications for new technologies within scientific disciplines. It can also be immensely helpful in increasing assay sensitivity as well as making assays and sensor technologies more reliable with optical density determination being an important parameter. New material and methodology for determining optical density open interesting perspectives for investigation, which would lead toward general enhancement for efficiency in laboratory biochemical analyses. The importance of optical density has been demonstrated most recently bringing about useful applications from enzymatic assays in biochemical research and clinical diagnostics. By merging new tech and getting the underlying workings better, the area can keep changing, making a path for more effective, keen, and targeted tests in many uses. Ongoing digging into the info holes noted in this look will make the handiness of optical density in enzyme tests better and help push forward improvements in ways to diagnose.

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