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Synthesis Strategies, Characterization and Emerging Applications of CuS Nanoparticles: A short Review

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Abstract:
Copper sulfide (CuS) nanoparticles have gained significant attention because of their unique structural, optical, electrical and catalytic properties. This review summarizes the major synthesis strategies for CuS nanoparticles, including precipitation, sol–gel, hydrothermal, solvothermal, chemical and green synthesis methods. The influence of synthesis parameters on crystal structure, morphology, particle size, optical properties and surface characteristics is discussed. Various characterization techniques such as XRD, SEM, TEM, EDX, FTIR, Raman and UV–Visible spectroscopy are highlighted for understanding the properties of CuS nanoparticles. Their emerging applications in gas sensing, photocatalysis, solar cells, batteries, supercapacitors, environmental remediation, antimicrobial activity and biomedical applications are also reviewed. The challenges and future prospects of CuS nanoparticles for advanced technological applications are briefly discussed.

Keywords: CuS nanoparticles; Copper sulfide; Optical properties; Photocatalysis; Energy storage; Biomedical applications.

1. Introduction

Copper sulfide (CuS) nanoparticles have attracted considerable attention in recent years because of their distinctive structural, optical, electrical, catalytic, and chemical properties. CuS is an important copper chalcogenide material whose properties are strongly influenced by crystal structure, stoichiometry, particle size, morphology, surface defects, and synthesis conditions. In particular, covellite CuS exhibits a characteristic layered hexagonal structure and unusual electronic characteristics, which contribute to its potential in sensing, photocatalysis, energy conversion and storage, optoelectronics, and biomedical applications. Shamraiz et al. (2016) reviewed the diverse properties and applications of CuS nanostructures and highlighted their potential in photocatalysis, gas sensing, lithium-ion batteries, supercapacitors, solar cells, photoelectrochemical devices, and biosensing. Several synthesis approaches have been developed to prepare CuS nanoparticles with controlled size, morphology, and composition. Conventional methods include chemical precipitation, co-precipitation, sol–gel, hydrothermal, solvothermal, thermolysis, and solution-based techniques, while sonochemical, microwave-assisted, electrochemical, and biological approaches have also been investigated. Kundu and Pradhan (2014) demonstrated that CuS nanostructures with different morphologies could be obtained through a simple template-free solution method by controlling solvent composition, reaction temperature, reaction duration, precursor ratio, and counterions. They obtained spherical and nanotubular CuS assemblies and reported optical band-gap values of approximately 1.88–2.16 eV. Shamraiz et al. (2016) further emphasized that the selection of synthesis route provides an effective means of controlling CuS morphology and, consequently, its functional properties. More recently, green synthesis methods using plant extracts, microorganisms, and other biological resources have received increasing attention because they can reduce the use of hazardous chemicals and provide relatively simple and environmentally compatible routes for nanoparticle preparation. The selection of synthesis route and reaction parameters, including precursor concentration, pH, temperature, reaction time, solvent composition, and the use of surfactants or capping agents, plays an important role in determining the physicochemical characteristics of CuS nanoparticles. Wang (2016) reported that different synthetic approaches can produce CuS nanospheres, nanocages, nanoplates, nanotubes, nanorods, and nanowires, demonstrating the strong relationship between synthesis conditions and morphology. The characterization