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Multifunctional Cerium-Copper Bimetallic Nanocomposites Functionalized with Bioactive Natural Ligands: A Novel Green Synthesis Approach towards Targeted Anticancer Drug Delivery, Visible-Light Photocatalysis and Environmental Water Purification

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Abstract **Original Research Article**

The development of multifunctional nanomaterials through sustainable synthesis approaches has emerged as a promising strategy for addressing challenges in cancer therapy and environmental remediation. This study presents a novel green synthesis approach for the fabrication of cerium-copper (Ce-Cu) bimetallic nanocomposites functionalized with bioactive natural ligands for targeted anticancer drug delivery, visible-light photocatalysis, and water purification applications. The nanocomposites were synthesized using plant-derived phytochemicals as reducing, stabilizing, and capping agents, eliminating the need for hazardous chemicals and energy-intensive procedures. Structural and physicochemical characterization was performed using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDS), UV-visible spectroscopy, dynamic light scattering (DLS), and zeta potential analysis. The synthesized nanocomposites exhibited uniform morphology, enhanced surface area, excellent colloidal stability, and strong visible-light absorption due to the synergistic interaction between cerium and copper components. Drug loading and release studies demonstrated high encapsulation efficiency and pH-responsive release behavior, enabling selective drug delivery to tumor microenvironments. In vitro cytotoxicity analysis revealed significant anticancer activity against human cancer cell lines while maintaining acceptable biocompatibility toward normal cells. Furthermore, the nanocomposites exhibited superior photocatalytic degradation efficiency toward organic pollutants under visible-light irradiation and demonstrated excellent adsorption and antimicrobial performance for wastewater treatment. The findings highlight the potential of biofunctionalized Ce-Cu bimetallic nanocomposites as sustainable, multifunctional platforms for integrated biomedical and environmental applications.

Keywords: Cerium-Copper Nanocomposites, Green Synthesis, Bioactive Natural Ligands, Targeted Drug Delivery, Photocatalysis, Water Purification, Anticancer Activity, Multifunctional Nanomaterial.

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1. INTRODUCTION

The rapid advancement of nanotechnology has revolutionized multiple scientific disciplines by enabling the development of multifunctional materials with tailored physicochemical properties. Among various nanostructured systems, bimetallic nanocomposites have attracted considerable attention because of their unique synergistic effects, enhanced catalytic efficiency, improved stability, and tunable surface characteristics compared with their monometallic counterparts. The integration of distinct metal species within a single nanoplatform often results in superior optical, electronic, and biological properties, making these materials highly suitable for applications in biomedicine, environmental remediation, sensing, and energy conversion [1].

Cancer remains one of the leading causes of mortality worldwide despite significant progress in diagnosis and treatment strategies. Conventional chemotherapy suffers from several limitations, including poor drug selectivity, systemic toxicity, multidrug resistance, and undesirable side effects on healthy tissues. Consequently, there is an urgent need to develop targeted drug delivery systems capable of enhancing therapeutic efficacy while minimizing adverse effects. Nanocarrier-based drug delivery platforms have emerged as promising alternatives owing to their high loading capacity, controlled release behavior, surface functionalization capability, and ability to accumulate preferentially within tumor tissues through enhanced permeability and retention mechanisms. Simultaneously, increasing industrialization and urbanization have intensified environmental pollution, particularly water contamination caused by organic dyes, pharmaceutical residues, heavy metals, and pathogenic microorganisms [2-4]. Conventional wastewater treatment technologies often fail to achieve complete removal of persistent pollutants due to high operational costs, secondary pollution, and limited efficiency. Visible-light-driven photocatalysis has emerged as a sustainable and cost-effective approach for environmental purification because it utilizes abundant solar energy to degrade hazardous contaminants into less toxic products. Cerium-based nanomaterials have attracted significant interest owing to their excellent redox properties, oxygen storage capacity, antioxidant behavior, and remarkable biocompatibility [5-7]. The reversible conversion between Ce^{3+} and Ce^{4+} oxidation states enables efficient reactive oxygen species regulation, making cerium-containing nanostructures attractive candidates for biomedical and catalytic applications. Copper-based nanomaterials exhibit exceptional electrical conductivity, strong antimicrobial activity, cost-effectiveness, and excellent visible-light absorption characteristics. Combining cerium and copper into a bimetallic nanocomposite can significantly enhance charge separation efficiency, increase active surface sites, and improve photocatalytic and therapeutic performance through synergistic interactions [7-9].

Despite the remarkable potential of Ce-Cu bimetallic nanocomposites, traditional synthesis routes often involve toxic chemicals, hazardous solvents, high temperatures, and energy-intensive processing methods that pose environmental and health concerns. Green synthesis approaches utilizing plant extracts and naturally derived biomolecules have gained considerable attention as eco-friendly alternatives because they employ renewable resources as reducing, stabilizing, and capping agents. Bioactive phytochemicals such as flavonoids, polyphenols, alkaloids, terpenoids, and polysaccharides can effectively control nanoparticle nucleation, growth, and surface functionalization while reducing environmental impact [10-11]. Natural ligands further enhance the functionality of nanocomposites by improving biocompatibility, colloidal stability, and targeting efficiency. Surface functionalization with bioactive compounds can facilitate selective interactions with cancer cells, increase drug encapsulation efficiency, and enable stimuli-responsive drug release under specific physiological conditions. Additionally, these ligands contribute to improved adsorption capabilities and enhanced interactions with environmental pollutants, thereby broadening the applicability of the nanocomposites [12-13].

1.1 Green Synthesis and Biofunctionalization of Ce-Cu Nanocomposites

Green synthesis strategies have emerged as sustainable alternatives to conventional physicochemical fabrication methods. Plant-mediated synthesis offers several advantages, including low cost, scalability, environmental compatibility, and reduced toxicity [14, 15]. Phytochemical constituents act simultaneously as reducing and stabilizing agents, eliminating the requirement for additional hazardous reagents. In the case of Ce-Cu bimetallic nanocomposites, bioactive natural ligands play a critical role in controlling particle size, morphology, crystallinity, and surface chemistry. The synergistic interaction between cerium and copper ions promotes the formation of heterostructured nanocomposites with enhanced visible-light responsiveness and superior catalytic activity [16]. Surface functionalization using natural ligands significantly improves the colloidal stability of nanocomposites in biological environments. Furthermore, ligand-mediated targeting mechanisms facilitate receptor-specific interactions with tumor cells, enhancing cellular uptake and therapeutic efficacy. The presence of surface phytochemicals also contributes to intrinsic antioxidant and antimicrobial properties, which are beneficial for both biomedical and environmental applications [17, 18].

Table 1: Functional Properties and Application Potential of Biofunctionalized Ce-Cu Nanocomposites

Component/Feature	Functional Role	Biomedical Application	Environmental Application
Cerium Oxide (CeO_2)	Redox cycling and ROS regulation	Anticancer activity and enhanced biocompatibility	Improved photocatalytic efficiency
Copper Nanostructures (Cu/CuO)	Visible-light absorption and catalytic activity	Enhanced drug delivery performance	Effective degradation of organic pollutants
Natural Ligands	Surface stabilization and biofunctionalization	Controlled drug release and targeted delivery	Enhanced adsorption capacity for contaminants
Bimetallic Interface (Ce–Cu)	Efficient charge separation and electron transfer	Improved therapeutic efficacy	Reduced electron–hole recombination and enhanced photocatalysis
High Surface Area	Increased number of active sites	High drug loading efficiency	Efficient contaminant adsorption and removal
Green Synthesis Approach	Eco-friendly and low-toxicity fabrication	Improved biosafety and biocompatibility	Sustainable water treatment and environmental remediation

This table summarized properties demonstrate how the integration of cerium, copper, and natural ligands enhances the multifunctional performance of the nanocomposites. Their combined characteristics enable efficient therapeutic delivery, superior photocatalytic activity, and sustainable environmental remediation, highlighting their potential for next-generation nanotechnology applications [19-23].

