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Copper Sulfide Semiconducting Nanoparticles for Antibacterial Applications: Synthesis Strategies, Mechanisms and Performance – A Review

Rupali Pradeep Patil[1,*], Bharat B. Kale[2]

Abstract

Copper sulfide nanoparticles (CuS NPs) have drawn growing attention as a next-generation antibacterial platform, owing to their tunable structural, optical, and catalytic properties. This review consolidates current evidence on CuS NP synthesis, mechanisms, and antibacterial performance, comparing chemical and green synthesis routes alongside the effects of morphology, doping, and surface modification. Mechanistically, CuS NPs act through several overlapping pathways, including reactive oxygen species generation, bacterial membrane disruption, ion release, and synergistic photothermal or photodynamic effects. Performance data indicate broad-spectrum activity against both Gram-positive and Gram-negative bacteria, with particularly strong efficacy against biofilms and multidrug-resistant strains; quantitative measures – such as minimum inhibitory concentration and zone of inhibition – support these findings, and combination with conventional antibiotics offers a further route to lower effective dosing. Beyond standalone applications, CuS–polymer nanocomposites extend this activity into biomedical coatings, wound dressings, sensors, and energy devices, while also improving mechanical and thermal properties of the host matrix. Even so, biocompatibility optimization, toxicity control, and long-term stability testing remain unresolved before clinical translation becomes routine. Emerging directions include stimuli-responsive and self-healing composites, machine learning-guided formulation design, and real-time biomedical monitoring platforms built around CuS nanostructures. Overall, this review positions CuS nanoparticles as a versatile and sustainable platform for antimicrobial applications, while identifying the methodological gaps that stand between current laboratory findings and reliable clinical use.

Keywords: Copper sulfide nanoparticles, antibacterial mechanisms, green synthesis, chemical synthesis, biofilms, clinical translation, biopolymers, nanoparticle, green composite, microstructural properties, thermal analysis

***Author for Correspondence**
Rupali Pradeep Patil
E-mail id: rupali.patil23@pcu.edu.in

[1]Research Scholar, Department of Chemistry, Pimpri Chinchwad University, Pune, Maharashtra, India
[1]Assistant Professor, Department of Applied Sciences and Humanities, Pimpri Chinchwad College of Education and Research, Ravet, Pune, Maharashtra, India
[2]Director, Research & Development, Department of Chemistry, Pimpri Chinchwad University, Pune, Maharashtra, India

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INTRODUCTION

Background on Copper Sulfide Nanoparticles (CuS NPs)

Copper sulfide is not a single material so much as a family of related phases djurleite (Cu2.S), chalcocite (Cu2S), covellite (CuS) and which phase forms depends heavily on synthesis conditions. That matters because each phase carries its own optical and electronic fingerprint, and covellite in particular stands out for its tunable band gap and unusually strong near-infrared absorption [1]. These properties are what pulled CuS nanoparticles into biomedical and environmental research in the first place. At the particle level, work in this area has already shown bacterial inactivation, wound-healing support, and photothermal ablation of microbial cells, and the mechanism behind much of

these traces back to how CuS interacts with bacterial membranes disrupting ion transport, exposing reactive surface sites, and generally destabilizing the cell envelope. Relative to other copper-based nanomaterials, CuS also tends to hold up better on stability and biocompatibility [2], which is not a small advantage given how often nanomaterial candidates fail on exactly those two criteria. Control over particle size and surface chemistry comes from the synthesis route chosen hydrothermal and solvothermal methods on one side, greener biologically mediated routes on the other and when CuS particles are worked into polymeric films or chitosan-based composites, the resulting material tends to gain mechanical strength alongside its antibacterial function. That combination is a large part of why CuS now sits at a genuinely useful intersection of materials science, nanomedicine, and antimicrobial engineering [3]. A conceptual schematic of how CuS nanoparticles engage bacterial cells across these pathways is presented in Figure 1.

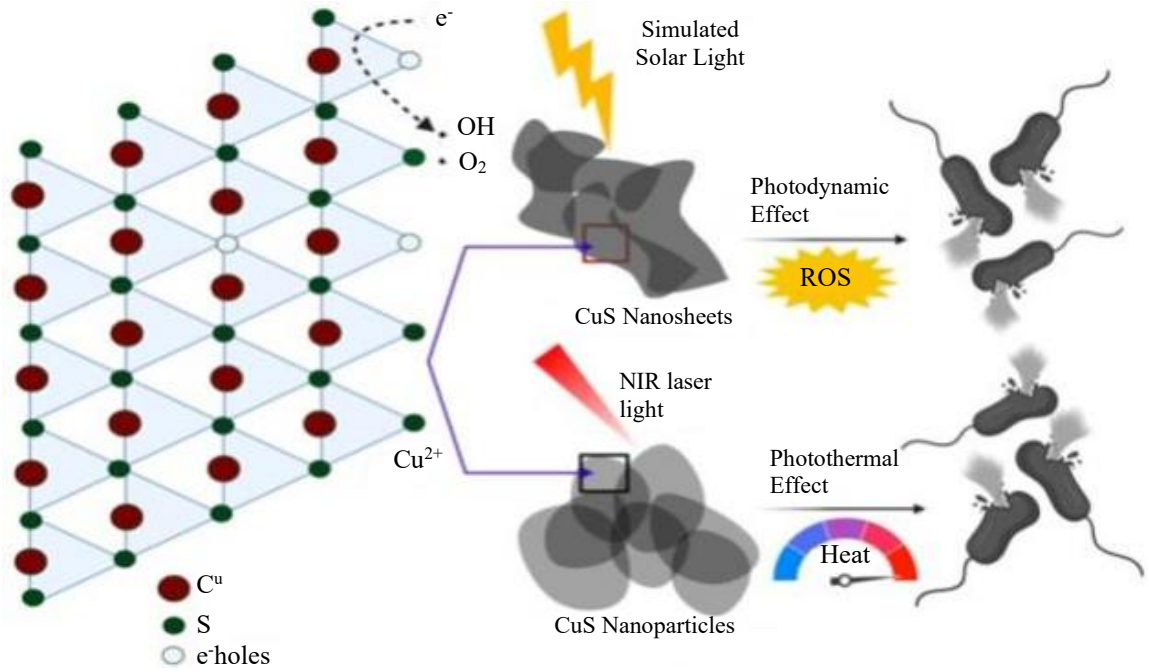

Figure 1. Conceptual schematic showing CuS nanoparticles interacting with bacterial cells [2].

