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Crystalline Copper Nanomaterials for Advanced Ceramic: A Comprehensive Review for Functional Ceramic Coating Approaches

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Copper nanoparticles (Cu NPs) are appealing candidates for advanced ceramic applications because of their remarkable physical, chemical, mechanical and antibacterial capabilities which have attracted much interest. This review provides an extensive analysis of the current state-of-the-

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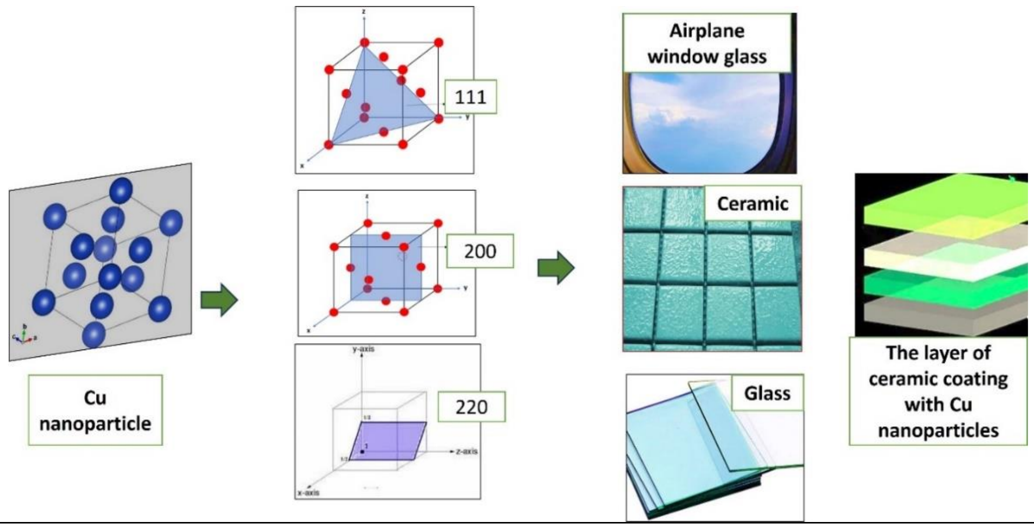
art synthesis, characterization and utilization of crystalline Cu NPs for functional ceramic coatings. Emphasis is placed on the unique attributes of copper nanostructures, including their high ratio of surface to volume, tunable optical and electronic properties and remarkable thermal and electrical conductivity. The review delves into various synthetic strategies such as chemical reduction, thermal decomposition and biological synthesis in achieving proper control over shape, size and crystallinity. Furthermore, the integration of copper nanomaterials into ceramic matrices is critically examined, unveiling their role in enhancing mechanical strength, thermal stability and antimicrobial activity. Particular attention is given to developing multifunctional ceramic coatings tailored for applications in energy storage, catalysis, sensing and biomedical fields. The review also discusses challenges and future perspectives, including the scalability of production processes, environmental considerations and the development of hybrid nanocomposites for next-generation advanced ceramic materials.

Graphical Abstract



Keywords: Crystalline; copper; ceramic coating; nanomaterials; phase analysis.

1. INTRODUCTION

Many technical advancements have been fueled by the search for superior materials, opening the door to the creation of cutting-edge applications in a variety of industries [1-2]. The field of nanomaterials has emerged as a frontier for unlocking unprecedented material properties and functionalities [3]. Among the diverse array of nanomaterials, crystalline Cu NPs have garnered significant attention because of their special thermal, electrical, optical and catalytic qualities which arise from their nanoscale dimensions and crystalline structure [4-11]. These unique characteristics render Cu NPs promising candidates for a variety of uses such as energy, electronics, catalysis and advanced ceramics [12-15]. Concurrently, the field of ceramics has undergone substantial advancements, driven by the ever-increasing demand for high-performance materials capable of withstanding extreme environments and providing superior functional properties [16-20]. Advanced ceramics, characterized by their exceptional hardness, chemical inertness and thermal stability have found widespread applications in industries such as aerospace, automotive, energy and electronics [21,22,23,24,25]. However, despite their remarkable properties, traditional ceramic materials often face limitations in terms of multi-functionality, durability and tailored performance [26]. This is where the synergistic integration of crystalline Cu NPs and advanced ceramics presents an exciting opportunity to overcome these challenges and unlock a new era of functional ceramic coatings [27,28]. By incorporating crystalline Cu NPs into ceramic coatings, it becomes possible to engineer coatings with unprecedented properties and functionalities [29-33]. The distinctive qualities of Cu NPs such as their high ratio of surface to volume, quantum confinement effects and tunable electronic structure can be harnessed to enhance the thermal stability, mechanical strength, electrical conductivity, catalytic action and other desirable properties of ceramic coatings [34-41]. Cu NPs exhibit excellent antimicrobial activity against a broad spectrum of viruses, bacteria and fungi [42]. This property makes Cu NPs reinforced ceramic coatings attractive for applications in food packaging, healthcare and water treatment systems [43-46]. These nanoparticles also exhibit tunable optical properties, including surface plasmon resonance which also can be utilized for applications in sensing, catalysis and optoelectronic devices when combined with ceramic matrices [46,47].