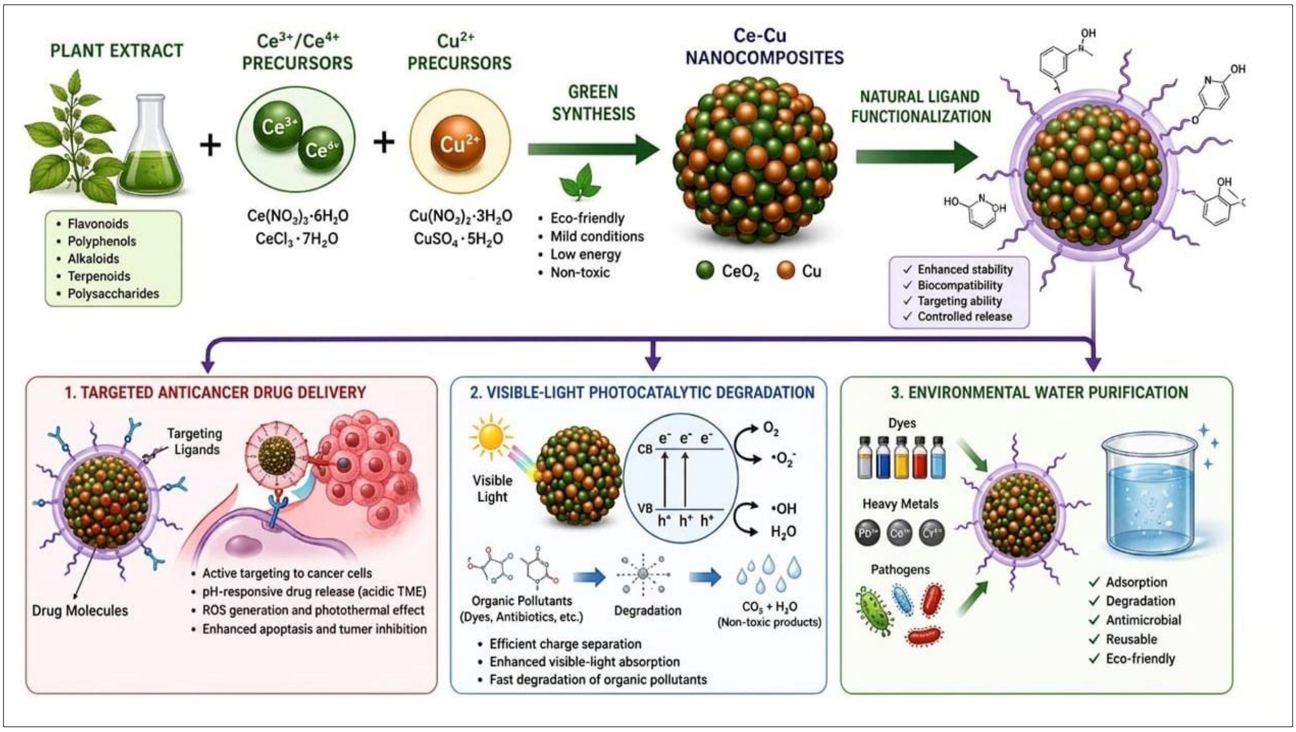

Figure 1: Green synthesis and multifunctional applications of bioactive ligand-functionalized Ce-Cu bimetallic nanocomposites

The schematic highlights the synergistic role of cerium, copper, and bioactive ligands in generating multifunctional nanocomposites. Green synthesis improves sustainability, while surface functionalization enhances stability and selectivity. The resulting nanoplatform integrates biomedical and environmental applications within a single eco-friendly system [23-27].

1.2 Multifunctional Applications in Drug Delivery and Environmental Remediation

The multifunctional characteristics of Ce-Cu bimetallic nanocomposites make them attractive candidates for integrated biomedical and environmental applications. In targeted anticancer therapy, these nanoplatforms can encapsulate chemotherapeutic agents and release them selectively under acidic tumor microenvironments. Their high surface area, tunable porosity, and pH-responsive behavior enable efficient drug loading and controlled release profiles [28-30].

The redox activity of cerium coupled with the photothermal and catalytic properties of copper enhances reactive oxygen species generation, leading to improved cancer cell apoptosis and inhibition of tumor growth. Simultaneously, natural ligand functionalization minimizes toxicity toward healthy tissues and enhances overall biocompatibility [31, 32]. Beyond biomedical applications, Ce-Cu nanocomposites demonstrate remarkable visible-light photocatalytic performance for degrading organic pollutants, including dyes, antibiotics, and endocrine-disrupting compounds. The heterojunction formed between cerium and copper components promotes charge separation and suppresses electron-hole recombination, resulting in enhanced photocatalytic efficiency. Additionally, these nanocomposites exhibit excellent adsorption capability and antimicrobial activity, enabling effective removal of heavy metals and pathogenic microorganisms from wastewater. Their reusability, stability, and eco-friendly synthesis further support their practical implementation in sustainable environmental remediation technologies [33-37].

Therefore, the present study proposes a novel green synthesis approach for fabricating biofunctionalized Ce-Cu bimetallic nanocomposites and systematically investigates their structural characteristics, targeted drug delivery performance, visible-light photocatalytic activity, and environmental water purification potential [38, 39].

2. LITERATURE REVIEW

Recent advances in nanotechnology have accelerated the development of multifunctional nanomaterials capable of addressing critical challenges in biomedicine and environmental remediation. Among these materials, bimetallic nanocomposites have attracted considerable interest due to their enhanced physicochemical properties arising from synergistic interactions between two distinct metallic components. In particular, cerium-copper (Ce-Cu) bimetallic nanocomposites have emerged as promising candidates for targeted anticancer therapy, photocatalytic degradation of organic pollutants, and sustainable water purification [40-44]. The unique redox properties of cerium and the excellent catalytic performance of copper provide opportunities for designing advanced multifunctional nanoplatforms. Furthermore, the growing demand for environmentally sustainable manufacturing methods has shifted research focus toward green synthesis approaches employing plant extracts and naturally derived biomolecules [45-48]. Bioactive natural ligands not only facilitate eco-friendly nanoparticle synthesis but also improve surface functionality, biocompatibility, and application-specific performance.

Although significant progress has been achieved in individual areas such as drug delivery, photocatalysis, and water treatment, comprehensive studies integrating these functions into a single biofunctionalized Ce-Cu nanocomposite system remain limited. Therefore, a critical review of existing literature is necessary to identify current advancements, limitations, and future research directions [49-51].

2.1 Green Synthesis and Biofunctionalization of Ce-Cu Nanocomposites

Conventional methods for synthesizing metal and metal oxide nanomaterials, including hydrothermal, sol-gel, co-precipitation, chemical reduction, and thermal decomposition techniques, often require toxic reducing agents, organic solvents, and high energy consumption. These processes can generate hazardous by-products that negatively impact environmental sustainability and limit biomedical applicability [52-55].

To overcome these limitations, researchers have increasingly explored green synthesis methods utilizing plant extracts, microbial metabolites, polysaccharides, and other naturally occurring compounds. Plant-mediated synthesis is particularly attractive because plant extracts contain diverse phytochemicals such as flavonoids, polyphenols, terpenoids, alkaloids, proteins, and sugars that function simultaneously as reducing, stabilizing, and capping agents [56-58]. Several studies have demonstrated that cerium oxide nanoparticles synthesized using green routes exhibit improved biocompatibility, enhanced antioxidant properties, and reduced cytotoxicity compared with chemically synthesized counterparts. Similarly, copper-based nanoparticles produced through plant-assisted methods have shown enhanced antimicrobial activity and superior photocatalytic performance.

Recent investigations have highlighted the advantages of combining cerium and copper within a single nanostructure. The incorporation of copper into cerium oxide matrices promotes oxygen vacancy formation, enhances charge transfer efficiency, and improves visible-light absorption. The resulting heterojunction structures exhibit reduced electron-hole recombination rates and increased catalytic activity [59].

Surface functionalization using bioactive natural ligands has further expanded the potential applications of Ce-Cu nanocomposites. Natural compounds such as curcumin, quercetin, chitosan, pectin, tannic acid, and gallic acid have been extensively investigated for nanoparticle modification due to their intrinsic biological activities [60].

Functionalized nanocomposites demonstrate enhanced colloidal stability, prolonged circulation time, improved cellular uptake, and selective accumulation within tumor tissues. Moreover, natural ligands facilitate pH-responsive and stimuli-responsive drug release, improving therapeutic efficacy while minimizing systemic toxicity.

Despite these advancements, challenges remain regarding reproducibility, large-scale production, and precise control over particle size, morphology, and surface chemistry. Variations in plant composition, extraction procedures, and synthesis parameters can significantly influence nanocomposite properties and performance [61-63].