of CuS nanoparticles is essential for establishing their structure–property relationships. Goel et al. (2014) highlighted the importance of X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), Fourier-transform infrared spectroscopy (FTIR), UV–Visible spectroscopy, and photoluminescence spectroscopy for determining the structural, morphological, compositional, and optical characteristics of CuS nanoparticles. XRD is particularly important for identifying the crystalline phase and estimating crystallite size, whereas SEM/FESEM and TEM provide information regarding morphology, particle size, and nanostructure. EDX/EDAX is generally employed to confirm elemental composition, while FTIR and Raman spectroscopy provide information concerning chemical bonding and vibrational characteristics. UV–Visible spectroscopy is widely used to investigate optical absorption and band-gap behavior, whereas PL spectroscopy can provide information about defect-related electronic transitions and recombination processes. CuS nanoparticles have demonstrated considerable potential in gas and chemical sensing, photocatalytic degradation of pollutants, solar-energy conversion, lithium-ion batteries, supercapacitors, antimicrobial applications, and biomedical technologies. Shamraiz et al. (2016) reported applications of CuS nanostructures in gas sensing, photocatalytic degradation, lithium-ion batteries, organic solar cells, supercapacitors, photoelectrochemical devices, and electrochemical biosensing. Goel et al. (2014) particularly emphasized biomedical applications, including biomolecule and pathogen detection, molecular imaging, photothermal cancer therapy, drug delivery, and theranostic systems, which are associated with the strong optical and photothermal response of CuS nanoparticles. Thus, the combination of tunable optical properties, electrical behavior, high surface activity, and photothermal characteristics makes CuS an attractive multifunctional nanomaterial. Table 1 summarizes important physicochemical properties of CuS nanoparticles. CuS has a molecular mass of approximately 95.61 g mol^{-1} and, in its commonly discussed covellite phase, crystallizes in a hexagonal crystal system. The crystallographic refinement by Evans and Konnert (1976) established the covellite structure with space group $P6_3/mmc$ and lattice parameters of a = 3.7938 Å and c = 16.341 Å. The optical band-gap values reported for CuS nanostructures can vary considerably depending on morphology, particle size, stoichiometry, and measurement conditions; for example, Kundu and Pradhan (2014) reported values in the range of 1.88–2.16 eV for different CuS morphologies. At the nanoscale, CuS can exhibit high surface-to-volume ratios and abundant surface-active sites, which are particularly beneficial for catalytic and sensing applications. Figure 1 illustrates the crystal structure of copper sulfide corresponding to the hexagonal covellite phase. The structure consists of Cu and S atoms arranged in an ordered hexagonal framework with characteristic Cu–S interactions and layered structural features. According to Evans and Konnert (1976), covellite belongs to the $P6_3/mmc$ space group, with lattice parameters of approximately a = 3.79 Å and c = 16.34 Å. The crystal structure contains nonequivalent Cu and S sites and exhibits an unusual arrangement of copper and sulfur atoms. The structural characteristics of covellite are closely associated with its electronic behavior; theoretical investigations have shown that Cu–S interactions and S–S bonding contribute significantly to its electronic structure. Mazin (2011) discussed the unusual electronic and structural characteristics of covellite CuS and its mixed copper-valence behavior. In nanoparticle form, variations in particle size, surface structure, copper vacancies, and other defects can further modify the electronic and optical characteristics of CuS, thereby influencing its conductivity, light absorption, catalytic activity, and surface reactivity.