Cu NPs can be added to ceramic coatings to enhance their mechanical characteristics, such as hardness, toughness and wear resistance, due to the strong interfacial bonding between the nanoparticles and the ceramic matrix [48,49]. Cu NPs are relatively abundant and less expensive compared to noble metals like gold and platinum, making copper nanomaterials more economically viable for large-scale applications [50]. It can be synthesized in several ways, including chemical reduction, thermal decomposition and biological synthesis, allowing for better control over their size, shape and crystallinity [51-61]. The goal of this viewpoint evaluation is to offer a thorough investigation of the synergistic integration of crystalline Cu NPs and advanced ceramics, with a particular focus on functional ceramic coating approaches. It will delve into the synthesis methods, characterization techniques and structure-property relationships of Cu NPs in the context of ceramic coatings, shedding light on the fundamental principles and mechanisms governing their functionality. Moreover, the evaluation will draw attention to the possible uses of these functional ceramic coatings in various industries, showcasing their potential to revolutionize fields [62]. By bridging the gap between nanomaterials and advanced ceramics, this evaluation will open the door for the advancement of high-performance, multifunctional ceramic coatings that can withstand the most demanding environments while offering tailored functionalities.

2. METHODS, MATERIALS AND CHARACTERIZATION

2.1 Methods and Materials

One widely employed method is the chemical reduction route which makes use of copper precursor salts such as copper chloride, copper sulfate or copper nitrate as the source of copper ions. These precursor salts are then reduced by the addition of reducing agents like sodium borohydride, hydrazine, ascorbic acid or glucose [63,64]. To stabilize and prevent agglomeration of the formed nanoparticles, capping agents or stabilizers are incorporated such as polyvinylpyrrolidone (PVP), sodium citrate or cetyltrimethylammonium bromide (CTAB) [65-69]. Another synthesis approach is thermal decomposition where copper precursor complexes like copper acetylacetonate or copper cupferron complexes are heated in high-boiling solvents like phenyl ether, octyl ether or trioctylamine. Capping agents and stabilizers such as oleic acid, oleylamine or hexadecylamine are added to regulate the nanoparticle's dimensions and shape [70-72].

Electrochemical synthesis is an alternative method that involves the use of copper electrodes or copper salts in electrolyte solutions like sodium hydroxide, sulfuric acid or perchloric acid. Stabilizers like polyethelene glycol (PEG) or polyvinylpyrrolidone (PVP) are often employed to prevent aggregation [73-76]. The environmentally benign nature of biosynthesis or green synthesis techniques has drawn attention in recent years. These methods utilize plant extracts from leaves, fruits or bark or employ microbes like bacteria, fungi or algae as reducing agents and stabilizers. Biopolymers such as chitosan, starch or cellulose can also be used as capping agents in these green synthesis routes [77-81].

Cu NPs are susceptible to oxygen, so the preparation of copper nanoparticles is carried out in an inert atmosphere that is quite tough [82]. The choice of materials and synthesis method is governed by factors like the desired size, shape, stability and intended application of the Cu NPs, as well as environmental considerations.

2.2 Characterization

Table 2 describes various characterization techniques used in materials science and nanotechnology and the information they provide about the materials being studied. UV-visible spectrophotometry is used to analyze surface plasmon resonance, the size distribution of quantum dots, bandgap energy, doping and defect states, composition, electronic structure, stability, and optical properties [83,84]. FTIR (Fourier-transform infrared spectroscopy) helps

Table 1. The list of precursors used in Cu NPs synthesis with microbial source or capping agent and size

Precursor	Microbial source / capping agent	Size (nm)	References
Copper chloride	*Tinospora cordifolia* leaf extract	50.0 – 130.0	[39]
Cupric sulfate	*Centella Asiatica* leaf extract	20.0 – 30.0	[40]
Copper (II) acetate	oleylamine and oleic acid	60.0	[41]
Copper sulfate pentahydrate	leaves of Tilia	4.70 - 17.40	[42]
Copper sulfate	peppermint extract	137.0 – 146.0	[43]
Copper nitrate	*Salmonella typhimurium*	40.0 – 60.0	[44]
Copper sulfate	*Pseudomonas fluorescens*	40.0	[45]
Copper sulfate	*Syzygium aromaticum*	40.0 – 45.0	[46]
Copper chloride	*Stereum hirsutum*	5.0 – 20.0	[47]
Copper nitrate	*Agaricus bisporus*	10.0 – 60.0	[48]
Copper chloride	Ascorbic acid	200.0	[49]
Copper sulfate	*Ocimum sanctum* leaf	77.0	[50]

Table 2. Various Characterization techniques and their provided information.

Characterization Technique	Information	Reference
UV-Visible spectrophotometer	Surface plasmon resonance (SPR), size and size distribution of quantum dots, bandgap energy, doping and defect states, composition, electronic structure, stability and optical properties.	[85-87,83,84]
FTIR	Molecular structure, chemical composition and functional groups detect impurities or adulterants, product stability and degradation.	[88]
XRD	crystal flaws, average grain size, degree of crystallinity, and lattice constants and phases. Advanced XRD offers crystalline symmetry, strain, texture, preferred orientation and electron density information.	[89,90,91]
DLS	Particle size distribution, Hydrodynamic radius, polydispersity index (PDI), aggregation and stability, temperature and solvent effects and colloidal stability.	[92,93]
Zeta Potential	Surface charge, Colloidal stability, isoelectric point, surface properties, interactions of nanoparticles with dispersed system.	[94,95,96]
XPS	Chemical composition, elemental composition, chemical state, valence band structure and electronic state of the elements within a material.	[97,98]
TSM-ESM	Optical properties, size, shape and morphology, Refractive index Aggregation and stability, bandgap energy and composition of nanomaterials.	[99,100]
TGA/DSC	Composition, thermal stability, decomposition kinetics, oxidation, dehydration, desorption, melting, crystallization and glass transitions temperature.	[101,102]
Impedance Analyzer	Dielectric, conductive and capacitive properties.	[103,104]
Conductivity Analyzer	Electrical conductivity, including temperature-compensated conductivity values, calibration status, concentration calculations and alarm/control functions.	[105,106]
SEM	Surface morphology, composition, microstructure, surface roughness, texture, features and topography, grain boundaries, defects, cracks and porosity, distribution and concentration of elements.	[107,108]
TEM	Internal morphology, particle size, shape, crystal symmetry, lattice parameters, orientation, defect, impurities, strain, stress, electronic structure, chemical bonding and elemental composition.	[109,110]