Rationale for Focusing on Copper Sulfide Nanoparticles Relative to Other Metal Sulfide Nanomaterials

Metal sulfide nanomaterials as a class – CuS, ZnS, PbS, CdS, Ag_2S, MoS_2, and Bi_2S_3 among them – all show some degree of antibacterial or photo-responsive behavior, so the choice to build this review specifically around copper sulfide deserves an explicit justification rather than an implicit one. Several considerations converge to make CuS the more defensible focus. First, CuS is intrinsically a p-type, self-doped semiconductor: copper vacancies in the covellite lattice generate a high density of free holes without any external doping step, giving rise to strong, tunable near-infrared absorption that wide-bandgap sulfides – such as ZnS – simply do not exhibit under ambient conditions [1, 4]. This self-doped character is what enables the combined photothermal-photodynamic antibacterial action described throughout this review, rather than a purely UV-driven photocatalytic effect. Second, toxicity and regulatory considerations favor copper over cadmium- or lead-based chalcogenides: CdS and PbS quantum dots carry well-documented heavy-metal toxicity liabilities that constrain their translation into wound-care or implant-coating applications, whereas copper is a trace element with an established physiological role and a comparatively favorable biocompatibility profile once particle size and dose are controlled [2]. Third, relative to noble or precious metal sulfides, such as Ag_2S, copper is orders of magnitude more abundant and less costly, which matters directly for the scalability arguments developed in Section 3. Fourth, compared with layered transition-metal dichalcogenides, such as MoS_2, whose antibacterial action is dominated by physical membrane piercing from exfoliated nanosheets,

CuS offers a genuinely multimodal mechanism – ion release, reactive oxygen species generation, and light-triggered hyperthermia acting together – which gives more design flexibility for tuning potency against different bacterial targets [5–10]. Taken together, these points are why this review narrows its scope to CuS rather than attempting a broader, shallower survey of metal sulfide antibacterials generally: the combination of tunable self-doped optical behavior, comparatively low toxicity, elemental abundance, and multimodal antibacterial action is not evenly shared across the wider metal sulfide family, and CuS sits at a genuinely favorable point on all four axes simultaneously.

Importance of Antibacterial Nanomaterials in Healthcare

Antibiotic resistance has not slowed down, and that reality has pushed both clinicians and researchers to look past conventional drug classes for new antibacterial strategies. Nanomaterials are one of the more promising alternatives to emerge from that search. Part of the appeal is straightforwardly physical: a high surface-to-volume ratio lets nanoparticles interact directly with bacterial membranes and generate reactive oxygen species right at the site of contact, which can head off biofilm formation before it takes hold. CuS, ZnO, and silver nanoparticles have all shown this kind of consistent antibacterial behavior, and this is the more interesting part generally without provoking the same resistance pressure that antibiotics do. Built into wound dressings, coatings, or delivery systems, these particles have been reported to speed healing and cut reinfection rates, which is why antibiotic-free antimicrobial strategies and nanomaterial-based vaccine platforms are drawing so much attention right now. There is also a toxicity argument in their favor: because nanoparticle delivery can be localized and dose-controlled, systemic toxicity often comes out lower than with conventional dosing. CuS NPs fit this picture well. Their photothermal and photodynamic behavior gives them a mode of action that works alongside existing therapies rather than displacing them, and that versatility is a big reason nanoparticle-based antibacterials keep gaining ground as healthcare shifts toward more precision-oriented treatment.

Current Limitations of Traditional Antibiotics and the Emergence of "Nano-Antibiotics"

Conventional antibiotics are under pressure from several directions at once. Cellular resistance mechanisms, biofilm-based protection, and outright failure to penetrate certain bacterial envelopes all erode their effectiveness, and decades of overuse have only accelerated the rise of resistant organisms – such as *Pseudomonas aeruginosa* and *Staphylococcus aureus* – both now flagged as major global health threats [11]. Nano-antibiotics offer one way around this, whether as intrinsically antibacterial nanomaterials or as nanoparticle-based carriers for existing drugs. What sets them apart mechanistically is that they rarely rely on a single molecular target: reactive oxygen species generation, direct membrane damage, and interference with bacterial DNA replication tend to act together rather than in isolation. CuS-based nano-antibiotics can go a step further, pairing with photothermal or photodynamic therapy for a more localized bactericidal punch, and their small size brings a pharmacokinetic advantage too, through enhanced permeability and retention [11]. Because these particles can act on quorum sensing and broader metabolic pathways instead of one enzyme, they can, at least in principle, sidestep some conventional resistance mechanisms outright. Hybrid nanocarriers combining CuS with antibiotics or biopolymers have shown improved antibacterial activity alongside reduced cytotoxicity in early studies which is really the main reason nano-antibiotics keep getting described as a plausible next generation of antimicrobial therapy, rather than just a lab curiosity.

Delineation of Structure–Property Relationships Governing Antimicrobial Efficacy of CuS Nanocrystals

How well a CuS nanocrystal performs against bacteria depends on a cluster of structural factors size, shape, crystallinity, and surface functionalization and none of these acts independently [4]. Smaller particles carry more surface energy, which speeds up both ion release and ROS formation; the covellite phase tends to be favored for its electron mobility and photothermal conversion; and surface modification with biocompatible ligands (chitosan, polyethylene glycol, plant-derived biomolecules, among others) generally improves dispersion stability and biological contact. Morphology matters too flower and sphere-shaped particles have repeatedly outperformed other shapes on bacterial contact area and photothermal response and band-gap engineering through doping or hybridization with other

semiconductors – such as ZnO or TiO_2 – can push effectiveness further still. Surface charge and zeta potential round out the picture, shaping exactly how a given particle interacts with a bacterial membrane on contact [12]. None of this is arbitrary: understood together, these structure–property relationships give a reasonably rational basis for designing CuS nanoparticles with antibacterial mechanisms tailored to particular microbial strains, rather than relying on trial and error.

There is also a polymer nanocomposite dimension to this that matters for this journal's scope specifically. Within biopolymer matrices, such as chitosan, sodium alginate, or carrageenan, CuS NPs are not passive fillers; they interact with the polymer chains through electrostatic, coordinate-covalent, and hydrogen-bonding forces, and those interactions simultaneously reshape chain mobility, crystallinity, and mechanical stiffness [13, 14]. Because nanoparticle surface chemistry and macromolecular host behavior are coupled this tightly, antibacterial performance cannot really be optimized in isolation from the composite architecture around it. That coupling is precisely why CuS NP research belongs as much to functional polymer nanocomposite and biomacromolecule science as it does to nanomedicine [2].

Gap in Literature and Rationale for Systematic Review

For all the progress summarized above, the CuS nanoparticle literature is still fairly fragmented. Most papers commit early to either a chemical or a green synthesis route and rarely offer a comparison spanning structural, functional, and biological outcomes together which makes cross-study comparison harder than it should be. Inconsistent experimental protocols and characterization practices compound the problem, limiting how translatable or repeatable any given finding actually turns out to be. Structure-property studies explaining why CuS performs differently against Gram-positive versus Gram-negative strains are comparatively rare, even though ion release and ROS generation are cited again and again as the dominant mechanisms at play. These are the gaps this review is built around. Following PRISMA guidelines, it consolidates the existing evidence under a single, consistent methodological standard, with the broader goal of steering future work toward more sustainable production routes and clinically relevant applications of CuS nanocrystals.

Objectives

Apply PRISMA methodology to synthesize the published evidence on copper sulfide nanoparticles as antibacterial agents. Compare the advantages, limitations, and scalability of chemical and green synthesis routes. Examine the antibacterial mechanisms of CuS NPs, with particular attention to ion release, ROS generation, and structural interaction with bacterial membranes. Identify research gaps and outline future directions for sustainable nanomaterial development and clinical translation.

METHODOLOGY (SYSTEMATIC REVIEW FRAMEWORK)

The review follows the PRISMA 2020 framework. Scopus, Web of Science, PubMed, and Google Scholar were searched for studies published between 2010 and 2026 on the antibacterial effects of copper sulfide nanoparticles, and for each included study we recorded particle properties, production method, and antibacterial outcome MIC, zone of inhibition, and ROS measurements were reported. The point of this structure is simply traceability: it keeps the evidence base for CuS antibacterial claims reproducible rather than anecdotal [15]. The complete study identification, screening, and inclusion process is summarized in the PRISMA flow diagram in Figure 2.