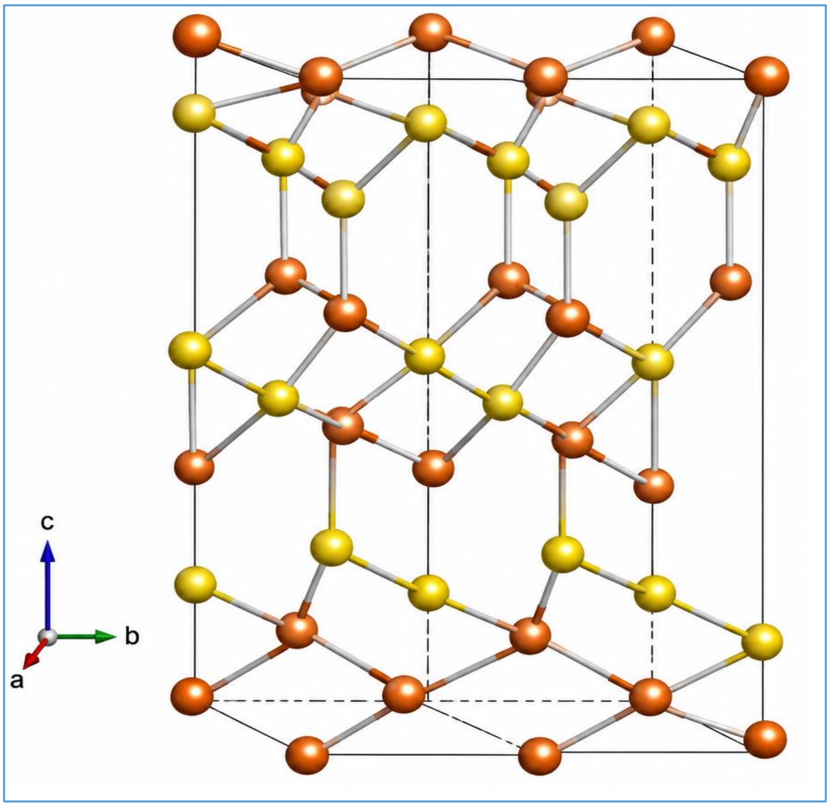

Figure 1. Crystal structure of copper sulfide

The electrical conductivity of CuS is vary considerably with stoichiometry and copper vacancies, while strong absorption in the visible and near-infrared regions contributes to its photothermal and optoelectronic properties. These physicochemical characteristics make CuS nanoparticles promising materials for different applications.

Table 1: Physicochemical properties

Sr. No.	Parameter	Value
1	Chemical formula	CuS
2	Molar mass	95.61 g mol^{-1}
3	Crystal system	Hexagonal
4	Lattice parameter, a	≈ 3.79 Å

5	Lattice parameter, c	≈ 16.34 Å
6	Density	≈ 4.6–4.8 g cm^{-3}
7	Band gap	≈ 1.2–2.0 eV
8	Melting point	≈ 500 °C
9	Particle size	≈ 5–100 nm
10	Specific surface area	≈ 20–150 m^2 g^{-1}
11	Electrical conductivity	≈ 10^{-2}–10^2 S cm^{-1}
12	Absorption edge	≈ 620–1030 nm
13	Refractive index	≈ 2.0–3.0

This short review summarizes the major synthesis strategies, characterization techniques, important functional properties and emerging applications of CuS nanoparticles, while also highlighting their potential challenges and future research prospects.

2. Literature survey

Copper sulfide nanoparticles have emerged as important semiconductor nanomaterials because of their distinctive structural, optical, electrical, catalytic, and photothermal properties. Earlier reviews have established that the morphology and dimensions of CuS nanostructures can be controlled through appropriate synthetic strategies, thereby enabling their properties to be tailored for specific applications (Goel et al., 2014; Shamraiz et al., 2016). Kundu and Pradhan (2014) reported a controlled solution-based synthesis of CuS nanostructured assemblies using a mild, template-free approach. By varying the solvent composition and reaction conditions, they obtained different morphologies, including spherical and nanotubular structures assembled from CuS nanoplates or nanoparticles. Their work demonstrated that solvent polarity, precursor ratio, reaction temperature, and reaction duration have important effects on nucleation and crystal growth. The study further showed that morphological control can significantly influence the catalytic behavior of CuS. This work is particularly important because it established a relatively simple route for producing morphology-controlled CuS nanostructures without complicated templates or high-temperature processing. In the same period, Ma et al. (2014) investigated the transformation of CuO nanoparticles into copper sulfide through sulfidation. Their study demonstrated that approximately 40 nm CuO nanoparticles could react with inorganic sulfide in aqueous media to generate several copper sulfide species, including crystalline covellite CuS and amorphous copper sulfide phases. X-ray absorption spectroscopy, XRD, and TEM were used to establish the structural transformation. The authors also observed that sulfidation involved changes in copper oxidation state and could modify the solubility and environmental behavior of the nanoparticles. This study is significant because it demonstrates that CuS nanoparticles can also form through transformation reactions and that their phase composition depends strongly on the chemical environment. Schaffie and Hosseini (2014) developed a biological approach for producing semiconductor copper sulfide nanoparticles directly from mine wastewater. Their process utilized contaminated water generated during copper mining and demonstrated simultaneous removal of copper ions and formation of copper sulfide nanoparticles. The synthesized particles exhibited a covellite composition with particle sizes of approximately 10–40 nm. This study provided an important alternative to conventional synthesis because it connected wastewater treatment with the production of useful semiconductor nanomaterials. Such approaches have potential advantages in terms of resource recovery, waste minimization, and sustainable nanomaterial production.