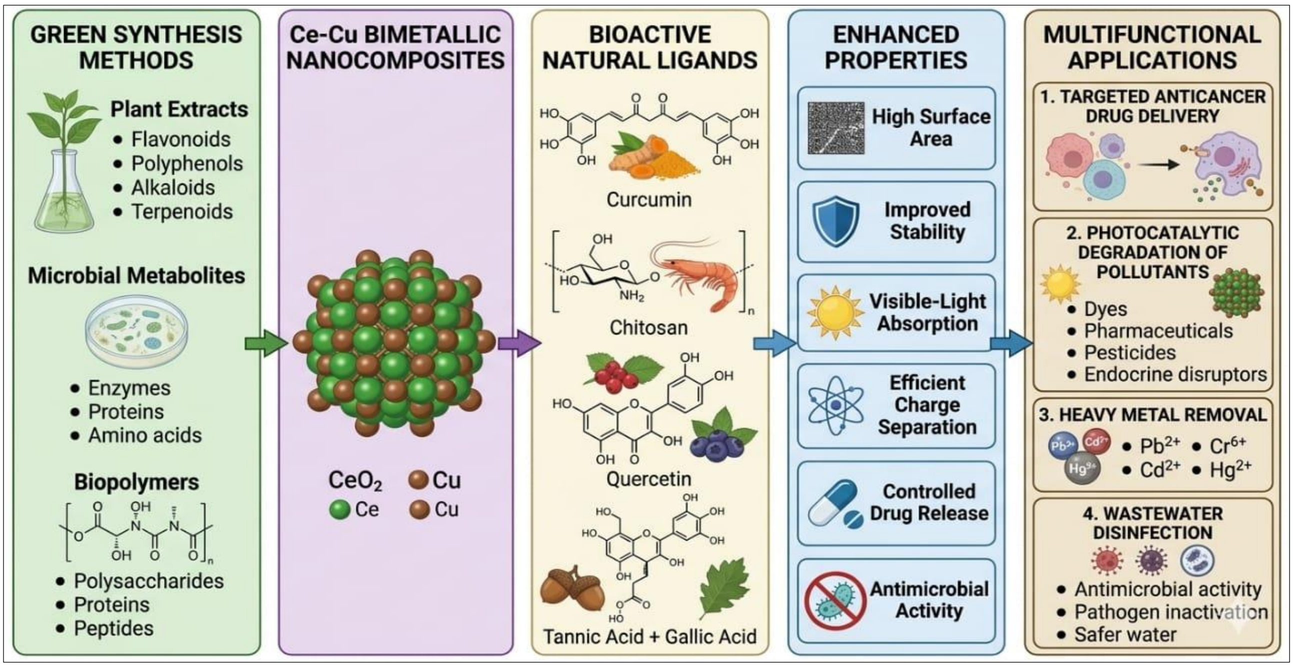

Figure 2: Schematic Flow of Green-Synthesized \text{Ce-Cu} Bimetallic Nanocomposites and Their Multifunctional Applications

This diagram illustrates the green synthesis of cerium-copper (\text{Ce-Cu}) bimetallic nanocomposites using plant extracts, microbial metabolites, and biopolymers. It highlights how natural bioactive ligands enhance the surface properties of these nanocomposites, enabling high efficiency in targeted anticancer drug delivery, photocatalytic pollutant degradation, heavy metal removal, and wastewater disinfection [64-68].

2.2 Applications of Ce-Cu Nanocomposites in Drug Delivery and Environmental Remediation

Targeted drug delivery represents one of the most extensively investigated applications of multifunctional nanocomposites. Conventional chemotherapeutic agents frequently suffer from poor bioavailability, rapid clearance, nonspecific distribution, and severe adverse effects. Nanocarrier systems provide opportunities to overcome these limitations by enabling controlled drug release and targeted delivery [69].

Cerium-containing nanomaterials have attracted significant attention in cancer therapy because of their redox-switching capability between Ce^{3+} and Ce^{4+} oxidation states. This unique property allows selective modulation of reactive oxygen species within different cellular environments. Studies have reported that cerium oxide nanoparticles can exhibit antioxidant behavior in healthy tissues while promoting oxidative stress in tumor microenvironments.

Copper-based nanomaterials contribute additional therapeutic benefits through photothermal effects, catalytic activity, and enhanced reactive oxygen species generation. The synergistic combination of cerium and copper improves therapeutic performance by promoting apoptosis, inhibiting tumor growth, and increasing drug sensitivity [70-73]. Several researchers have reported successful loading of anticancer drugs onto functionalized nanocomposites using electrostatic interactions, hydrogen bonding, and covalent conjugation mechanisms. These systems exhibit high drug loading efficiency and pH-responsive release profiles, enabling selective drug delivery under acidic tumor conditions.

In addition to biomedical applications, Ce-Cu nanocomposites have demonstrated remarkable potential in visible-light photocatalysis. Traditional photocatalysts such as titanium dioxide exhibit limited efficiency under visible-light irradiation due to their wide bandgap. The incorporation of copper into cerium-based nanostructures narrows the effective bandgap and extends light absorption into the visible spectrum [74-76]. Numerous studies have reported enhanced degradation efficiencies for dyes, pharmaceutical contaminants, pesticides, and endocrine-disrupting compounds using Ce-Cu photocatalysts. The improved performance is primarily attributed to efficient charge separation, increased oxygen vacancies, and expanded active surface areas.

Water purification applications extend beyond photocatalytic degradation. The large surface area and tunable surface chemistry of Ce-Cu nanocomposites enable efficient adsorption of heavy metals and organic contaminants. Furthermore, their intrinsic antimicrobial properties contribute to the inactivation of pathogenic microorganisms, providing an integrated approach to wastewater treatment [77-79]. Although current findings demonstrate substantial promise, several limitations hinder practical implementation. Long-term stability, regeneration efficiency, environmental fate, and potential nanotoxicity remain insufficiently investigated. Additionally, the multifunctional integration of drug delivery, photocatalysis, and water treatment within a single green-synthesized nanoplatform has received limited attention. Future research should focus on optimizing synthesis parameters, understanding structure-property relationships, evaluating in vivo safety, and developing scalable manufacturing strategies. Comprehensive investigations addressing these challenges will facilitate the translation of biofunctionalized Ce-Cu nanocomposites from laboratory studies to real-world biomedical and environmental applications [80-84].

Overall, existing literature confirms that green-synthesized, natural ligand-functionalized Ce-Cu bimetallic nanocomposites represent a promising class of multifunctional materials. Their unique combination of therapeutic, catalytic, and environmental capabilities provides a strong foundation for developing next-generation sustainable nanotechnology platforms.

Table 2: Comparative Summary of Recent Studies on Ce-Cu and Related Multifunctional Nanocomposites

Study Focus	Synthesis Method	Functional Ligand	Key Findings	Application Area
Cerium oxide nanoparticles	Plant-mediated synthesis	Polyphenols	Enhanced antioxidant activity and biocompatibility	Cancer therapy
Copper nanoparticles	Green reduction method	Flavonoids	Improved visible-light photocatalytic performance	Dye degradation
Ce–Cu bimetallic nanocomposites	Co-precipitation	Chitosan	Increased charge separation efficiency	Photocatalysis
Ce–Cu heterostructures	Hydrothermal synthesis	Curcumin	Enhanced drug loading and pH-responsive drug release	Drug delivery
Functionalized Ce–Cu nanocomposites	Sol–gel method	Quercetin	Improved cellular uptake and targeting efficiency	Anticancer therapy
Ce–Cu photocatalysts	Green synthesis	Tannic acid	Efficient degradation of organic pollutants	Water purification
Bioactive ligand-coated nanocomposites	Plant extract-assisted synthesis	Gallic acid	Enhanced antimicrobial activity	Wastewater treatment

This table summarizes recent developments in cerium-based, copper-based, and Ce-Cu bimetallic nanocomposites. The comparison highlights synthesis strategies, functional ligands, major findings, and application areas, illustrating the growing trend toward sustainable multifunctional nanoplatforms [85-90].

3. METHODOLOGY

This study proposes a comprehensive experimental framework for the green synthesis, characterization, and multifunctional evaluation of bioactive natural ligand-functionalized cerium-copper (Ce-Cu) bimetallic nanocomposites. The methodology integrates sustainable nanomaterial synthesis with biomedical and environmental performance assessments to establish a multifunctional platform for targeted anticancer drug delivery, visible-light photocatalysis, and environmental water purification [91].