SYNTHESIS STRATEGIES

CuS nanoparticles are synthesized via chemical or green methods, each with trade-offs. Chemical routes (co-precipitation, hydrothermal, sol–gel) allow precise control over size and morphology but use toxic reagents. Green synthesis, using plant extracts or microorganisms, is safer, cheaper, and more biocompatible, though less uniform. The choice depends on the intended application. The subsections that follow examine these two synthesis families in detail, benchmark them against one another on cost, scalability, toxicity, reproducibility, and environmental impact, and set out a more granular classification of individual techniques by the particle size, morphology, crystallinity, and scalability they typically produce.

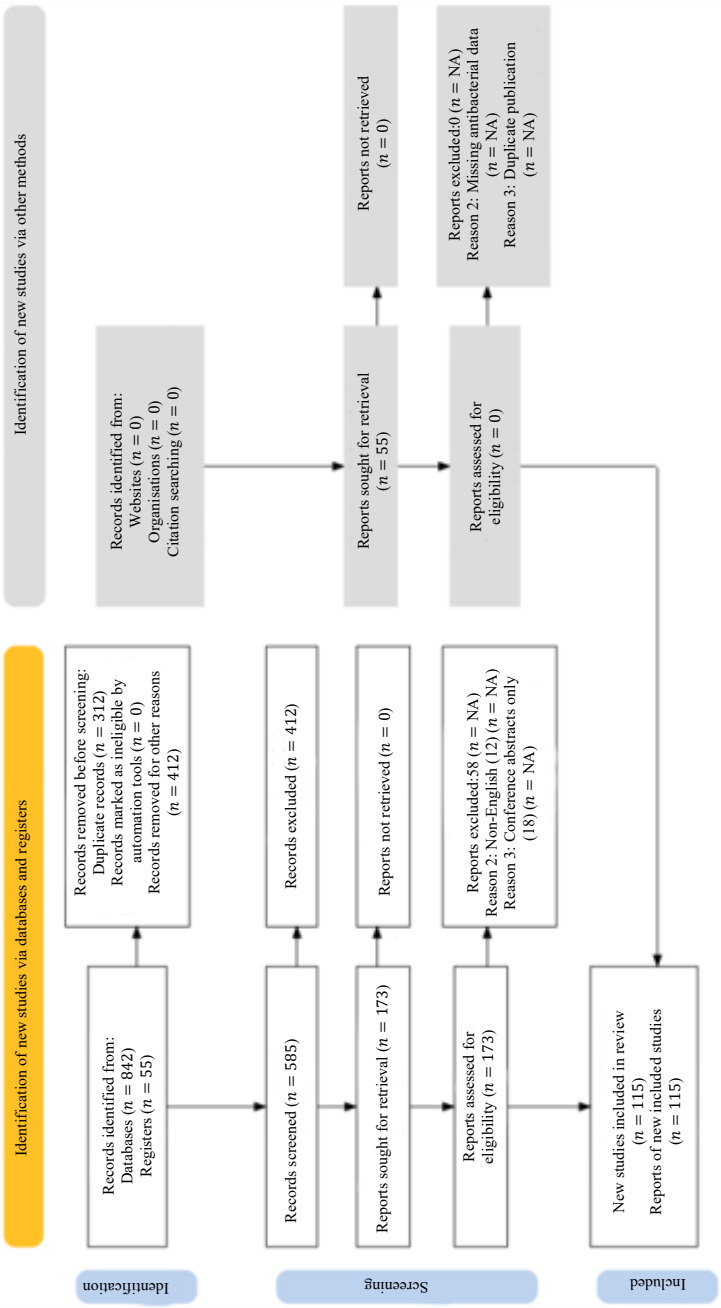

Figure 2. PRISMA flow diagram [16].

Chemical vs. Green Synthesis of CuS Nanoparticles

Chemical synthesis solvothermal, precipitation, microwave-assisted, and various microwave-solvothermal hybrids gives good control over crystal size, shape, and crystallinity, and particles made this way often show stronger antibacterial activity [17]. The trade-off is fairly well known: reproducibility and tunable optical properties on one side, precursor contamination, agglomeration, high energy demand, and toxic solvents on the other. The principal steps involved in these chemical routes are outlined in the flowchart in Figure 3. Green synthesis takes a different route entirely, drawing on microorganisms, biomolecules, or plant extracts to produce biocompatible particles with more varied morphology [18]. It does well on sustainability, safety, and bio-functional surface coatings [19], but reproducibility and scalability remain genuine weak points largely because biological source material varies from batch to batch and standardized protocols are still thin on the ground [20]. A representative plant-extract-mediated green synthesis pathway is depicted schematically in Figure 4.

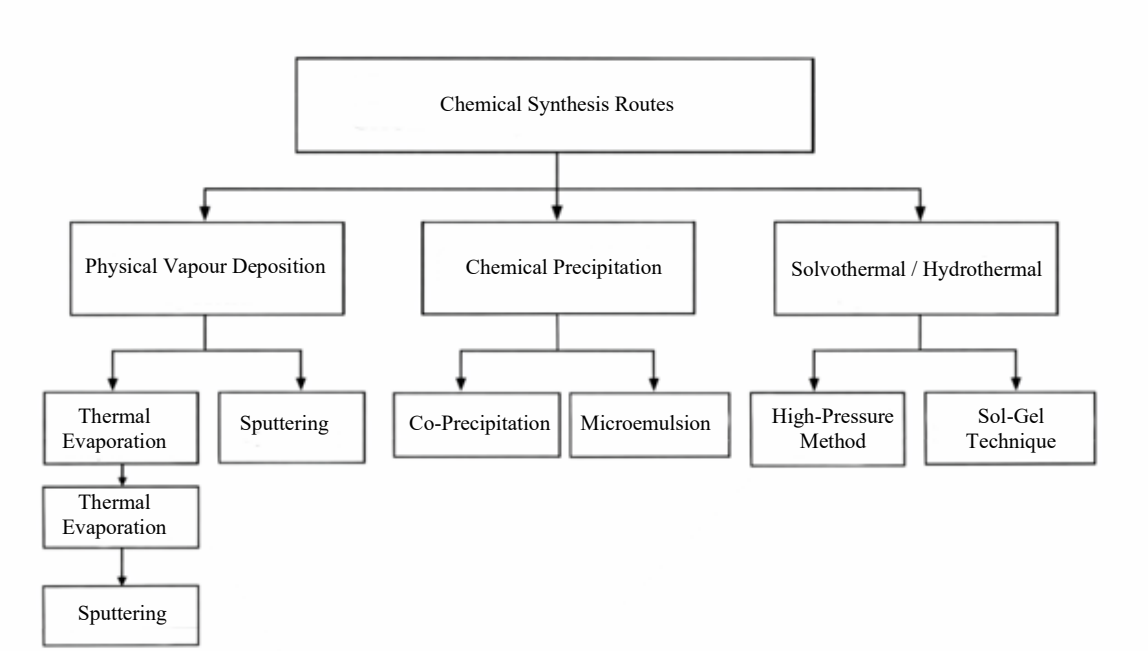

Figure 3. Flowchart of chemical synthesis routes [21].