Saldanha et al. (2014) developed a generalized one-pot route for preparing copper chalcogenide nanocrystals without conventional hot-injection procedures. Their method operated at moderate temperatures of approximately 200–220 °C and enabled the synthesis of copper sulfide and related mixed chalcogenide nanocrystals. The study highlighted the importance of precursor chemistry and reaction conditions in controlling the composition and formation of copper chalcogenide nanomaterials. Such one-pot approaches are valuable because they simplify synthesis while providing improved control over the resulting nanocrystals. Shamsipur et al. (2014) investigated the electrochemical preparation and thermal characteristics of CuS nanoparticles. Copper sulfide nanoparticles with different sizes and morphologies were produced by electrolysis using a copper plate as the anode in aqueous sodium sulfide solution. The authors demonstrated that the applied electrolysis voltage and sulfide-ion concentration could influence the morphology and particle size. This study established electrochemical synthesis as another feasible approach for producing CuS nanomaterials and emphasized the role of processing parameters in controlling nanoparticle characteristics. Singh et al. (2015) reported a simple one-pot sonochemical method for synthesizing CuS nanoparticles for solar-cell applications. Copper acetate and thiourea were employed as precursors, while the effects of sonication time, ultrasonic bath temperature, and annealing temperature on the synthesized nanoparticles were investigated. Structural, morphological, and optical properties were studied using XRD, SEM, TEM, and UV–Visible spectroscopy. Their work demonstrated that sonochemical processing can provide a comparatively simple route for producing CuS nanoparticles with properties suitable for photovoltaic applications. Krishnamoorthy et al. (2015) synthesized CuS nanoparticles through a sonochemical route using copper nitrate and thiourea. XRD confirmed the formation of hexagonal CuS, while FESEM indicated nanoparticle sizes of approximately 50 nm. The electrochemical properties were evaluated using cyclic voltammetry and electrochemical impedance spectroscopy. A specific capacitance of approximately 62.77 F g^{-1} was reported at a scan rate of 5 mV s^{-1}, indicating promising pseudocapacitive behavior. This study demonstrated that nanoscale CuS can function as an electrochemically active material and highlighted its potential for energy-storage applications. Shamraiz et al. (2016) provided a comprehensive review of the synthesis and applications of CuS nanostructures. They classified the reported synthesis approaches into solvothermal, aerosol, solution-based, and thermolysis methods. Their review showed that CuS nanostructures have been investigated for photocatalytic degradation, cancer-cell ablation, lithium-ion batteries, gas sensing, organic solar cells, field emission, supercapacitors, photoelectrochemical cells, and biosensing. The authors emphasized that different synthetic methods can produce substantial variations in particle morphology, crystallinity, and surface properties, which ultimately determine the functional performance of CuS. Goel et al. (2014) reviewed the synthesis and biomedical applications of CuS nanoparticles and highlighted the importance of controlling nanoparticle size, shape, and surface characteristics. Different morphologies, including nanospheres, hollow nanospheres, nanoplates, and nanorods, were reported. The authors noted that XRD, SEM, TEM, EDS, FTIR, UV–Visible spectroscopy, and photoluminescence spectroscopy are important tools for determining the structural, compositional, morphological, and optical properties of CuS nanoparticles. In biomedical applications, CuS nanoparticles were investigated for biomolecule sensing, molecular imaging, photothermal therapy, drug delivery, and theranostics. Their strong optical absorption and photothermal response make CuS particularly interesting for light-mediated biomedical applications. Rai et al. (2020) reported an environmentally friendly route for the preparation of CuS nanoparticles using a plant extract. The synthesized material was characterized using UV–Visible spectroscopy, FTIR, XRD, TEM, SEM, and particle-size analysis. XRD confirmed the formation of hexagonal CuS, while the average particle size was below 100 nm. The nanoparticles exhibited plate-like and agglomerated morphologies. The study also examined biological activity, including antibacterial and cytotoxic behavior, demonstrating the potential of biologically synthesized CuS nanoparticles for biomedical and antimicrobial applications. Such green synthesis approaches are particularly attractive because plant-derived compounds can act as reducing, stabilizing, and capping agents during nanoparticle formation. Agarwal et al. (2021) synthesized precursor-dependent CuS nanoparticles by varying the amount of sulfur precursor and investigated their multifunctional catalytic behavior. The resulting CuS nanoparticles were used for photocatalytic oxidation of aromatic alcohols, degradation and reduction