understand the molecular structure, chemical composition, functional groups, impurities, product stability, and degradation [88]. X-ray diffraction (XRD) provides information on crystal flaws, grain size, crystallinity, lattice constants, and phases. Advanced XRD techniques can also reveal crystalline symmetry, strain, texture, and electron density [90,91,111]. Dynamic Light Scattering (DLS) measures particle size distribution, hydrodynamic radius, polydispersity index, aggregation, stability, and the effects of temperature and solvents on colloidal systems

[93]. Zeta Potential analysis gives insights into surface charge, colloidal stability, isoelectric point, and surface properties of nanoparticles [95, 96]. X-ray photoelectron spectroscopy (XPS) is employed to determine the chemical and elemental composition, chemical state, valence band structure, and electronic state of elements within a material [97,98]. The passage also mentions TSM-ESM (likely referring to Transmission Scanning Micro spectrophotometry - Electron Scanning Microscopy) which provides information on optical properties, size, shape, morphology, refractive index, aggregation, stability, bandgap energy and composition of nanomaterials [99,100]. Thermal analysis techniques like TGA (Thermogravimetric Analysis) and DSC (Differential Scanning Calorimetry) are used to study composition, thermal stability, decomposition kinetics, and various thermal transitions. Impedance and conductivity analyzers measure dielectric, conductive, and capacitive properties, as well as electrical conductivity and related parameters [101,102]. Finally, microscopy techniques such as Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are described. SEM provides information on surface morphology, composition, microstructure, roughness, and elemental distribution [108]. TEM offers insights into internal morphology, particle characteristics, crystal structure, defects, electronic structure, chemical bonding, and elemental composition at a higher resolution [110].

3. RESULTS AND DISCUSSION

3.1 UV-visible Spectrophotometry

UV-visible spectroscopy is utilized when the atom or molecule absorbs the radiation even at a high frequency of light generated by electronic excitation [112]. Copper nanomaterials have been investigated under UV-visible light. The spectrum was determined over a range of wavelengths spanning from 250.0 to 800.0 nm as obtained in Fig. 1. From observation, it was studied that the Cu NPs demonstrate a strong absorbing peak within the wavelength region extending from 550.0 to 650.0 nanometers [113,114]. The spectrophotometer [VARIAN CARY, Model: 5000] captured the Cu NPs optical absorption spectrum in wavelength 550.0 to 900.0 nm [112]. The absorption peak exhibits the synthesized Cu NPs at about 570.0 nm [112]. From previous studies, the obtained Cu NPs band gap was 2.1 eV [115,116], 1.98–2.02 eV [117], 2.14 eV [118] and 2.3 eV [112,119].

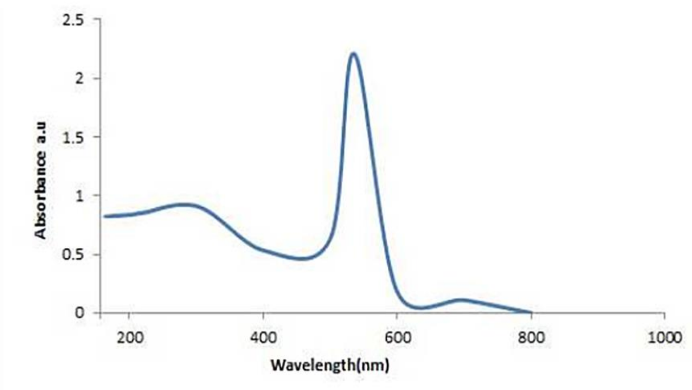


Fig. 1. UV-visible range of artificially produced copper-chitosan nanoparticles [120]

Table 3. Green synthesis using various plants in copper nanoparticles and their wavelength in UV

Copper salts	Particle size (nm)	Wavelength (nm)	Reference
Copper chloride	15.0–20.0	560.0–580.0	[121]
Copper chloride	45.0	585.0	[122]
Copper chloride	48.0	560.0	[123]
Copper sulfate pentahydrate	45.0-110.0	560.0	[124]
Copper sulfate pentahydrate	15.0-20.0	585.0	[125]
Copper sulfate pentahydrate	27.60	563.0	[126]

Copper salts	Particle size (nm)	Wavelength (nm)	Reference
Copper sulfate pentahydrate	76.0	588.0	[127]
Copper sulfate	5.0-40.0	570.0	[128]
Copper sulfate	50.0-100.0	531.0	[129]
Copper sulfate	15.0-30.0	576.0	[130]
Copper acetate	16.50	570.0	[131]
Copper acetate	12.0	580.0	[132]