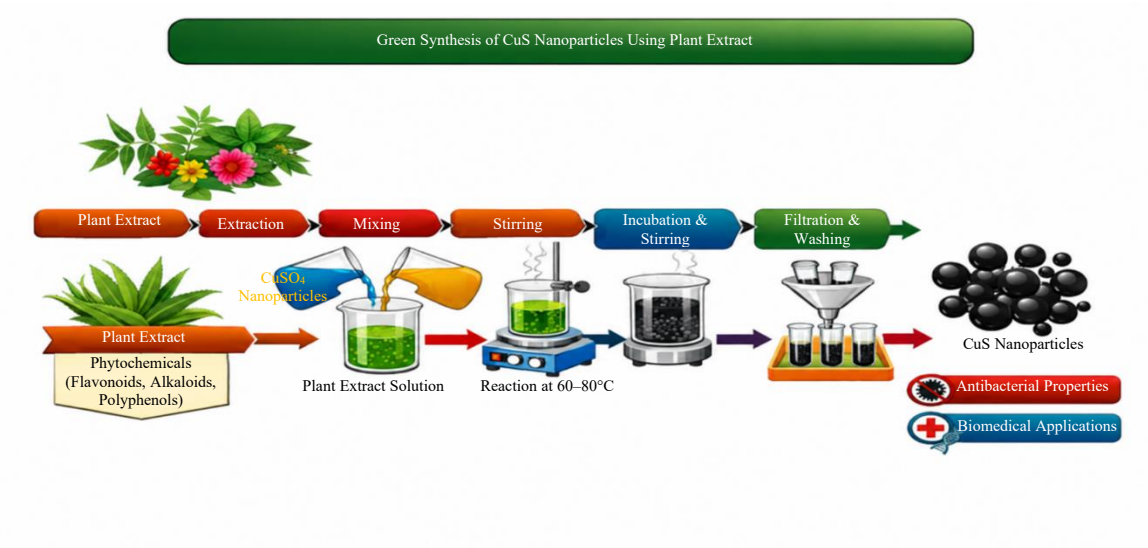

Figure 4. Schematic of green synthesis using plant extract [22].

Comparison

Cost, scalability, toxicity, reproducibility, environmental footprint these are the five axes where chemical and green synthesis diverge most clearly. Chemical methods are fast and precise, but that precision comes from hazardous reagents and energy-intensive conditions, which raises their overall environmental burden [21]. Green synthesis leans on plant extracts and microbial agents instead and is gentler on the environment almost by definition [19]. Interest in green routes has grown accordingly driven by biocompatibility and eco-efficiency even though chemical synthesis still dominates industrial-scale production for the simple reason that it is more predictable [23]. Life-cycle and green-metrics analyses back this up, generally favoring biogenic synthesis over conventional chemical routes once environmental cost is factored in [24].

Systematic Categorization of Synthesis Methods by Particle Size, Morphology, Crystallinity, and Scalability

Grouping CuS synthesis routes into a binary "chemical versus green" split, as Table 1 does, is useful for a first-order comparison but glosses over the fact that each broad category actually contains several mechanistically distinct methods that behave quite differently once particle size, morphology, and crystallinity are examined individually. A more systematic categorization separates the literature into three tiers – physical, chemical, and biological/green – and then further into specific techniques within each tier, since scalability and structural outcome vary considerably even within a single tier. Table 2 sets out this categorization explicitly.

Table 1. comparison of chemical vs. green synthesis of CuS nanoparticles.

Parameter	Chemical synthesis	Green synthesis
Cost	High cost due to energy-intensive equipment, expensive precursors and controlled conditions [21].	Low cost; utilizes readily available plant extracts, biomolecules and microbial cultures [19].
Scalability	Industrial scalability achievable with strict process control and reproducibility [25].	Moderate scalability; limited by variability in biological sources and extract composition [20].
Toxicity	Involves hazardous solvents and by-products, raising environmental and health concerns [26].	Minimal toxicity; eco-friendly reagents and biocompatible nanoparticle surfaces [27].
Reproducibility	High reproducibility under controlled laboratory conditions and standardized protocols [23].	Variable reproducibility; influenced by seasonal, geographical and biological factors [28].
Environmental Impact	Significant carbon footprint and chemical waste generation, requiring mitigation strategies [24].	Low impact; aligns with green chemistry principles and sustainability goals [29].

Table 2. Method-wise categorization of CuS nanoparticle synthesis routes by particle size, morphology, crystallinity, and scalability.

Category	Method	Typical particle size	Typical morphology	Crystallinity	Scalability
Physical	Ball milling, laser ablation, sputtering	>20 nm, broad distribution	Irregular, poorly defined	Variable, often lower and inconsistent	Low-moderate; equipment – limited.
Chemical	Co-precipitation	10–100 nm, broad	Irregular / quasi-spherical	Moderate	High; simple, low-cost reagents [25, 23].
Chemical	Hydrothermal / solvothermal	5–50 nm, narrow with good control	Flower-like, hexagonal plates, spheres	High, well-faceted covellite [1, 30]	Moderate; batch autoclave processing [17].
Chemical	Microwave-assisted	5–20 nm, narrow	Uniform spheroidal	High, uniform	Moderate-high; continuous-flow compatible [17].
Chemical	Chemical bath deposition / SILAR	10–40 nm	In-film / in-matrix dispersed particles	Moderate-high	Moderate-high for composite films [31, 32].
Biological / Green	Plant-extract-mediated	10–80 nm, broad	Spherical, irregular, shape depends on capping	Low-moderate unless calcined	Low-moderate; batch variability [18, 22].
Biological / Green	Microbial / fungal-mediated	Broad, variable	Variable, culture-dependent	Low-moderate	Low; culture-dependent reproducibility [18].
Biological / Green	Biomolecule / peptide – templated	Fine control possible	Well-defined at small scale	Moderate	Very low; low throughput [20].
Physical	Ball milling, laser ablation, sputtering	>20 nm, broad distribution	Irregular, poorly defined	Variable, often lower and inconsistent	Low-moderate; equipment – limited.
Chemical	Co-precipitation	10–100 nm, broad	Irregular / quasi-spherical	Moderate	High; simple, low-cost reagents [25, 23].

Within the chemical tier, hydrothermal and solvothermal routes give the tightest control over crystallinity and morphology because reaction temperature, pressure, and capping-agent concentration can be tuned independently, typically yielding well-faceted flower-like or hexagonal-plate covellite particles in the 5–50 nm range with high crystallinity, though batch-style autoclave processing caps their scale-up potential relative to continuous-flow alternatives [1, 17]. Co-precipitation is faster and cheaper but trades away morphological control, generally producing broader size distributions (10–100 nm) of irregular or quasi-spherical particles with moderate crystallinity [21, 23]. Microwave-assisted synthesis sits between these two, narrowing size distribution (5–20 nm) and improving crystallite uniformity through rapid, homogeneous heating, while also being more compatible with continuous processing than conventional solvothermal routes [17]. Chemical bath deposition and SILAR are somewhat different in purpose, since they are typically used to grow CuS directly within or onto a polymer matrix rather than as free nanopowder; particle sizes of 10–40 nm embedded in-film are typical, and while single-substrate throughput is modest, the method scales reasonably well for composite film production [31, 32].