of water pollutants, and synthesis of pharmaceutically important triazole compounds. Their findings demonstrated that changes in precursor concentration can modify the properties and catalytic activity of CuS nanoparticles. This work further illustrates the importance of synthesis optimization in obtaining CuS materials with suitable active sites and catalytic performance. Ain et al. (2022) reviewed recent developments in Cu_xS_γ nanostructures, with particular emphasis on synthesis, morphology, biosensing, imaging, and cancer-related applications. The authors highlighted the strong near-infrared absorption of small copper sulfide nanostructures and explained that their optical response can be adjusted through changes in stoichiometry. CuS-based nanostructures were discussed for biosensors, photoacoustic imaging, and photothermal cancer treatment. Their review indicates that the combination of tunable optical properties, relatively low material cost, and nanoscale surface characteristics makes copper sulfide an attractive platform for multifunctional applications. Yabuki et al. (2022) investigated copper-sulfide nanoparticle electrodes for electrochemical carbon dioxide reduction. The electrode was prepared through thermal decomposition of sulfur and a copper–amine complex precursor, producing a film containing $Cu_{1.8}S$ and CuS nanoparticles. The copper sulfide electrode demonstrated electrochemical activity for CO_2 reduction and produced C_2 products, including ethylene. This work expands the application range of copper sulfide nanomaterials from conventional sensing and energy-storage applications toward electrocatalytic environmental technologies. Tetyana et al. (2023) investigated the synthesis, characterization, and electrochemical properties of CuS nanoparticles for non-enzymatic glucose detection. Their work demonstrated the usefulness of CuS as an electroactive sensing material for glucose analysis in blood samples. The study combined structural and morphological characterization with electrochemical measurements to establish the sensing performance of the nanoparticles. This research highlights the importance of CuS surface activity and charge-transfer characteristics for developing low-cost electrochemical biosensors. Jeon et al. (2023) addressed an important limitation associated with conventional CuS nanoparticle synthesis, namely low production yield and harsh reaction conditions. They developed a high-concentration copper-complex precursor method capable of producing CuS nanoparticles at room temperature and atmospheric pressure. Increasing precursor concentration reduced particle size while improving yield, and nanoparticles of approximately 17 nm were obtained without severe agglomeration. The synthesized CuS nanoparticles also exhibited strong near-infrared absorption and excellent photothermal performance. This work is particularly relevant for future industrial applications because scalable synthesis with lower energy requirements is essential for translating laboratory-scale CuS nanomaterials into practical technologies. Tripathi et al. (2024) investigated the influence of polyvinylpyrrolidone (PVP) molecular weight on the synthesis of ultrasmall CuS nanoflakes. Their work focused on controlling nanoparticle morphology and size through the interaction between PVP and the growing CuS surface. The resulting ultrasmall CuS nanostructures were investigated for photothermal and photoacoustic applications. This study demonstrates that polymer-assisted synthesis provides an effective strategy for controlling nanoscale morphology and surface properties, which are critical parameters for biomedical applications. Lafta and Salman (2024) reported the green synthesis of CuS nanoparticles using myrtle leaf extract and evaluated their antibacterial properties. The synthesized nanoparticles were characterized using FTIR, AFM, UV–Visible spectroscopy, FESEM–EDX, and XRD. The crystallite size determined from XRD was approximately 21.4 nm, and antibacterial activity was evaluated against Staphylococcus aureus and Escherichia coli. Their results support the growing interest in plant-mediated synthesis as an economical and environmentally compatible approach for producing CuS nanoparticles with biological functionality. More recently, Al-Adhreai et al. (2025) investigated Bi-doped CuS nanoparticles prepared by a chemical co-precipitation method. Pure CuS and Bi-doped samples containing different Bi concentrations were characterized using diffraction, spectroscopic, and microscopic techniques. XRD confirmed the hexagonal CuS phase, while the crystallite size increased from approximately 15.15 nm for undoped CuS to 16.22 nm for the 10 wt.% Bi-doped sample. UV–Visible diffuse-reflectance measurements showed that the optical band gap decreased from approximately 1.38 eV for pure CuS to 1.23 eV after higher Bi incorporation, indicating enhanced visible-light absorption. The study also investigated the photocatalytic properties of the prepared materials, demonstrating the potential of dopant engineering for modifying the functional properties of CuS nanoparticles.