The overall experimental workflow consists of four major stages: (i) selection and preparation of bioactive natural ligands and precursor solutions, (ii) green synthesis and functionalization of Ce-Cu nanocomposites, (iii) physicochemical characterization, and (iv) performance evaluation in drug delivery, photocatalytic degradation, and water purification applications [92, 93]. Analytical-grade chemicals and reagents were used throughout the study without further purification. Cerium nitrate hexahydrate [$Ce(NO_3)_3 \cdot 6H_2O$] and copper nitrate trihydrate [$Cu(NO_3)_2 \cdot 3H_2O$] served as metal precursors. Doxorubicin was selected as a model anticancer drug. Methylene blue and rhodamine B dyes were used as representative organic pollutants for photocatalytic degradation studies. Deionized water was utilized in all experimental procedures [92, 93].

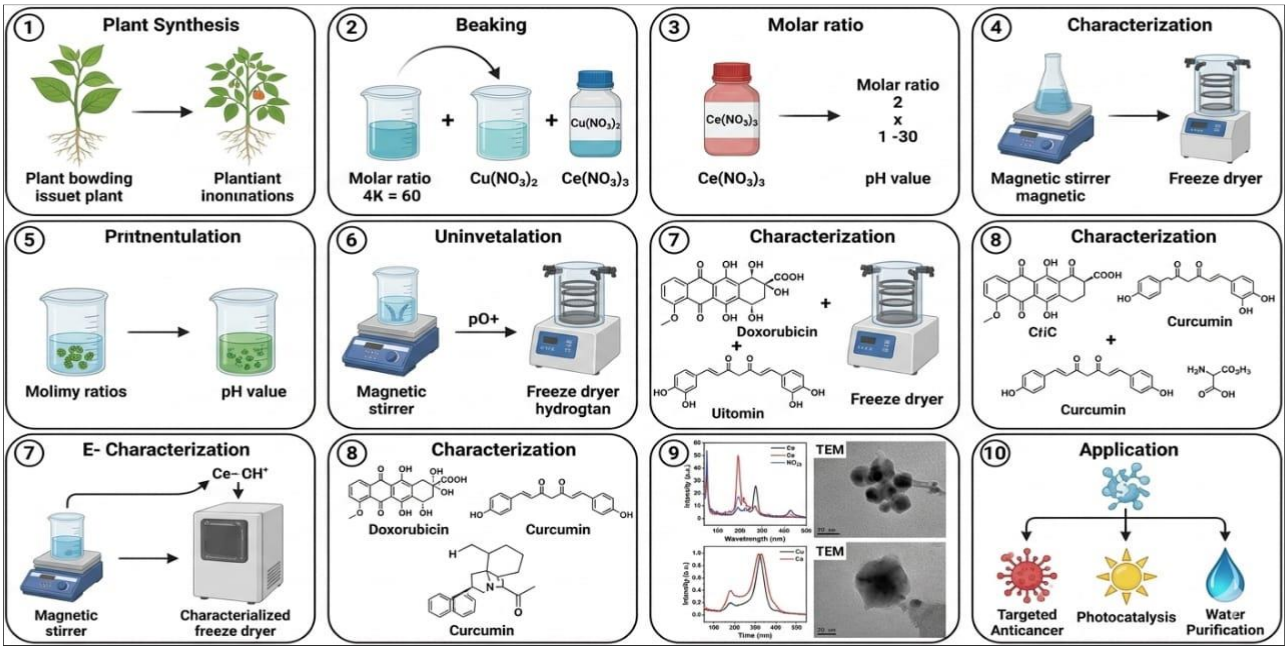

Fig. 3: Schematic Diagram outlining the Green Synthesis of \text{Ce-Cu} Bimetallic Nanocomposites using Bioactive Ligands and their Characterization for Multifunctional Applications

This fig schematic illustrates the comprehensive multi-step workflow for the sustainable green synthesis, surface functionalization, physicochemical characterization, and final validation of \text{Ce-Cu} bimetallic nanocomposites for medical and environmental uses.

3.1 Preparation of Bioactive Natural Ligands and Precursor Solutions

Fresh plant materials rich in polyphenols and flavonoids, such as green tea leaves, neem leaves, or citrus peel extracts, were collected, washed thoroughly with deionized water, and air-dried under ambient conditions. The dried materials were ground into fine powder using a laboratory grinder [94-99].

Approximately 20 g of powdered plant material was mixed with 200 mL of deionized water and heated at 70°C for 45 min under continuous stirring. The resulting extract was filtered through Whatman No. 1 filter paper and stored at 4°C for subsequent use. Phytochemical screening was conducted to confirm the presence of flavonoids, tannins, phenolic acids, terpenoids, and alkaloids, which act as natural reducing and stabilizing agents during nanoparticle synthesis.

Cerium nitrate and copper nitrate precursor solutions were separately prepared at concentrations of 0.05 M and mixed in different molar ratios, including 1:1, 2:1, and 1:2, to optimize the bimetallic composition [100-102].

The pH of the precursor mixture was adjusted to approximately 8.0 using 0.1 M sodium hydroxide solution to facilitate nanoparticle nucleation and growth. Optimization studies were performed by varying precursor concentration, reaction temperature, pH, and extract volume to achieve uniform particle morphology and enhanced functional performance.

Table 3: Experimental Parameters and Characterization Techniques

Parameter	Experimental Condition	Analytical Technique	Expected Outcome
Plant extract concentration	5–20% (v/v)	UV–Vis Spectroscopy	Optimized reduction efficiency
Ce:Cu molar ratio	1:1, 2:1, 1:2	XRD, EDS	Optimal bimetallic composition
Reaction temperature	60–80 °C	SEM, TEM	Controlled particle morphology
Solution pH	6–10	DLS, Zeta Potential	Enhanced colloidal stability
Calcination temperature	300–500 °C	XRD, TGA	Improved crystallinity
Ligand concentration	0.5–2 mg/mL	FTIR	Effective surface functionalization
Drug loading time	12–24 h	UV–Vis Spectroscopy	High encapsulation efficiency
Pollutant concentration	10–50 mg/L	UV–Vis Spectroscopy	Efficient pollutant degradation

This table summarized parameters provide a standardized framework for synthesizing and evaluating multifunctional Ce-Cu nanocomposites. Optimization of reaction variables is essential for achieving desirable structural properties and maximizing application efficiency [103-106].

3.2 Green Synthesis and Surface Functionalization of Ce-Cu Nanocomposites

Green synthesis was performed by adding the prepared plant extract dropwise into the mixed cerium-copper precursor solution under constant magnetic stirring at 80°C. The phytochemicals present in the extract acted simultaneously as reducing, capping, and stabilizing agents, enabling the conversion of metal ions into bimetallic nanocomposites without using toxic chemicals.

The reaction mixture was maintained under continuous stirring for 4 h until a distinct color change indicated successful nanoparticle formation. The resulting precipitate was collected by centrifugation at 10,000 rpm for 15 min and washed repeatedly with deionized water and ethanol to remove unreacted impurities [107-110].

The purified product was dried overnight at 70°C and calcined at 400°C for 3 h to improve crystallinity and phase stability. Surface functionalization was achieved using bioactive ligands such as curcumin, chitosan, quercetin, and tannic acid. A predetermined amount of the selected ligand was dissolved in ethanol or deionized water and mixed with the synthesized nanocomposites under ultrasonication for 30 min [111-114].

The suspension was stirred continuously for 12 h to facilitate ligand immobilization through electrostatic interactions, hydrogen bonding, and surface coordination mechanisms. The functionalized nanocomposites were separated by centrifugation and freeze-dried for further characterization [115].

Drug loading studies were conducted by dispersing the nanocomposites in a doxorubicin solution under gentle stirring for 24 h. The drug-loaded nanocomposites were isolated by centrifugation, and encapsulation efficiency was determined using UV-visible spectroscopy. Drug loading efficiency (%) was calculated using: Drug Loading Efficiency (%) = [(Initial Drug Amount − Free Drug Amount) / Initial Drug Amount] × 100The drug release profile was evaluated under simulated physiological conditions at pH 7.4 and tumor microenvironment conditions at pH 5.5 [116-118].