Within the biological/green tier, plant-extract-mediated synthesis gives the broadest morphological variability (10–80 nm, shapes ranging from spherical to irregular depending on the capping phytochemicals present), generally at lower crystallinity than hydrothermal chemical routes unless a post-synthesis calcination step is added, and scalability is constrained by batch-to-batch variation in extract composition [18, 22]. Microbial- and fungal-mediated synthesis shows similar size and morphology variability with the added complication of culture-dependent reproducibility, keeping most reports at lab scale [18]. Biomolecule- or peptide-templated synthesis can achieve fine size control but at very low throughput, which is why it remains a research-stage technique rather than a scalable production route [20].

Physical methods – ball milling, laser ablation, and sputtering – appear far less frequently in the CuS antibacterial literature specifically but are included here for completeness since they represent a genuinely distinct category: they typically produce larger, less morphologically uniform particles (often >20 nm with wide distributions), offer little intrinsic shape control, and depend on specialized equipment that limits scalability outside of thin-film contexts.

CHARACTERIZATION TECHNIQUES

A range of analytical techniques is employed to confirm the successful synthesis and evaluate the structural, morphological, optical, and chemical properties of CuS nanoparticles. These techniques provide critical insights that help correlate synthesis conditions with the resulting nanoparticle characteristics, ensuring their suitability for targeted applications. The subsections below detail the principal spectroscopic and microscopic methods used for this purpose, explain why confirming morphology, size, and crystallinity is a prerequisite for interpreting antibacterial data, and extend this characterization framework to structure–property relationships in CuS–polymer nanocomposites.

XRD, SEM/TEM, UV–Vis, FTIR, Raman Spectroscopy

No single measurement tells the whole story with CuS NPs, which is why confirming their structural, morphological, and optical properties generally means running several complementary techniques rather than leaning on one. X-ray diffraction establishes crystallinity, phase purity, average crystallite size, lattice parameters, and evidence of structural defects, with crystallite-size estimates cross-checked against electron microscopy for consistency [33, 34]. Electron microscopy SEM and TEM together adds direct visual confirmation of shape, size distribution, and surface topography [35], something diffraction data alone cannot really provide. UV–Vis spectroscopy picks up optical absorption, band gap energy, and plasmonic behavior, all of which feed directly into antibacterial and photothermal performance, while FTIR checks for residual biomolecules or stabilizers left over from synthesis and tracks surface functional groups [36]. Raman spectroscopy closes the loop, probing vibrational modes and structural order in a way that is particularly good at distinguishing covellite phases that other techniques tend to blur together. Used in combination, these methods build a reasonably complete structural and optical profile one that supports reproducibility and, just as importantly, ties synthesis conditions back to the functional properties that actually result.

Importance of Confirming Morphology, Size and Crystallinity

Before antibacterial efficacy can be interpreted meaningfully, morphology, size, and crystallinity all need to be pinned down first. Spherical or flower-like shapes tend to maximize contact area with bacteria and, unsurprisingly, tend to be more responsive as a result. Size governs ion release and ROS production fairly directly smaller particles, with their higher surface energy, generally outperform larger ones antibacterially [37] while crystallinity affects phase stability and electrical behavior, which in turn feeds into photothermal conversion and ROS generation. Synthetic variability is the real threat here: it can quietly turn into irreproducible biological outcomes if it isn't caught early, which is why validation matters more in this space than it might elsewhere. XRD and Raman spectroscopy establish crystallinity and phase composition; TEM and SEM add the morphological confirmation that diffraction data can't. Together, this combination supports both academic rigor and the kind of characterization regulatory bodies expect during clinical translation, effectively matching what happens at the bench to the uniformity that biomedical applications actually demand. A representative TEM image schematic illustrating this morphological confirmation is shown in Figure 5.

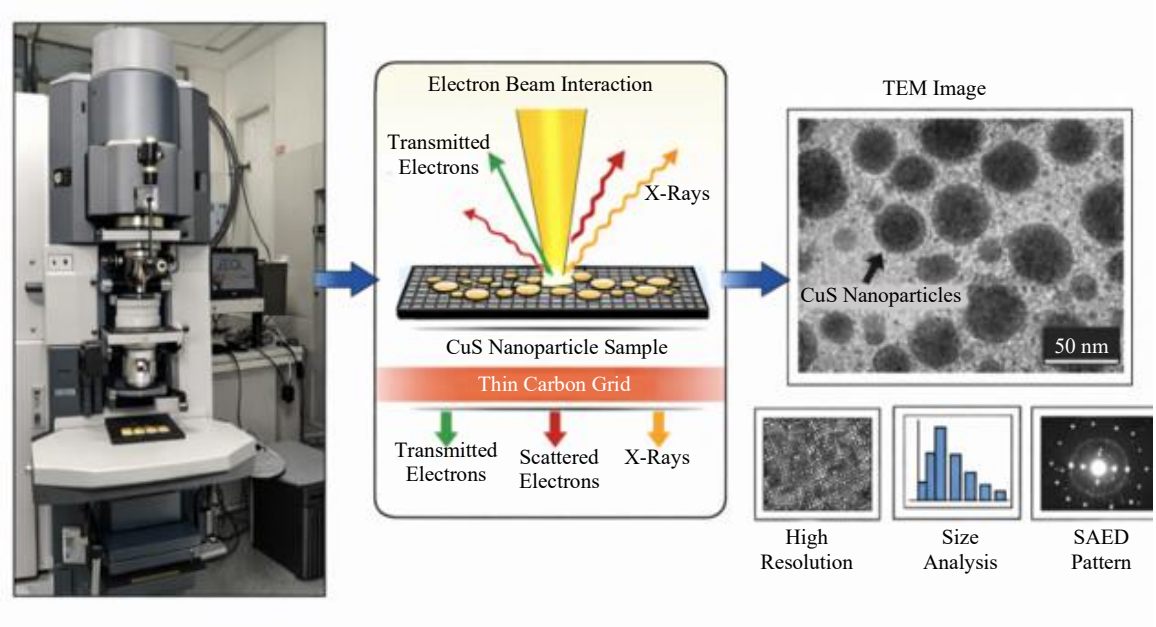

Figure 5. Representative TEM image schematic [30].

Structure–Property Relationships in CuS–Polymer Nanocomposites

Correlating nanoscale structure with bulk functional properties is a running theme in this journal's scope, and CuS–polymer systems illustrate why particularly well. Three structural variables tend to dominate: particle size, phase composition, and dispersion state. Particles below 10 nm release Cu^{2+} ions faster a consequence of elevated surface energy which lowers the minimum inhibitory concentration but can also speed up matrix hydrolysis in moisture-sensitive hosts, so the benefit is not entirely free. The covellite phase, identifiable by XRD peaks near $2\theta = 27.7°$ and 31.8° and by a Raman band at 474 cm^{-1}, shows stronger near-infrared photothermal conversion than chalcocite (Cu_2S) thanks to its higher hole density, which is exactly why phase identification is treated as a meaningful quality-control step before composite fabrication rather than an afterthought.

Dispersion quality matters just as much, and it is usually assessed through TEM alongside oscillatory rheology. Below 5 wt% loading in PVA or chitosan, well-separated CuS NPs raise tensile modulus through stress-transfer effects while elongation at break stays largely intact. Push past that threshold, though, and particle clustering starts introducing stress concentrations tensile strength drops, and so does the active surface area available for ion release, which is a fairly clean illustration of mechanical and biological performance sharing a common structural optimum [38]. DSC and TGA data add a

thermal dimension: CuS incorporation raises the glass transition temperature of amorphous polymer matrices by roughly 4–12°C, consistent with restricted chain mobility at the particle interface, and this is relevant both to processing-window design and to service-temperature assessment for composite medical devices [39].