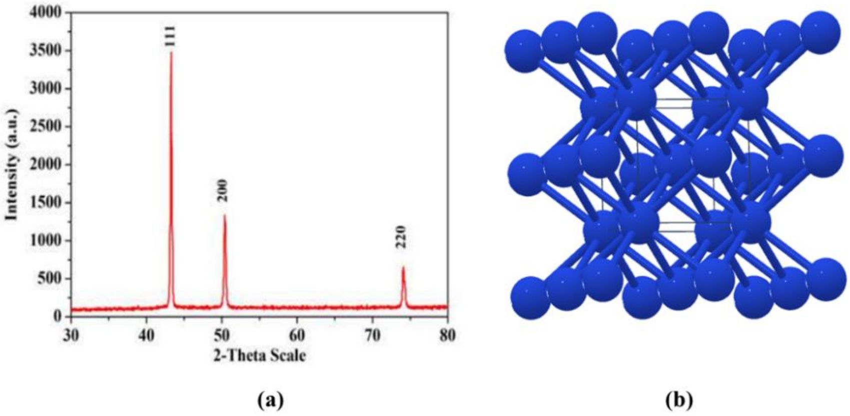


Fig. 2. (a) X-ray diffraction of copper nanoparticles [133] and (b) crystal structure of copper nanomaterial [134]

The spectrum exhibits several notable features. There's a broad, low-intensity absorption band in the 200 to 400 nm range, which falls within the ultraviolet region [120]. This is followed by a sharp, intense peak centered around 550.0 to 600.0 nm, reaching a maximum absorbance of approximately 2.20 [120]. This prominent peak likely corresponds to strong absorption in the green-yellow part of the visible spectrum. After this peak, the absorbance drops rapidly, approaching zero by about 700.0 nm and remaining very low through the rest of the measured range [120]. From the green synthesis, the colloidal Cu NPs synthesized for 12.0 hours at 70.0 ^{0}C exhibited a distinctive absorbing peak at 536.0 nm in Fig. 1. These exhibited the reduction of Cu^{2+} ion due to the green synthesis like chitosan which was monodisperse [120]. The blue shift was recorded as a range in a surface plasmon resonance (SPR) for metallic nanoparticles in reducing size [135] as nano-sized Cu NPs showing SPR around 500.0 to 600.0 nm [136].

It was studied that the absorption peaks of Cu NPs from the green synthesis in the visible light spectrum in a range of 530.0 to 590.0 from Table 3. [121-132]. The distinct absorption peaks were obtained due to the presence of green molecules which caused the reducing size by the reduction process [137,138]. As the size of the particles decreases, the band gap energy is increased [139].

3.2 X-ray Diffraction (XRD)

The crystallinity and structure of artificially generated Cu NPs were described using X-ray diffraction techniques [133]. The obtained X-ray diffraction pattern of Cu NPs is shown in Fig. 2. where the cubic lattice of copper was confirmed by the diffraction at 2θ= 43.28 ^{0}, 50.40 ^{0} and 74.81 ^{0} which relate to respectively the (111), (200) and (220) planes [133, 111]. The standard pattern for the pure face-centered cubic phase of copper nanoparticles [JCPDS No. 040836] exhibits good agreement with all of the diffraction patterns. CuO or Cu_2O impurity diffraction was absent as Cu NPs were synthesized [133]. The high crystallinity nature shows extremely intense diffraction and the nano-crystallinity nature of particles nature responsible for the remarkable broadening of the diffraction [133,140].

The face-centered cubic (FCC) crystal structure is the most common crystal structure observed in crystalline Cu NPs [111]. In the FCC structure, the copper atoms are arranged in a cubic pattern, containing one atom in the middle of each of the six faces and one atom at each of the cube's corners. [141]. The lattice parameter of the copper's face-centered cubic crystal structure is typically reported as approximately 3.615 Å (Angstrom) at room temperature [142].

The quantitative investigation using the whole powder pattern fitting (WPPF) approach confirms the impact of precursor concentration on copper crystal formation. By using copper sulfate pentahydrate ($CuSO_4{\cdot}5H_2O$) as a precursor combined with sodium hydroxide, starch and ascorbic acid at precursor concentrations of 0.08 M, 0.09 M and 0.10 M, cubic crystals were produced with percentages of metallic copper of 79.0 %, 95.0 % and 96.0 % respectively Fig. 4. [143]. This is because The accessibility of a greater amount of $Cu(OH)_2$ increases the likelihood that more cupric ions will be reduced by the reducing agent ascorbic acid into cuprous oxide, cupric oxide and ultimately metallic copper (Cu) with the increase in the concentration of precursors from 0.08 M to 0.10 M [143]. That's why there isn't enough $Cu(OH)_2$ created with lesser concentrations of the precursor to support a reduction reaction that would produce a mixture of Cu_2O and metallic copper (Cu). This is where the reduction reaction starts when the radical semi-dehydro-ascorbate acid is produced [143].

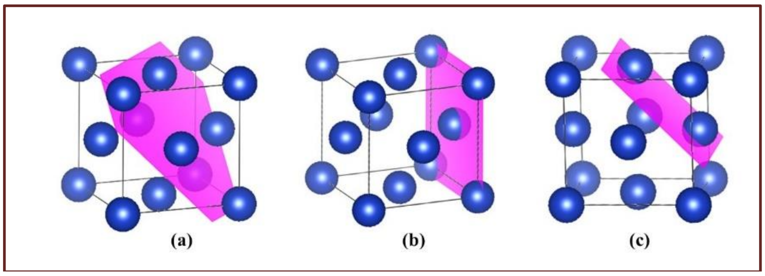


Fig. 3. Unit cell structure of Cu NPs with (a) (111), (b) (200) and (c) (220) miller indices [133,142].