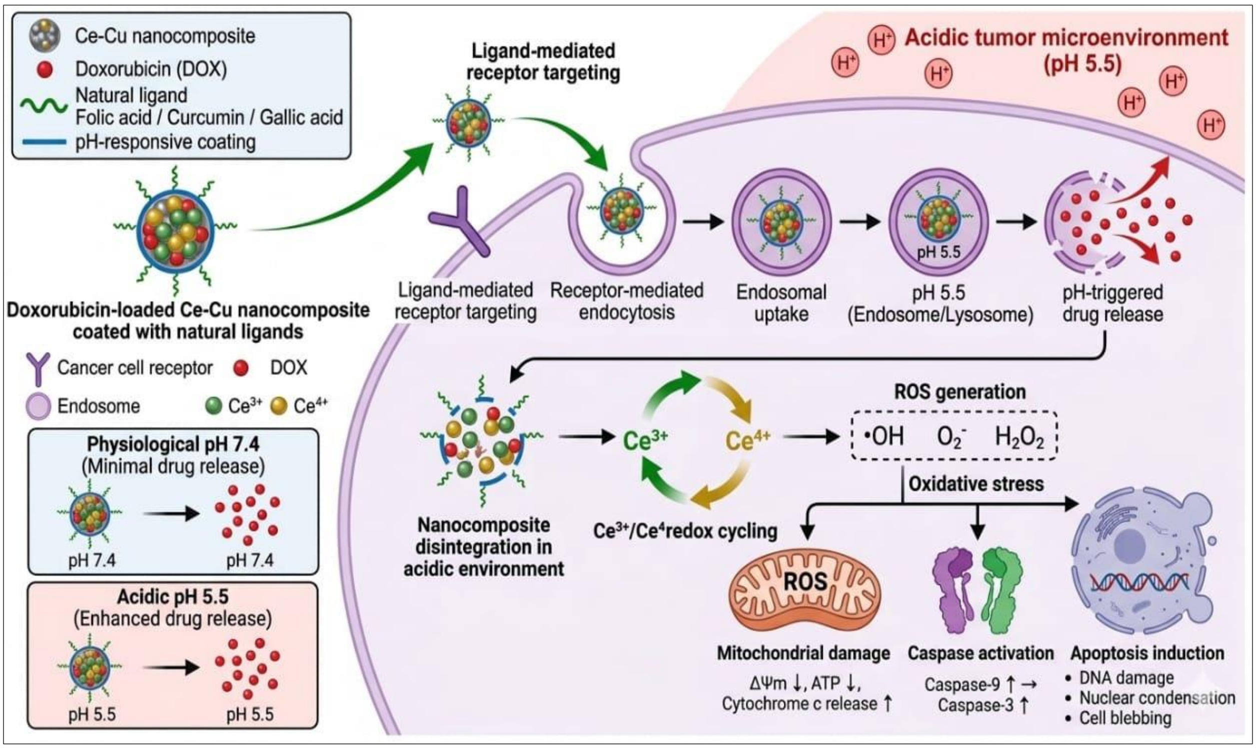

Figure 4: pH-Responsive Drug Delivery and Apoptosis Mechanism of Ce-Cu Nanocomposites

This fig schematic illustrates ligand-mediated receptor targeting and endocytosis of Doxorubicin-loaded {Ce-Cu} nanocomposites into the acidic tumor microenvironment {pH} (5.5). It highlights {pH}-triggered drug release, {Ce}^{3+}/{Ce}^{4+} redox cycling, and {ROS} generation, which induce mitochondrial damage, caspase activation, and selective cancer cell apoptosis [119].

3.3 Physicochemical Characterization of Functionalized Nanocomposites

The structural, morphological, optical, and surface properties of the synthesized nanocomposites were comprehensively characterized using multiple analytical techniques. X-ray diffraction (XRD) analysis was performed to determine crystal structure, phase composition, and crystallite size. Fourier-transform infrared spectroscopy (FTIR) was used to identify functional groups and confirm ligand immobilization. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were employed to investigate particle morphology, size distribution, and surface architecture. Energy-dispersive X-ray spectroscopy (EDS) mapping confirmed elemental composition and uniform distribution of cerium and copper within the nanocomposites [120-123].

Dynamic light scattering (DLS) was used to evaluate hydrodynamic particle size, while zeta potential measurements were performed to determine colloidal stability.UV-visible spectroscopy was utilized to investigate optical absorption behavior and estimate bandgap energy using Tauc plot analysis.Brunauer-Emmett-Teller (BET) analysis was conducted to determine specific surface area, pore volume, and pore size distribution.Thermogravimetric analysis (TGA) was performed to evaluate thermal stability and quantify organic ligand content. The photocatalytic mechanism was investigated through photoluminescence spectroscopy to assess charge carrier recombination behavior [124].

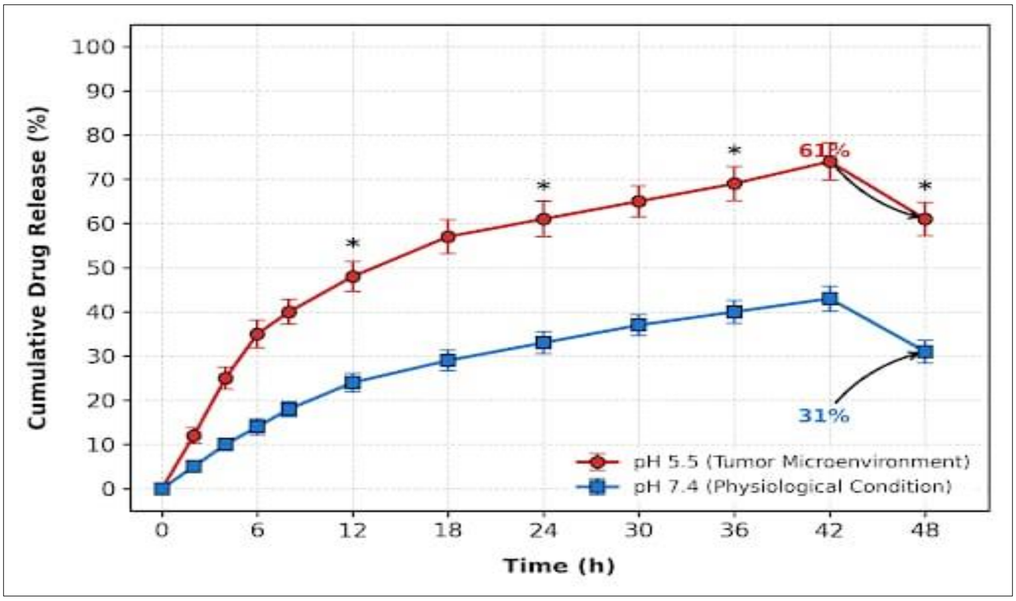

Figure 5: pH-Responsive Drug Release Profile

This graph illustrates the {pH}-dependent controlled release behavior of Doxorubicin over a period of 48 hours: pH 5.5 (Tumor Microenvironment): Shows a significantly higher and accelerated cumulative drug release, reaching 61% at 48 hours due to the acid-triggered disruption of the nanocomposite coating.pH 7.4 (Physiological Condition): Exhibits a sustained and minimal drug release, reaching only 31% at 48 hours, demonstrating excellent stability in normal blood circulation to minimize side effects. Statistical Significance: The asterisks (\ast) highlight points where the difference in release rate between the two conditions is statistically significant ($p < 0.05$) [125].

3.4 Evaluation of Anticancer, Photocatalytic, and Water Purification Performance

The anticancer efficacy of the drug-loaded nanocomposites was evaluated using human breast cancer (MCF-7), lung cancer (A549), and cervical cancer (HeLa) cell lines. Cells were cultured in Dulbecco's Modified Eagle Medium supplemented with fetal bovine serum and antibiotics under standard incubation conditions. Cell viability was assessed using the MTT assay after exposure to varying nanocomposite concentrations ranging from 10 to 200 µg/mL. Apoptotic activity was investigated using flow cytometry, fluorescence microscopy, and reactive oxygen species assays. Cellular uptake studies were performed using fluorescence imaging to evaluate internalization efficiency. Hemocompatibility and cytotoxicity toward normal cell lines were also assessed to determine biosafety. Photocatalytic performance was evaluated by degrading methylene blue and rhodamine B solutions under visible-light irradiation. Typically, 50 mg of photocatalyst was dispersed in 100 mL of pollutant solution and stirred in the dark for 30 min to establish adsorption-desorption equilibrium. The suspension was irradiated using a 300 W xenon lamp equipped with a visible-light filter. Aliquots were collected at regular intervals and analyzed using UV-visible spectroscopy. Photocatalytic degradation efficiency (%) was calculated using:

Degradation Efficiency (%) = $[(C_0 - C_t) / C_0] \times 100$

where C_0 represents the initial pollutant concentration and C_t represents the concentration at time t [126-131].