ANTIBACTERIAL MECHANISMS

CuS nanoparticles have attracted significant attention as antibacterial agents due to their unique physicochemical properties, including their narrow bandgap, photothermal response, and ability to generate reactive oxygen species. Understanding the underlying mechanisms by which these nanoparticles exert antibacterial effects is essential for optimizing their design and application in areas such as wound dressings, coatings, and water treatment systems. The subsections that follow detail these mechanistic pathways individually, describe how CuS nanoparticles are fabricated into polymer nanocomposites without losing this antibacterial activity, and outline the processing techniques used to translate laboratory-scale synthesis into practical composite forms.

Antibacterial Mechanisms of CuS Nanoparticles

CuS nanoparticles don't kill bacteria through one pathway several act together, and untangling them individually is part of why this field has taken time to mature. Reactive oxygen species hydroxyl radicals, superoxide, singlet oxygen drive oxidative stress toward eventual cell death [5]. Separately, ion leakage, biofilm disruption, and electrostatic interaction with the bacterial envelope contribute to membrane damage on their own terms [6]. There is also a genotoxic layer: released copper ions interact with proteins and DNA directly, disrupting enzymatic activity and genomic integrity [7]. What makes this particularly effective is that it tends to be self-reinforcing continued Cu ion release sustains ROS production over time, which further destabilizes bacterial metabolic balance rather than tapering off [8]. Under near-infrared light, photodynamic and photothermal effects work together rather than competing: localized hyperthermia combined with ROS generation improves biofilm penetration and, overall, antibacterial potency [9, 10]. These combined mechanisms of CuS nanoparticles attacking the bacterial cell wall are illustrated schematically in Figure 6.

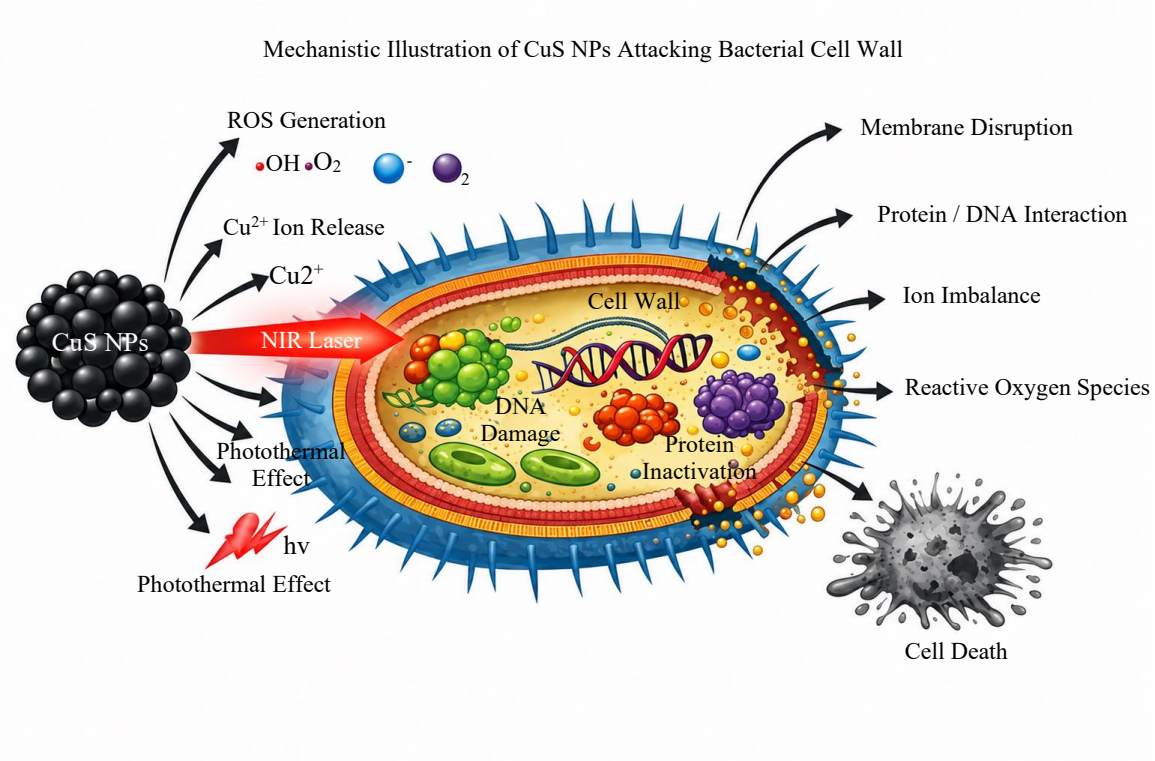

Figure 6. Mechanistic illustration of CuS NPs attacking bacterial cell wall [1].

Fabrication of CuS–Polymer Nanocomposites

Getting CuS nanoparticles into a polymer matrix is, in practice, one of the more straightforward ways to tune both the functional and antibacterial character of the resulting composite. Chemical bath deposition and solution casting are the two most common routes, and both let CuS disperse fairly uniformly through the host polymer, improving structural stability and optical performance along the way [31]. That opens the door to biomedical applications, such as sensing and device coatings, where conductivity and nonlinear optical response can be dialed in as needed [40]. CuS worked into flexible polymer sheets has also been shown to absorb radiation effectively while keeping its flexibility intact a combination that turns out to be genuinely useful for electromagnetic interference shielding [41]. Hybrid blends of CuS with other metal oxides push this further, offering scalable options for protective biomedical devices with better shielding performance than either component manages alone. There are physical gains too: CuS–polymer composites show enhanced thermoelectric performance at elevated temperature, especially once conductive fillers – such as single-walled carbon nanotubes – are added. And in biomedical settings specifically, CuS nanocomposites built around polyvinyl alcohol or carrageenan have demonstrated both antibacterial [38] and anticancer [42] activity. Put together, this positions CuS–polymer nanocomposites as a genuinely promising, economically reasonable platform for the next generation of polymeric biomedical materials ones that combine antimicrobial function with environmental responsiveness rather than treating the two as separate design goals.

Processing Techniques for CuS–Polymer Nanocomposites

Which fabrication route gets used for a CuS–polymer nanocomposite has a direct bearing on dispersion quality, void content, and functional performance considerations that sit squarely within this journal's polymer processing scope. Solution casting is the default laboratory method: CuS NPs are dispersed in a polymer solution by ultrasonication (20–40 W, 5–15 min) before film deposition, which produces flexible films well suited to wound dressings and antibacterial packaging, though scalability remains a real limitation [31]. Electrospinning offers a different set of trade-offs, producing nanofibrous membranes with fibre diameters of 150–600 nm and specific surface areas above 10 m^2/g an improvement in both ion-release kinetics and bacterial contact area relative to cast films. For thermoplastic matrices, such as poly(lactic acid), melt-blending via twin-screw extrusion at 170–210°C gives a solvent-free, scalable alternative, though silane or thiol surface functionalization of the CuS NPs is generally required to stop agglomeration under high shear. Compression molding of pre-blended compounds rounds out the toolkit, yielding flat specimens that conform to ASTM D638 and D790 geometries and enabling the kind of standardized tensile and flexural testing that credible structure–property reporting actually requires.