3. Synthesis methods of CuS nanoparticles

Figure 2 illustrates the major synthesis routes used for the preparation of copper sulfide nanoparticles, including chemical precipitation, co-precipitation, sol–gel, hydrothermal, solvothermal, sonochemical, microwave-assisted, thermal decomposition, electrochemical and green synthesis methods.

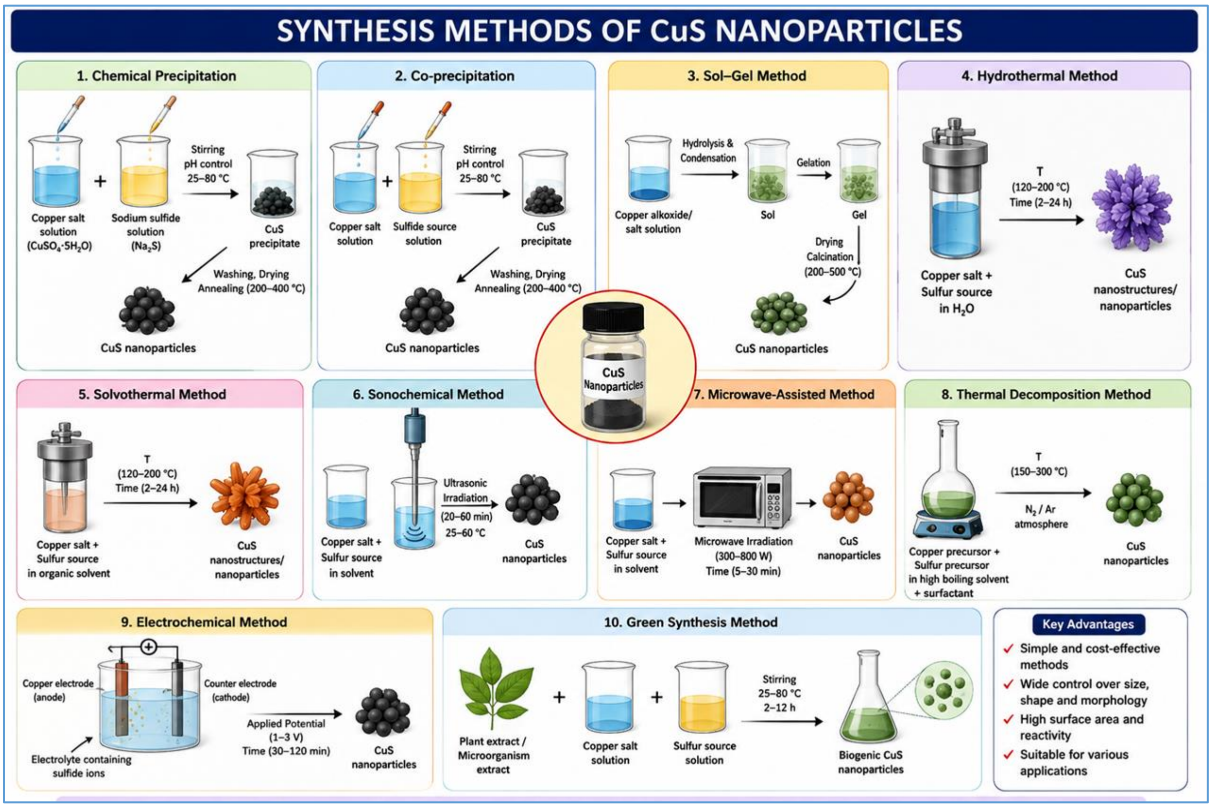

Figure 2. Different synthesis methods of CuS nanoparticles

Among these approaches, precipitation and solution-based methods are widely preferred because of their simplicity, low cost, and ease of controlling particle size through precursor concentration, pH, temperature, and reaction time. Shamraiz et al. (2016) reported that solution, solvothermal, aerosol, and thermolysis routes are among the important fabrication approaches for CuS nanostructures, with the synthesis conditions strongly influencing their morphology and crystallinity. Hydrothermal and solvothermal techniques employ elevated temperature and pressure and are particularly useful for obtaining well-crystallized CuS nanostructures with controlled morphologies. Sonochemical synthesis uses ultrasonic irradiation to enhance nucleation and particle formation; Singh et al. (2015) successfully synthesized CuS nanoparticles using copper acetate and thiourea through a one-pot sonochemical process for solar-cell applications. Microwave-assisted synthesis provides rapid and uniform heating and can significantly reduce reaction time; Nafees et al. (2013) reported an aqueous microwave-assisted route for producing spherical CuS nanoparticles using copper acetate and sodium thiosulfate without surfactants or templates. Similarly, microwave irradiation has been used to produce porous CuS aggregates consisting of approximately 10 nm nanoparticles, demonstrating the potential of rapid heating for controlling nanoscale morphology. Electrochemical synthesis provides another route in which copper ions and sulfide species react under an applied