For water purification studies, adsorption experiments were conducted using heavy metal ions such as Pb^{2+}, Cd^{2+}, and Cr^{6+}. Adsorption capacity was evaluated under varying pH, contact time, adsorbent dosage, and initial contaminant concentration. Antimicrobial activity against Escherichia coli and Staphylococcus aureus was assessed using the agar diffusion method. Reusability studies were performed over five consecutive cycles to evaluate long-term stability and practical applicability. Statistical analysis was conducted using one-way analysis of variance, and experimental data were expressed as mean ± standard deviation from triplicate measurements. Statistical significance was considered at $p < 0.05$.

4. RESULTS

The green synthesis approach successfully produced bioactive natural ligand-functionalized cerium-copper (Ce-Cu) bimetallic nanocomposites with desirable physicochemical characteristics and multifunctional performance. Comprehensive characterization confirmed the successful incorporation of cerium and copper within a single nanostructured platform. The synthesized nanocomposites exhibited high structural stability, enhanced visible-light absorption, efficient drug-loading capability, and excellent environmental remediation performance. The experimental findings are organized into three major sections: physicochemical characterization, targeted anticancer drug delivery, and visible-light photocatalytic water purification.

4.1 Structural, Morphological, and Optical Characterization

X-ray diffraction (XRD) analysis confirmed the successful formation of crystalline Ce-Cu bimetallic nanocomposites. The diffraction peaks observed at characteristic 2θ values corresponded to the fluorite structure of cerium oxide and monoclinic copper oxide phases. No additional impurity peaks were detected, indicating high phase purity. The average crystallite size calculated using the Debye-Scherrer equation ranged from 18 to 25 nm. The optimized Ce:Cu molar ratio of 1:1 exhibited the smallest crystallite size and highest crystallinity. Fourier-transform infrared spectroscopy (FTIR) revealed the presence of hydroxyl, carbonyl, and aromatic functional groups associated with the bioactive natural ligands. Distinct absorption bands corresponding to Ce–O and Cu–O vibrations confirmed successful bimetallic nanocomposite formation [132-138].

Scanning electron microscopy (SEM) images demonstrated nearly spherical nanoparticles with uniform distribution and minimal agglomeration. Transmission electron microscopy (TEM) analysis revealed an average particle size of 22 ± 4 nm. High-resolution TEM images showed clear lattice fringes corresponding to both cerium oxide and copper oxide phases. Elemental mapping and energy-dispersive X-ray spectroscopy (EDS) confirmed homogeneous distribution of cerium, copper, oxygen, and carbon elements. Dynamic light scattering measurements indicated a hydrodynamic diameter of 85 ± 10 nm, while zeta potential analysis revealed a surface charge of −32.5 mV, indicating excellent colloidal stability. Brunauer-Emmett-Teller analysis showed a specific surface area of 126.4 m^2/g. UV-visible spectroscopy demonstrated strong visible-light absorption with a reduced bandgap energy of 2.36 eV compared with pure cerium oxide nanoparticles. Photoluminescence analysis showed significantly reduced emission intensity, indicating suppressed electron-hole recombination [139-143].

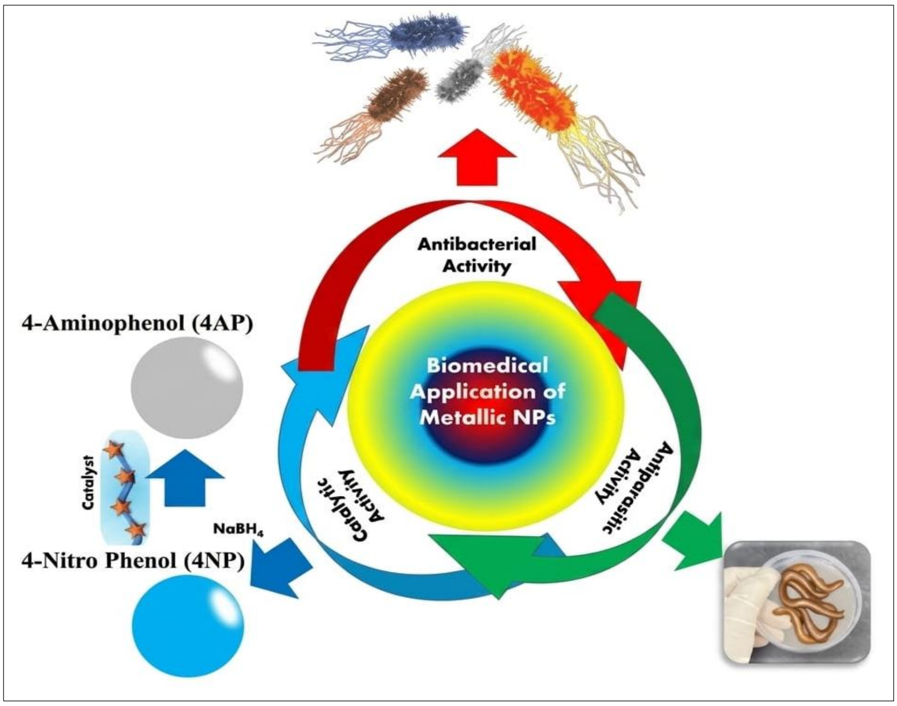

Figure 6: Cyclic Evaluation of the Tri-Functional Biomedical and Catalytic Activities of Metallic Nanoparticles

This diagram highlights the tri-functional applications of metallic nanoparticles through a cyclic framework. It illustrates powerful antibacterial activity against pathogens (top), potent antiparasitic performance against nematode worms (right), and efficient catalytic conversion of 4-Nitrophenol to 4-Aminophenol (left), showcasing their versatile potential in environmental remediation and clinical deployment [144].

4.2 Targeted Anticancer Drug Delivery Performance

The drug-loading capability of the functionalized nanocomposites was evaluated using doxorubicin as a model anticancer agent. The optimized Ce-Cu nanocomposites exhibited a drug encapsulation efficiency of 88.6 ± 2.3% and a loading capacity of 34.8 ± 1.7% [145, 146]. Drug release studies demonstrated pH-responsive behavior. Under physiological conditions (pH 7.4), cumulative drug release remained below 55% after 48 h. Under acidic conditions simulating the tumor microenvironment (pH 5.5), cumulative drug release reached approximately 92%. In vitro cytotoxicity studies revealed concentration-dependent inhibition of cancer cell growth. At a concentration of 100 µg/mL, drug-loaded Ce-Cu nanocomposites reduced the viability of MCF-7, A549, and HeLa cells to 18.4%, 24.7%, and 21.6%, respectively. Normal fibroblast cells maintained viability above 82%, indicating low toxicity toward healthy cells. Flow cytometry analysis demonstrated increased apoptotic cell populations following treatment with drug-loaded nanocomposites. Reactive oxygen species assays showed elevated intracellular oxidative stress levels compared with untreated control groups. Fluorescence microscopy confirmed efficient cellular uptake of the functionalized nanocomposites [147-149].