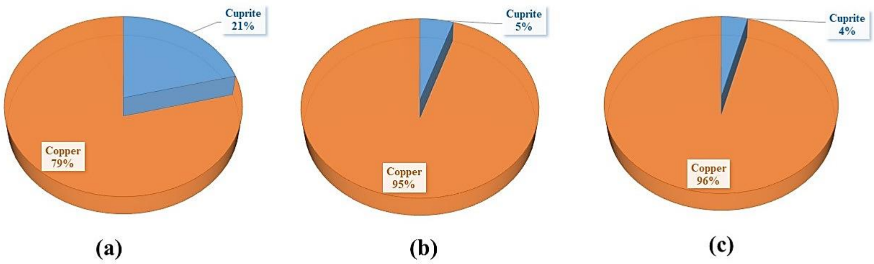


Fig. 4. Cu NPs crystalline phase percentage as determined by the WPPF method concerning precursor concentration [143].

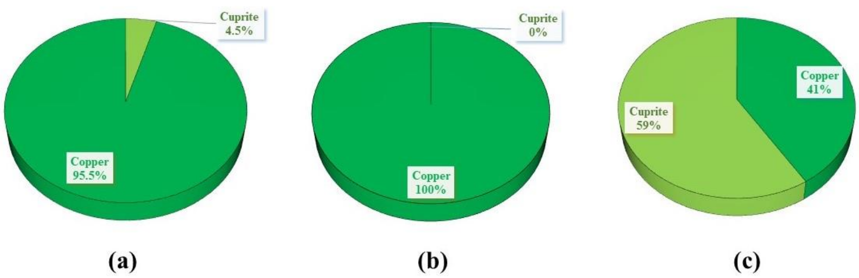


Fig. 5. Crystalline phase percentage of Cu NPs by WPPF method by reaction medium [144]

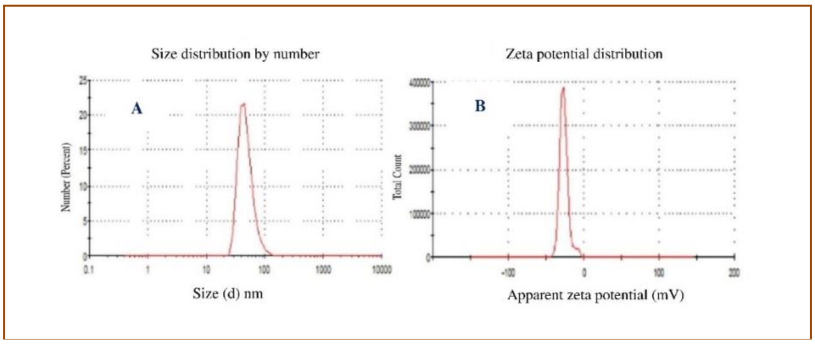


Fig. 6. (A) Copper nanoparticles' particle size distribution and (B) their zeta potential [145]

The impact of the reaction medium on copper crystal formation is also confirmed by the quantitative analysis employing the Whole Powder Pattern Fitting (WPPF) method [144]. By using copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) as a precursor with the presence of a reducer such as ascorbic acid, it was shown that 95.50 % of the metallic copper phase formed in a water medium, 100.0 % of the metallic copper phase formed in methanol and 41.0 % of the metallic copper phase and 59.0 % of the cuprite phase formed in methanol-water Fig. 5. [144]. This indicates that methanol is the ideal medium for the synthesis of pure metallic copper phases and that an azeotropic mixture of methanol and water is the optimum option for the concurrent emergence of metallic copper and cuprite phases [144].

3.3 Zeta Potential

The determination of zeta potential in Cu NPs is vital in elucidating information regarding their stability, surface charge and interplay with the neighbouring medium [146]. The surface electrical charges of Cu NPs were examined using zeta potential analysis [145]. The stability of the formed colloidal Cu NPs was evaluated by this method. The degree of inherent stability in a colloid can be identified by the zeta potential magnitude [145]. According to research, when Cu NPs were stable, their zeta potential values were either more positive than +30.0 mV or more negative than -30.0 mV [147]. As per Fig. 6B, the zeta potential of the Cu NPs was established at -26.0 mV. It was supposed to be determined that the bio-transformed Cu NPs possess considerable stability [148]. The surface charge of the nanoparticles is what causes the electrostatic repulsion between them. Long-term stability is achieved when the nanoparticles have a negative charge because they do not cluster together [145].

3.4 Transmission Electron Microscope (TEM)

Metal nanoparticles in the nano range and their spherical shape were verified in the Transmission electron microscopy (TEM) image [149]. TEM is the most popularly used technique that identifies small-size nanoparticles by photographing microscopic nanoparticles, obtaining information and their phase crystallographic orientation by diffraction pattern by using energy spectrum analysis to determine their chemical composition [150].