potential, whereas green synthesis employs plant extracts, microorganisms, or other biological resources as environmentally friendly stabilizing and reducing media. More recently, Decker et al. (2024) demonstrated aqueous and flow-based synthesis of covellite CuS nanocrystals with sizes of approximately 5 ± 2 nm, highlighting the potential of water-based and scalable synthesis for sustainable CuS production. Thus, the choice of synthesis method plays a crucial role in controlling the crystal phase, particle size, morphology, surface area, optical properties, and functional performance of CuS nanoparticles, which ultimately determines their suitability for sensing, photocatalysis, energy storage, solar-energy conversion, environmental remediation, and biomedical applications.

4. Emerging applications of CuS nanoparticles

Figure 3 illustrates the major applications of copper sulfide nanoparticles, which arise from their unique optical, electrical, semiconductor, catalytic, and photothermal properties. CuS nanoparticles possess strong visible and near-infrared absorption, high surface activity, and tunable electronic properties, making them attractive for a wide range of technological applications. Shamraiz et al. (2016) reviewed the use of CuS nanostructures in gas sensing, photocatalytic degradation, lithium-ion batteries, supercapacitors, organic solar cells, field-emission devices, photoelectrochemical cells, and electrochemical biosensing. In gas-sensing applications, the high surface-to-volume ratio and electrical conductivity of CuS nanoparticles facilitate interaction with target gas molecules and changes in electrical resistance, making them promising for detecting various toxic and environmental gases. CuS nanoparticles are also effective photocatalytic materials because of their strong light absorption and suitable electronic structure, and have been investigated for degradation and reduction of organic pollutants and environmental contaminants.