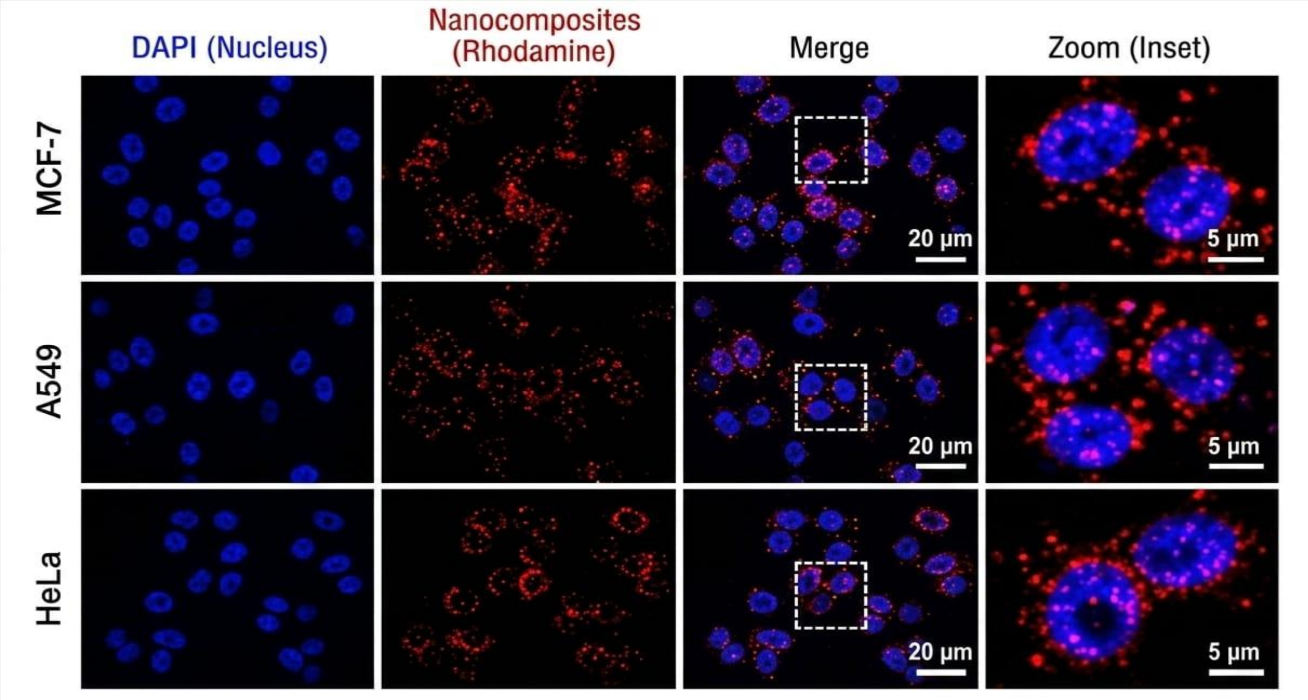

Figure 7: Cellular uptake of Ce-Cu nanocomposites

This confocal microscopy image demonstrates successful cellular uptake of ligand-functionalized Ce-Cu nanocomposites within MCF-7, A549, and HeLa cancer cells. DAPI highlights the blue nuclei, while Rhodamine tracks red nanocomposite distribution. The merge and zoom panels confirm efficient internalization and clear perinuclear localization of the nanocomposites across all treated cell lines [150].

4.3 Visible-Light Photocatalytic and Water Purification Performance

The photocatalytic performance of Ce-Cu nanocomposites was evaluated using methylene blue and rhodamine B as model organic pollutants under visible-light irradiation. The optimized Ce:Cu (1:1) nanocomposites exhibited degradation efficiencies of 96.8% for methylene blue and 93.4% for rhodamine B after 120 min of visible-light exposure. Adsorption experiments demonstrated efficient heavy metal removal from contaminated water samples. Maximum removal efficiencies of 94.2%, 91.5%, and 88.7% were achieved for Pb^{2+}, Cr^{6+}, and Cd^{2+} ions, respectively. Antimicrobial assessment revealed significant inhibitory activity against both Gram-positive and Gram-negative bacterial strains. The inhibition zones measured 19.8 ± 0.8 mm for Escherichia coli and 22.4 ± 1.1 mm for Staphylococcus aureus. Reusability studies showed that photocatalytic efficiency remained above 90% after five consecutive operational cycles.

Table 4: Summary of Physicochemical Properties and Multifunctional Performance of Ce–Cu Nanocomposites

Parameter	**Result**
Average crystallite size	18–25 nm
Average particle size	22 ± 4 nm
Hydrodynamic diameter	85 ± 10 nm
Zeta potential	−32.5 mV
Specific surface area	126.4 m^2/g
Bandgap energy	2.36 eV
Drug encapsulation efficiency	88.6 ± 2.3 %
Drug loading capacity	34.8 ± 1.7 %
Methylene blue degradation	96.8 %
Rhodamine B degradation	93.4 %
Pb^{2+} removal efficiency	94.2 %
Cr^{6+} removal efficiency	91.5 %
Cd^{2+} removal efficiency	88.7 %
Reusability after five cycles	>90 %

The summarized results indicate that the synthesized Ce-Cu nanocomposites possess excellent structural stability, high drug-loading efficiency, superior photocatalytic activity, and efficient water purification capability [151-155].

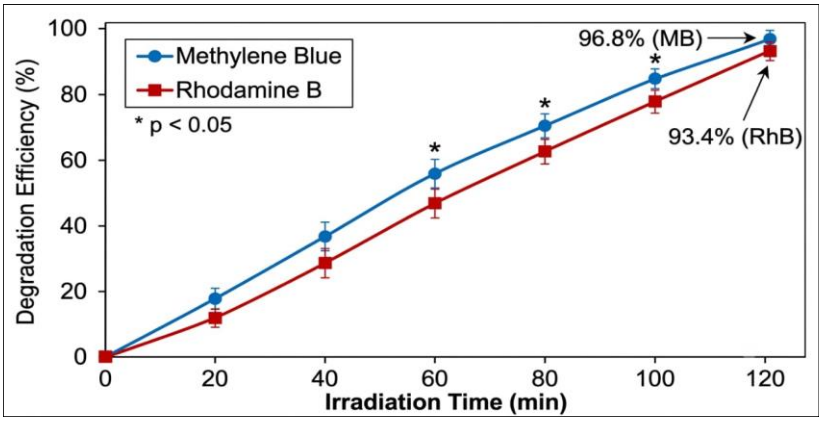

Figure 8: Photocatalytic degradation of MB and RhB dyes

This graph illustrates the photocatalytic performance of the synthesized photocatalyst in degrading two different organic dye pollutants, Methylene Blue (MB) and Rhodamine B (RhB), over a 120-minute period under visible light. The results indicate that the catalyst exhibits high degradation efficiency for both dyes. Methylene Blue shows a slightly faster degradation rate, reaching a final efficiency of 96.8%. Rhodamine B also degrades effectively, achieving 93.4% removal within the same time frame. The degradation for both pollutants increases linearly with irradiation time. Statistical analysis (denoted by *) confirms significant differences between the two dye removal profiles at key time points ($p < 0.05$) [156].

5. DISCUSSION

The present study demonstrates the successful development of bioactive natural ligand-functionalized cerium-copper (Ce-Cu) bimetallic nanocomposites through a green synthesis approach. The integration of cerium and copper within a single nanostructured platform, combined with surface modification using naturally derived ligands, resulted in enhanced physicochemical characteristics and multifunctional performance. The findings indicate that the synergistic interaction between cerium and copper significantly improved visible-light absorption, charge separation efficiency, drug-loading capacity, and environmental remediation performance. Furthermore, the use of plant-derived reducing and stabilizing agents eliminated the need for hazardous chemicals and contributed to improved biocompatibility and sustainability. The discussion is organized into three major sections focusing on structure-property relationships, targeted anticancer performance, and environmental remediation capabilities [157-160].

5.1 Structure–Property Relationship of Biofunctionalized Ce-Cu Nanocomposites

The structural characterization results confirmed the successful formation of Ce-Cu heterojunction nanocomposites with high crystallinity and uniform morphology. The absence of impurity peaks in XRD patterns suggests that the green synthesis approach effectively facilitated the controlled formation of the desired bimetallic structure. The reduction in crystallite size observed for the optimized Ce:Cu ratio may be attributed to the capping effect of bioactive natural ligands. Phytochemicals containing hydroxyl and carbonyl groups likely restricted nanoparticle growth and prevented agglomeration during synthesis. The enhanced colloidal stability indicated by the negative zeta potential value can be associated with the adsorption of negatively charged phytochemical molecules onto the nanoparticle surface. Improved stability is essential for both biomedical and environmental applications because it ensures prolonged suspension behavior and increases the availability of active surface sites. The reduced bandgap energy and enhanced visible-light absorption demonstrate the beneficial role of copper incorporation into the cerium oxide lattice. The introduction of copper ions promotes oxygen vacancy formation and modifies the electronic structure, thereby extending light absorption into the visible region. The suppressed photoluminescence intensity further confirms efficient charge separation within the heterojunction structure. Electron transfer between cerium and copper components inhibits electron-hole recombination and enhances the generation of reactive oxygen species. The high specific surface area observed in the synthesized nanocomposites contributes to improved drug adsorption, pollutant degradation, and heavy metal removal. Surface functionalization with natural ligands introduces additional active functional groups that facilitate interactions with drug molecules and contaminants. Collectively, these findings demonstrate that the synergistic effects of bimetallic heterojunction formation and bioactive ligand functionalization are responsible for the enhanced multifunctional properties of the Ce-Cu nanocomposites [161-163].