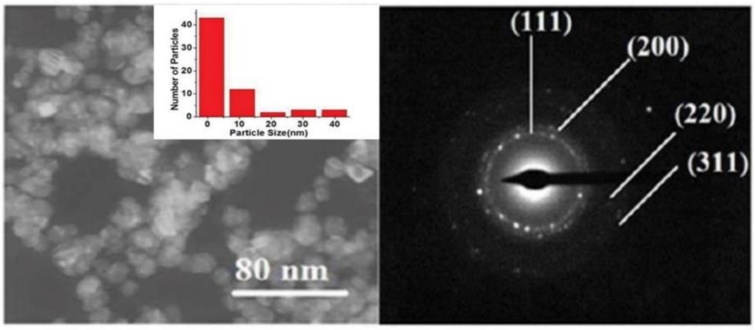


Fig. 7. TEM internal morphology, SAED pattern and particle size distribution of copper nanoparticles [151]

The as-prepared copper nanoparticles were evaluated using TEM which identified the morphology and particle size [151]. Fig. 7. shows TEM internal, SAED patterns and particle size dispersion of prepared Cu NPs which the gum kondagogu extract helped to stabilize. The TEM image showed that most of the nanoparticles were spherical and polycrystalline because there are different contrast zones in a single nanoparticle [151]. The average diameter and interplanar spacing were calculated using Image J software. The copper nanoparticles from TEM that were investigated have a particle size of 19.0 nm [151]. The interplanar spacing of four diffraction rings was determined in the SAED pattern Fig. 7 as 0.20, 0.18, 0.13 and 0.11 nm [151]. The FCC crystalline nature of Cu [JCPDF no. 71-4610, Fm-3m, a= 0.3617 nm, d_{111}= 0.20883 nm, d_{200}= 0.18085 nm, d_{220}= 0.12788 nm, d_{311}= 0.10906 nm] resultant was studied [152]. The distribution of particle size in Fig. 7 proved that the nanoparticles were in the range of 1.0 to 10.0 nm [151]. In other studies, the average nanoparticle size range was recorded as 15.0 ± 2.0 nm [149], 30.0 to 50.0 nm [151] and 2.0 -10.0 nm [153].

4. FUNCTIONAL APPLICATION ON CERAMIC COATING

Although polymer/metal nanocomposites are a good option not much is known about their biological characteristics. It is suggested to use a polymer-based nanocomposite, like Cu NPs as a biostatic coating and to systematically correlate the properties of the material with biological impacts. [154]. Numerous investigators have documented empirical evidence of the nanocomposite's potential to precisely release metal species and in the end to impede or decelerate the proliferation of living things, including fungus and other harmful microbes [154]. There are several practical approaches for managing corrosion. The most popular method for preventing metal from corroding is coating [155]. However, the polymer coating's long-term corrosion resistance steadily decreases because of its insufficient resistance to corrosive solutions penetrating the metal/coating interface [155]. Coatings have recently incorporated nanoparticles to enhance their mechanical, chemical, and optical characteristics. Nanocoating is composed of layers that are less than 100.0 nm in size or contain components at the nanoscale [155]. Because of its many advantages, including surface hardness, adhesive properties, durability and high-temperature corrosion resistance, nano coatings are utilized to reduce the effects of corrosive environments [155]. The use of advanced bio-ceramics in wound healing applications has been crucial to therapeutic techniques. Bio-ceramic materials have been considered as possible materials for wound healing because of their biocompatibility which enables the healing site to receive the proper reaction [156]. The traditional shortcomings of wound dressing materials used in biomedical applications can be addressed by functionalizing biomaterials with a variety of biosensing ceramics, including copper oxide, titanium oxide, zinc oxide, zirconium oxide, bioactive glass and so on to create a wide range of promising dressing agents [156]. To prevent external microorganism infection at the wound site during the healing period, surface modification of dressing ceramic materials with possible antimicrobial agents has been investigated as a wound-healing material [156]. A method utilizing Cu NPs to create nanocoatings for the tile industry has been suggested. Following a typical processing protocol, ceramics were fast-fired at 1200.0 °C in an air environment to mimic an industrial process [157]. The ceramic nanocoating was hydrophobic and had a metallic sheen, making it multipurpose. X-ray diffraction was used to examine the surface crystallizations, which led to the discovery of copper oxide nanocrystals [157]. The suitability of copper substrates coated in ceramic insulating coating for usage in thick film technology was evaluated [158]. Screen printing was used to create the ceramic coating which was heated between 820.0 °C and 1000.0 °C. The dielectric composition included unique glass and aluminium oxide [158]. Voltage breakdown, bulk and surface insulation resistance and dielectric constant were among the electrical characteristics of the coatings under investigation. In ceramic coating, substrates made of lead, bismuth, ruthenium, barium, palladium, silver and copper are employed as system resistors (or conductors) [158].

If the microstructure of these coatings is suitable, copper-based coatings with a hard ceramic phase can offer an engineering solution for components exposed to particle erosion settings [159]. Single-phase brittle materials are believed to be harmed by the formation and spread of subsurface lateral cracks, whereas micromachining and ploughing cause damage to single-phase ductile copper [159]. Consequently, it is anticipated that a multi-component system consisting of ductile metal particles, like copper, and hard, brittle ceramic particles will be resilient enough to withstand hits from particles at a 90.0 ° angle and hard enough to deflect eroding particles at low-impact angles [159]. More aggressive passivation results from a glassy alloy's surface having a larger free energy than the matching crystalline solid's surface [160]. Utilizing Cu NPs, this property is developed. To take advantage of these benefits, additional research and development work is necessary [160].

Table 4. Various functional applications on ceramic coating.