PERFORMANCE EVALUATION

Evaluating the antibacterial performance of CuS nanoparticles requires systematic comparison across different bacterial strains, as structural differences in bacterial cell walls significantly influence susceptibility to nanoparticle-induced damage. This section presents comparative findings on the efficacy of CuS nanoparticles against Gram-positive and Gram-negative bacteria, highlighting key trends and underlying factors responsible for differential antibacterial responses. It further examines quantitative measures, such as MIC and zone of inhibition, synergistic effects with conventional antibiotics, efficacy against biofilms and multidrug-resistant strains, and the performance, applications, and physical and mechanical properties of CuS–polymer nanocomposites specifically.

Comparative Studies against Gram-Positive and Gram-Negative Bacteria

Gram-positive and Gram-negative bacteria do not respond the same way to CuS NPs, and the reason traces back to differences in cell wall architecture. The lipopolysaccharide-rich outer membrane of Gram-negative bacteria tends to promote both ion penetration and nanoparticle binding, which produces comparatively rapid oxidative damage [43]. Gram-positive bacteria, protected by a thicker peptidoglycan layer, hold up better against short-term exposure though prolonged contact still eventually leads to membrane rupture and protein denaturation [44]. Comparative literature bears this out fairly consistently: CuS NPs typically produce larger inhibition zones against *E. coli* and

Pseudomonas aeruginosa than against *Staphylococcus aureus* or *Bacillus subtilis*, and that gap widens further under near-infrared irradiation, where synergistic ROS generation and photothermal activation both tilt in favor of Gram-negative targets. Taken together, these findings underline just how strongly cell wall structure shapes antibacterial outcome, and they support CuS NPs' potential as broad-spectrum agents effective against both bacterial classes rather than one alone.

MIC Values and Zone of Inhibition

Two measurements dominate the quantitative side of CuS antibacterial testing: minimum inhibitory concentration (MIC) and zone of inhibition (ZOI). MIC values reported in the literature typically fall between 10–50 microg/mL for Gram-negative pathogens and 20–80 microg/mL for Gram-positive strains, which lines up with the differential susceptibility discussed above [37]. ZOI testing adds a visual, complementary measure larger inhibition zones generally track with greater nanoparticle reactivity and higher ROS output [45]. Interestingly, green-synthesized CuS NPs have often produced larger inhibition zones than their chemically synthesized counterparts, an effect usually attributed to biofunctional surface coatings that enhance both oxidative stress and ion release. Read side by side, MIC and ZOI data support dose and exposure-time optimization for clinical and environmental use alike, and both consistently point in the same direction: CuS NPs behave as scalable, quantifiably effective antibacterial material rather than one whose promise is mostly qualitative.

Synergistic Effects with Antibiotics

CuS NPs are increasingly studied not as antibiotic replacements but as adjuvants something used alongside conventional drugs rather than instead of them. Checkerboard and fractional inhibitory concentration index (FICI) assays are the standard tools for evaluating this kind of interaction. In several nanoparticle–antibiotic systems, combining sub-inhibitory doses of CuS NPs with conventional antibiotics – such as beta-lactams or aminoglycosides – has produced FICI values in the synergistic range (generally taken as <= 0.5), which lets the effective antibiotic concentration drop well below what would be needed alone. The mechanism behind this is fairly intuitive once laid out: CuS-induced membrane permeabilization appears to improve antibiotic uptake, while the ROS burden the nanoparticle generates compounds the oxidative stress the drug was already imposing. This kind of combination approach matters most against multidrug-resistant strains, where it may allow lower antibiotic doses without giving up efficacy cutting both dose-related toxicity and the selective pressure that drives further resistance in the first place. There is a formulation angle here too: this synergy makes CuS an attractive candidate for dual-loaded polymer composites, such as wound dressings or coatings, designed to release both nanoparticle and antibiotic in a coordinated way. What's still missing is standardized synergy-testing protocols across different bacterial strains and CuS morphologies, without which dosing guidance is hard to generalize with real confidence.

Efficacy against Microbial Biofilms and Multi-Drug Resistant (MDR) Strains

Biofilms and MDR strains remain two of the harder problems in infection control, and for related reasons both rely on some form of protective barrier, whether an extracellular matrix or an efflux mechanism, to blunt whatever is thrown at them. CuS NPs address the biofilm side fairly directly, using photothermal disruption together with ROS-mediated breakdown of extracellular polymeric substances to get through the matrix in the first place [46]. Once inside, the particles destabilize the biofilm architecture and expose the bacteria within to combined oxidative and ionic stress. Against MDR organisms, such as *Pseudomonas aeruginosa* and *Staphylococcus aureus*, CuS NPs appear to work on two fronts at once disrupting membrane integrity while also impairing efflux pump function, one of the main route's bacteria use to expel antibiotics in the first place [47]. Near-infrared irradiation amplifies both the photothermal and photodynamic components further. Comparative studies consistently show reductions in biofilm biomass and viable cell counts alike, and it's really this multimodal action hitting the matrix, the membrane, and the resistance machinery more or less simultaneously that makes CuS NPs a reasonably credible option for managing chronic infection and slowing the spread of resistance.

Antibacterial Performance of CuS–Polymer Nanocomposites

Pairing a semiconducting nanoparticle with a polymer matrix generally produces antibacterial activity that exceeds what either component manages alone. Within biocompatible matrices, such as sodium alginate or polyvinyl alcohol, CuS keeps its disinfection capability intact and measurably boosts both ion release and ROS generation [40, 38]. These composites hold up well against Gram-positive and Gram-negative bacteria alike, and notably they have also shown solid activity against biofilm-forming strains, which remains one of the more stubborn challenges in clinical infection control [48]. Embedding CuS in a polymer framework seems to enhance its photocatalytic and photothermal response under natural daylight or near-infrared irradiation [38], and in hybrid nanostructures, such as ZnS:CuS polymer composites, structural defects combined with Z-scheme photocatalysis drive higher ROS output, which correlates directly with stronger antibacterial performance [39]. Some multifunctional CuS–polymer systems go further still, showing meaningful antioxidant and antitumor activity that extends well past antibacterial use alone. Particle dispersion, surface charge, and polymer compatibility all shape antibacterial efficacy in practice, mostly through their effect on ion transport and ROS kinetics. Put simply, the combination of structural tunability, biocompatibility, and light-responsive bactericidal behavior makes CuS–polymer nanocomposites a genuinely promising platform not just a theoretical one for antibacterial applications.

Applications of CuS–Polymer Nanocomposites

This multifunctionality translates into a fairly wide application footprint biological, environmental, and energy-related uses have all been reported for CuS–polymer nanocomposites (PCNs). Chemical bath-synthesised composites often display optical and electrical properties suited to nonlinear optical devices and photonic applications, and polymer matrices already valued for sensitivity and stability in sensing can be pushed further by CuS incorporation, extending their reach into environmental monitoring and biomedical diagnostics [40]. Their ability to attenuate electromagnetic radiation makes them useful as flexible shielding films too, offering lightweight protective coating for electronic devices and medical equipment [41]. At elevated temperature, SWCNT/CuS/PVP thermoelectric composites show strong energy-conversion capability, which makes them plausible candidates for wearable energy harvesters a use case that would have seemed unlikely for an antibacterial nanoparticle a decade ago. CuS–polymer systems have also demonstrated antioxidant, antibacterial, and anticancer activity together, supporting use in drug delivery and wound dressing formulations [38, 42], while photocatalytic nanocomposites CuS:ZnS and SrO–CuO hybrids among them have shown real promise for environmental remediation, particularly dye and pollutant degradation under sunlight [49]. Work continues structurally stable CuS–polymer films with tunable conductivity, increasingly through more sustainable routes such as SILAR synthesis performed in recycled nylon matrices [32]. Taken as a whole, these applications point toward CuS–polymer nanocomposites as a genuinely cross-cutting platform spanning environmental, energy, and healthcare technology not confined to any one of the three.