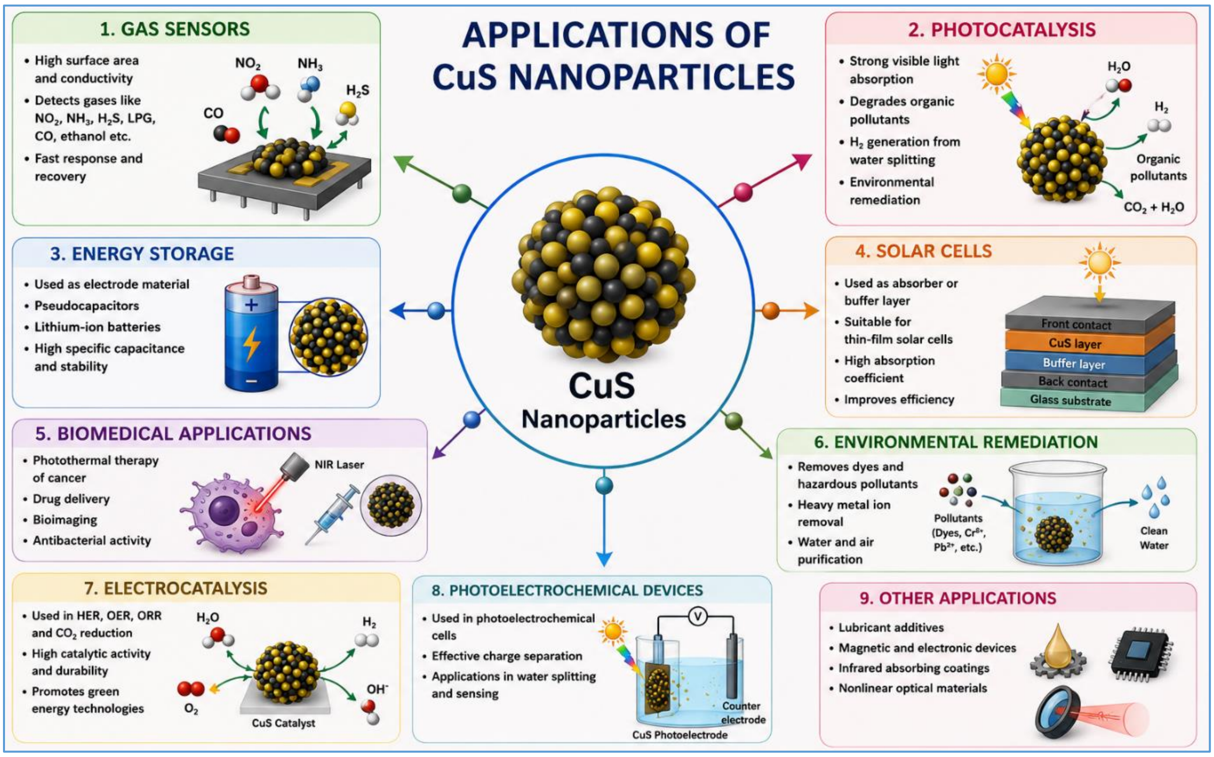

Figure 3. Applications of CuS nanoparticles

Krishnamoorthy et al. (2015) demonstrated the electrochemical activity of CuS nanoparticles and reported pseudocapacitive behavior with a specific capacitance of about 62.77 F g^{-1}, indicating their potential for supercapacitors and other energy-storage devices. CuS is further explored as an electrode or functional material in lithium-ion batteries, solar cells, photoelectrochemical devices, and electrocatalytic systems because of its electrical conductivity and light-absorption characteristics. In the biomedical field, CuS nanoparticles have received considerable attention because of their strong near-infrared photothermal response and surface functionalization capability. Goel et al. (2014) reported applications of CuS nanoparticles in biomolecule and pathogen detection, molecular imaging, photothermal cancer therapy, drug delivery, and theranostic systems. Wang et al. (2016) further highlighted the potential of CuS nanoparticles for imaging, photothermal therapy, combinational cancer treatment, and drug-delivery applications. In addition, CuS nanoparticles can be employed for environmental remediation, including photocatalytic removal of dyes and other organic pollutants from contaminated water. Their catalytic and photoactive properties also make them promising for electrocatalysis and solar-driven chemical reactions. The diverse applications shown in Figure 3 demonstrate that CuS nanoparticles are versatile multifunctional materials with considerable potential in sensing, photocatalysis, energy storage and conversion, solar-energy technologies, environmental protection and biomedical applications.

5. Conclusions

Copper sulfide nanoparticles are promising multifunctional semiconductor nanomaterials owing to their unique structural, optical, electrical, catalytic and photothermal properties. This review has summarized the major synthesis strategies, including precipitation, co-precipitation, sol–gel, hydrothermal, solvothermal, sonochemical, microwave-assisted, thermal decomposition, electrochemical, and green synthesis methods. The physicochemical properties of CuS nanoparticles are strongly dependent on synthesis conditions, crystal structure, particle size, morphology, stoichiometry, and surface defects. Advanced characterization techniques such as XRD, FESEM, TEM, EDX, FTIR, Raman, UV–Visible and PL spectroscopy are essential for understanding their structure–property relationships. Owing to their high surface activity, strong optical absorption, tunable electronic properties, and good catalytic and photothermal behavior, CuS nanoparticles have considerable potential for gas sensing, photocatalysis, solar cells, energy storage, environmental remediation, electrocatalysis, antimicrobial activity, and biomedical applications. Future research should focus on green and scalable synthesis, precise control of morphology and stoichiometry, CuS-based nanocomposites, improved stability and systematic optimization of sensing and energy-related performance. CuS nanoparticles represent a versatile platform for the development of advanced materials and next-generation multifunctional devices.

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