Serial No.	Functional Application	Reference
1.	A regulated release of metal species can be achieved by using copper nanocomposite which can also eventually slow down or even stop the growth of pathogenic germs and other living things like fungi. It serves as a bacteriostatic and antifungal covering.	[154]
2.	Copper nanomaterials are widely used in corrosion protection coatings and inhibitors.	[155]
3.	Copper materials have been considered as possible materials for wound healing because of their biocompatibility which enables the healing site to receive the proper reaction.	[156]
4.	Copper oxide nanocrystals are used as a coating in tiles industries to improve metallic shine and hydrophobic characteristics.	[157]
5.	The suitability of copper substrates coated in ceramic insulating coating for usage in thick film technology was evaluated. It is used in insulation resistance.	[158]
6.	To increase erosion resistance, copper-ceramic coatings were sprayed with plasma and melted using a laser.	[159]
7.	Glass is coated with copper to improve its mechanical qualities and strengths.	[160]
8.	Effective in resisting bacteria by applying it to clothes, mattresses, walls and equipment.	[161]
9.	Strong functionality in antiviral filters and coating.	[162]
10.	A sensible choice for wound care, skin care products, dental amalgam, gloves, and assistance to inhibit bacteria inside the pipe.	[163]
11.	Improve the shelf life of food by resisting bacterial pathogens.	[164]

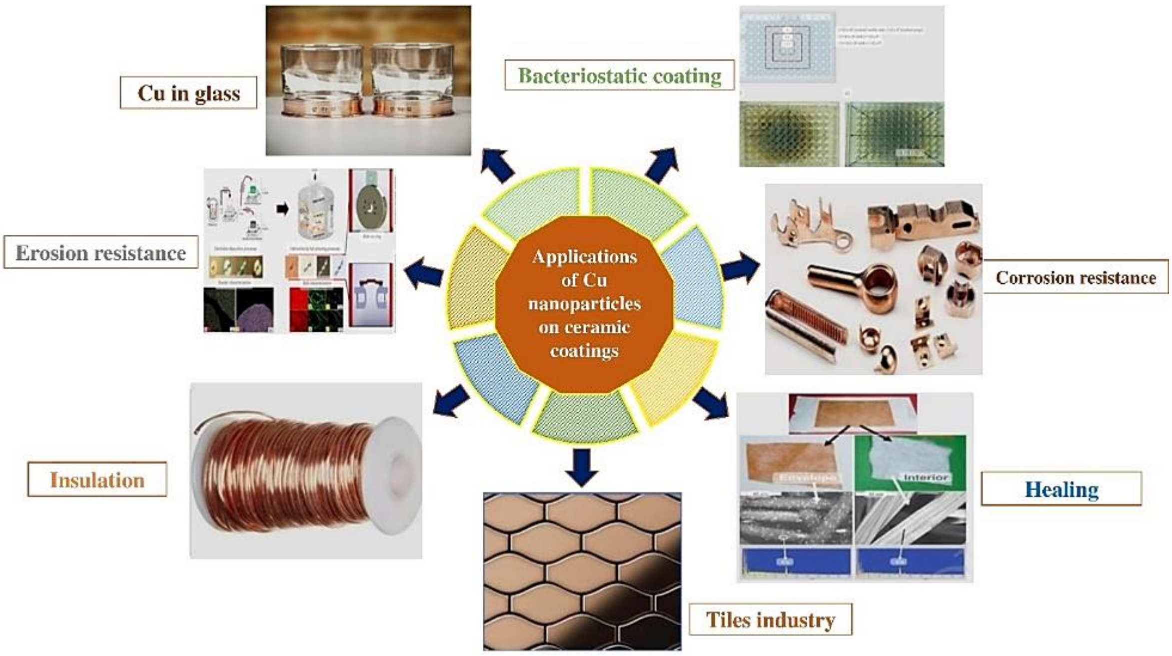


Fig. 8. Functional application of copper nanomaterials for ceramic coating substrate