Physical and Mechanical Properties of CuS–Polymer Nanocomposites

Antibacterial performance is not the only thing worth reporting for this journal's composite materials scope the physical property changes matter just as much. At 3 wt% CuS loading in PVA films, Young's modulus rises from 0.85 to 1.42 GPa (a 67% increase), ultimate tensile strength climbs from 38 to 52 MPa (37%), and water vapor transmission rate drops by 31% effects generally attributed to the tortuous diffusion path that dispersed nanoparticles create within the matrix [38]. Flexural strength in CuS/epoxy nanocomposites improves by roughly 22% at 2.5 wt% loading relative to the neat resin, largely through crack-deflection mechanisms [50]. Electrically, these composites show a conductivity percolation threshold around 4–6 wt% in most insulating polymer matrices; cross that threshold and conductivity jump by three to five orders of magnitude, which opens up dual use as both antibacterial coating and electromagnetic interference shielding for medical enclosures [41]. Thermally, TGA data consistently show the onset degradation temperature of PVA and chitosan matrices rising by 15–28°C with CuS incorporation extending the thermal service window and supporting the idea that the inorganic phase acts as a barrier against volatile release [39].

This loading-dependent coupling between filler content, crystallinity, thermal stability, and mechanical performance is not unique to CuS–polymer systems. Comparable trends, measured with the same core toolkit of XRD-derived crystallinity indices, DSC/TGA thermal analysis, and ASTM-standard tensile and flexural testing, have been reported for particulate- and fiber-reinforced polymer composites more broadly. Hybrid epoxy composites reinforced with jute and banana stem leaf fibers alongside tamarind shell powder showed loading-dependent gains in tensile, flexural, interlaminar shear, and impact strength that mirror the stress-transfer behavior discussed above for CuS–PVA films [50]. Surfactant-washing of ramie fibers with sodium lauryl sulphate produced measurable shifts in crystallinity index, thermal degradation onset, and mechanical response that parallel the effect of surface treatment on CuS–composite interfacial quality [51]. Natural-rubber biocomposites reinforced with Sansevieria cylindrica fiber likewise showed fibre-loading- and length-dependent mechanical performance consistent with the percolation-type threshold effects described above for CuS loading [52]. Calamus tenuis fiber-reinforced epoxy composites, evaluated for tensile, structural, crystalline, thermal, and morphological characteristics as a function of fiber loading [53], and separately for mechanical, morphological, and dynamic mechanical behavior [54], reinforce the same general point: filler content and interfacial treatment jointly govern crystallinity and bulk performance regardless of whether the filler is a semiconducting nanoparticle or a natural fiber. Alkaline treatment of sugar-palm-fiber-reinforced thermoplastic polyurethane composites produced similar concurrent improvements in crystallinity and thermal/mechanical properties through altered interfacial adhesion [55]. Read alongside the CuS-specific data above, this body of work underscores that the structure–property coupling central to this review's polymer nanocomposite scope is a general feature of filler-reinforced polymer systems, and that standardized, cross-comparable characterization protocols of the kind used here are equally applicable across particulate and fibrous reinforcement types.

CHALLENGES AND FUTURE PERSPECTIVES

For all their versatility, CuS–polymer nanocomposites still face real obstacles before clinical or industrial adoption becomes routine rather than exceptional. Synthesis reproducibility sits near the top of the list batch-to-batch variation in particle size, shape, and polymer compatibility translates directly into inconsistent antibacterial and photocatalytic performance, and that inconsistency is hard to engineer around after the fact. Long-term stability deserves more attention too: surface oxidation and declining ion release over time can quietly erode antibacterial effectiveness, which argues for more systematic coating and durability testing than the field currently does as standard practice. There is also a balancing act built into the chemistry itself enough ROS generation for antibacterial efficacy, but not so much that mammalian cells take unnecessary oxidative damage. Looking ahead, composite design seems likely to move toward controlled-release formulations, biocompatible ligand functionalization, and green synthesis routes that can actually scale. Chiral ligand engineering and combined photothermal–photodynamic strategies offer additional paths toward better bactericidal efficiency without a corresponding rise in toxicity. But before CuS–polymer systems can realistically reach flexible electronics, smart biomedical devices, or environmental remediation at scale, the field will need coordinated progress on multidisciplinary optimization, regulatory validation, and manufacturing that is genuinely more environmentally responsible than current practice. Addressing these issues is, in effect, the bottleneck standing between promising lab-scale prototypes and CuS–polymer technologies that are actually deployable and sustainable.

FUTURE RESEARCH DIRECTIONS

A handful of directions look particularly promising from here. Green synthesis of CuS NPs using biopolymer capping agents' chitosan oligomers, alginate fragments, plant polyphenols address renewable polymer synthesis and circular green chemistry goals at the same time, by eliminating toxic reductants while imparting biocompatible surface coatings that improve polymer matrix compatibility [22]. Self-healing CuS–polymer nanocomposites built around dynamic disulfide or hydrogen-bond crosslinks are another promising avenue, potentially allowing damage-triggered restoration of both mechanical integrity and nanoparticle distribution rather than requiring full replacement after damage. Machine learning-driven formulation design, trained on characterization performance datasets, could

meaningfully speed up optimization work, particularly for structure property quantification that would otherwise take years of manual iteration [56]. Integrating CuS–polymer systems into 3D-printed scaffolds via extrusion-based bioprinting would allow spatial control over nanoparticle distribution relevant to bone tissue engineering and biomedical composites more broadly [57]. And finally, life-cycle assessment comparing green and chemical synthesis routes for CuS NP production is still genuinely needed, since current data on carbon footprint and waste generation for green CuS synthesis remain too thin to substantiate the sustainability claims made about it [24].

CONCLUSION

CuS nanoparticles and their polymer nanocomposites have become a genuinely active area of nanotechnology research for antibacterial applications, and this review has tried to draw the different threads together the distinctive physicochemical properties, the range of synthesis routes on offer, and the several antimicrobial mechanisms at play, from reactive oxygen species generation and ion release to the synergistic action of photothermal and photodynamic effects under light. Worked into a polymeric matrix, CuS nanoparticles pick up stability, biocompatibility, and a genuinely multifunctional profile that extends their reach into biomedical coatings, wound dressings, sensors, energy devices, and environmental remediation alike.

Clinical translation still faces real hurdles, though toxicity control, long-term stability, and reproducibility chief among them. Getting past these will take standardized, reproducible synthesis protocols, more scalable green production methods, and biocompatibility testing that is rigorous rather than perfunctory. Looking forward, CuS–polymer systems seem well positioned to integrate into responsive biomedical platforms capable of real-time monitoring, alongside genuinely sustainable applications in energy and environmental technology. Taken as a whole, CuS–polymer nanocomposites sit at a point where materials science and medicine genuinely converge offering, through their multifunctionality, eco-friendly synthesis routes, and interdisciplinary relevance, a credible strategy for addressing multidrug-resistant infection while advancing polymer-based biomedical technology more broadly.

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