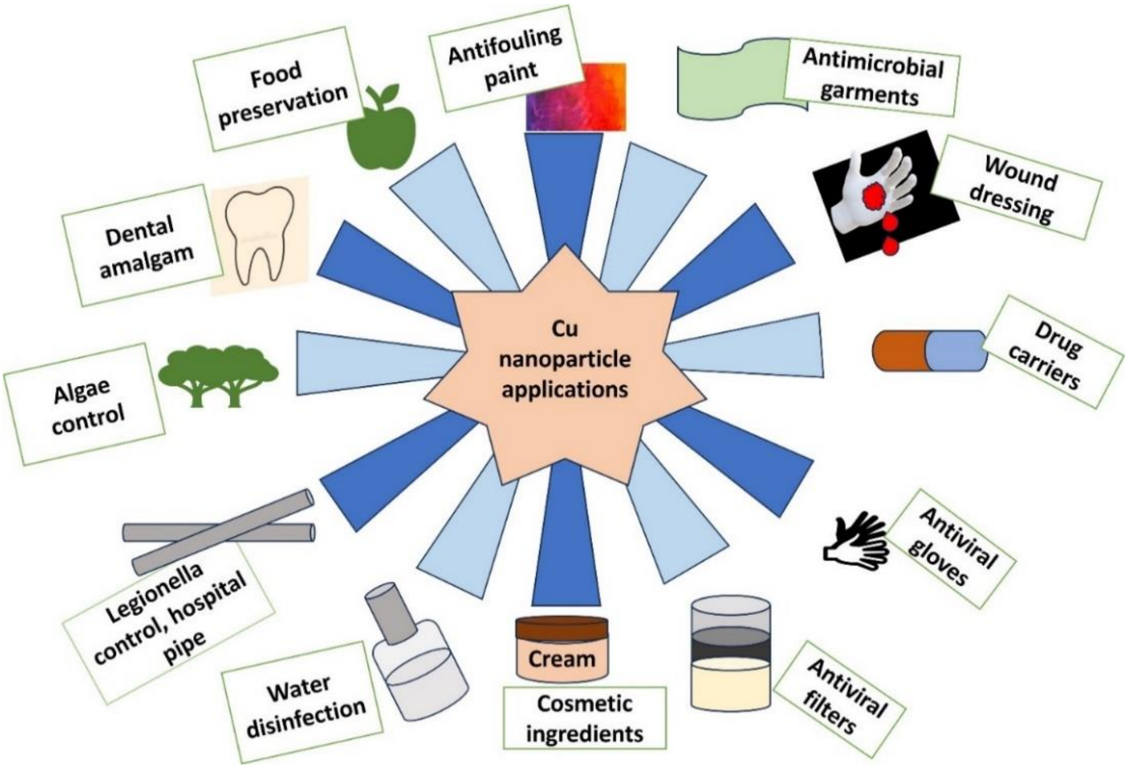


Fig. 9. Different aspects in the functional application of Cu NPs

4.1 Another Functional Application of Copper Nanomaterials

Cu NPs have drawn a lot of interest because of their special qualities and their uses in a variety of industries. These nanomaterials have unique physicochemical qualities that make them useful for a variety of functional applications, including a high surface-to-volume ratio, increased reactivity, and tunable optical and electrical properties [165]. Cu NPs have emerged as promising additives for antifouling paints due to their potent antimicrobial and antifouling properties against marine organisms [166]. It can be used to give clothing antimicrobial qualities because of its strong antimicrobial activity against a variety of bacteria, fungi, metallic concentrations and viruses [167,168-174]. The antimicrobial properties of Cu NPs can help reduce odour-causing microorganisms, improving the freshness and hygiene of the garments [175]. However, the incorporation of Cu NPs into wound dressings can provide antimicrobial protection, accelerate healing, and potentially reduce the risk of wound infections, offering promising advancements in wound management [176]. Cu NPs can be embedded or coated onto the glove material, allowing for a gradual and regulated discharge of copper ions, and providing long-lasting antiviral protection [177]. The emission of reactive oxygen species (ROS) and the liberation of copper ions by Cu NPs exhibit antiviral activity against various viruses, including influenza, HIV and SARS-CoV-2 (the virus-causing COVID-19) [178].

The antiviral activity of Cu NPs can help inactivate or reduce the presence of airborne or waterborne viruses, enhancing the effectiveness of filtration systems [179]. It also exhibits antioxidant activity and promotes collagen production, helping to reduce wrinkles and improve skin elasticity [180]. Cu NPs can help reduce hyperpigmentation and improve skin tone by inhibiting the production of melanin [181]. Numerous bacteria, viruses, and protozoa are among the many waterborne diseases that it may successfully inactivate and eradicate, making them suitable for point-of-use or centralized water treatment systems, reducing the risk of water pollution and improving water quality [182]. A demonstration of Cu NPs promising applications in controlling Legionella bacteria, which can cause Legionnaires' disease and prevent their growth in hospital water distribution systems and pipes [183].

Cu NPs have also been explored for their potential in controlling algal blooms in water bodies [184]. Their antimicrobial properties make them effective against various algal species. It can inhibit algal growth and photosynthesis, providing a promising solution for managing harmful algal blooms [184]. Cu NPs have been investigated as a potential additive in dental amalgam, a widely used dental restorative material [185]. Incorporating Cu NPs into the amalgam matrix can enhance its mechanical properties, antibacterial activity, and durability, leading to improved dental restorations [186]. The antimicrobial and antioxidant properties of Cu NPs make them attractive for food preservation applications [187]. They can be added to packaging materials or used as coatings to increase the shelf life of food goods by preventing the growth of bacteria that cause spoiling and lowering oxidative deterioration [188].

5. CONCLUSION

The integration of crystalline Cu NPs into advanced ceramics has shown to be a viable route for developing functional ceramic coatings with enhanced properties. This perspective review has highlighted the unique attributes of copper nanostructures, including their exceptional optical, electronic and antimicrobial properties which make them attractive candidates for various applications. we have explored the synthetic strategies for producing copper nanomaterials to provide exact control over crystallinity, form and size Additionally, we have discussed the incorporation of these nanomaterials into ceramic matrices, unveiling their potential to enhance mechanical strength, thermal stability, and antimicrobial activity. The development of multifunctional ceramic coatings tailored for applications in energy storage, catalysis, sensing, and biomedical fields has been a focal point. The synergistic combination of Cu NPs and ceramic matrices has demonstrated remarkable potential in addressing the ever-increasing demands for advanced materials with superior performance. Despite the significant progress made, several challenges remain to be addressed. Scalability of production processes, environmental considerations and the development of hybrid nanocomposites with tailored properties are areas that require further exploration. However, there is little question that the development of synthesis processes, characterization techniques and a deeper comprehension of the links between structure and property will open the door to the creation of next-generation ceramic materials with hitherto unheard-of functions. As we continue to push the boundaries of material science, crystalline Cu NPs hold immense promise for the development of advanced ceramics, offering a multitude of opportunities for innovation in functional ceramic coating approaches.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of manuscripts.

DATA AVAILABILITIES

All the data is collected from available sources as previously published articles.

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COMPETING INTERESTS

The authors have declared that no competing interests exist.

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