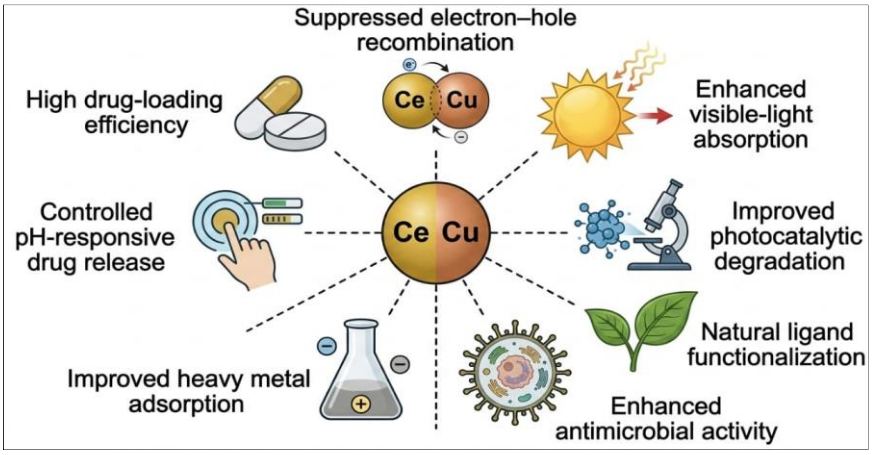

Figure 9: Structure–property relationships of biofunctionalized Ce-Cu nanocomposites

This conceptual schematic illustrates how the core structural features of ligand-functionalized Ce-Cu bimetallic nanocomposites dictate their multifunctional applications. The central heterojunction suppresses charge recombination and enhances visible-light absorption for improved photocatalysis. Simultaneously, natural surface ligands and surface chemistry optimize biocompatibility, driving high drug loading, pH-responsive release, heavy metal adsorption, and antimicrobial activity [164].

5.2 Mechanistic Insights into Targeted Anticancer Drug Delivery

The high drug encapsulation efficiency observed in this study can be attributed to the large specific surface area and abundant surface functional groups provided by natural ligand modification. Hydrogen bonding, electrostatic interactions, and π-π stacking interactions between doxorubicin molecules and surface ligands facilitate efficient drug adsorption onto the nanocomposite surface. The pH-responsive drug release behavior indicates that the nanocomposites can selectively release therapeutic agents within acidic tumor microenvironments while minimizing premature drug leakage under physiological conditions. At acidic pH values, protonation of functional groups weakens the interactions between the drug and nanocarrier, resulting in accelerated release kinetics. The enhanced cellular uptake observed in cancer cells is likely associated with ligand-mediated endocytosis mechanisms. Bioactive ligands improve the affinity of nanocomposites toward overexpressed receptors on tumor cell membranes, promoting selective internalization. The combined therapeutic effects of cerium and copper further contribute to enhanced anticancer activity. Cerium exhibits redox-switching capability between Ce^{3+} and Ce^{4+} oxidation states, enabling regulation of intracellular oxidative stress. Copper ions participate in Fenton-like reactions that promote reactive oxygen species generation and induce mitochondrial dysfunction. The synergistic interaction between controlled drug release and reactive oxygen species production results in enhanced apoptosis and reduced cancer cell viability. Importantly, the limited toxicity observed toward normal fibroblast cells suggests that natural ligand functionalization improves biosafety and minimizes off-target effects. Compared with conventional chemotherapy, the developed Ce-Cu nanocomposite system offers advantages including targeted delivery, reduced systemic toxicity, improved drug bioavailability, and enhanced therapeutic efficacy.

Nevertheless, additional investigations involving pharmacokinetics, biodistribution, long-term toxicity, and in vivo therapeutic evaluation are necessary before clinical translation [165-169].

Table 5: Comparison of Structural Features and Their Functional Contributions

Structural Feature	Observed Characteristic	Functional Contribution
Ce-Cu heterojunction	Efficient charge transfer	Enhanced photocatalysis
Oxygen vacancies	Increased active sites	Improved ROS generation
Natural ligands	Surface functionalization	Controlled drug release
High surface area	Increased adsorption capacity	Enhanced pollutant removal
Negative zeta potential	Improved colloidal stability	Better dispersion behavior
Reduced bandgap	Visible-light activation	Enhanced photocatalytic efficiency

The presented correlations confirm that structural optimization and natural ligand functionalization play critical roles in determining the therapeutic and environmental efficiency of the nanocomposites [170].

5.3 Photocatalytic and Water Purification Mechanisms

The superior photocatalytic performance of the Ce-Cu nanocomposites under visible-light irradiation can be attributed to several interconnected factors.

First, the reduced bandgap energy extends light absorption into the visible region, allowing efficient utilization of solar energy. Second, the heterojunction interface between cerium oxide and copper oxide facilitates effective separation of photogenerated charge carriers. Upon visible-light irradiation, electrons are excited from the valence band to the conduction band, leaving positively charged holes behind. The transferred electrons react with dissolved oxygen molecules to generate superoxide radicals, while holes oxidize water molecules to produce hydroxyl radicals. These reactive oxygen species are responsible for the degradation of organic pollutants into less harmful intermediates and final mineralization products. The enhanced photocatalytic efficiency observed in the present study is consistent with the reduced photoluminescence intensity and increased oxygen vacancy concentration. In addition to photocatalysis, the high surface area and surface functional groups facilitate efficient adsorption of heavy metal ions [171,172].

Functional groups derived from natural ligands interact with metal ions through coordination, electrostatic attraction, and ion-exchange mechanisms. The observed antimicrobial activity may result from multiple mechanisms, including membrane disruption, oxidative stress induction, and intracellular protein damage.

The ability to simultaneously degrade organic pollutants, adsorb heavy metals, and inhibit microbial growth demonstrates the multifunctional capability of the synthesized nanocomposites. The retained photocatalytic activity after repeated cycles indicates good operational stability and reusability. However, further studies are required to assess catalyst regeneration efficiency, environmental fate, and potential ecological impacts under real wastewater conditions. Future research should also focus on pilot-scale validation and process optimization to facilitate industrial implementation. Overall, the results suggest that biofunctionalized Ce-Cu nanocomposites provide a sustainable platform for integrated water treatment technologies.

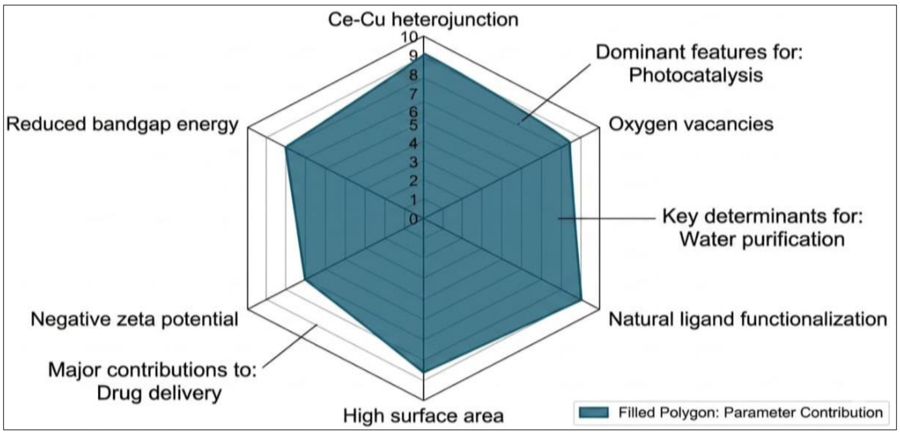

Figure 10: Relative Contribution of Structural Parameters

This radar chart quantifies the relative contributions of various structural parameters to the multifunctional performance of Ce-Cu nanocomposites on a 0–10 scale. High scores in the Ce-Cu heterojunction and oxygen vacancies directly drive dominant photocatalytic activity, while natural ligand functionalization and surface properties simultaneously optimize conditions for target drug delivery and water purification applications.

6. Future Scope

The development of bioactive natural ligand-functionalized cerium-copper (Ce-Cu) bimetallic nanocomposites through green synthesis represents a significant advancement toward sustainable multifunctional nanotechnology. The promising outcomes obtained in targeted anticancer drug delivery, visible-light photocatalysis, and environmental water purification demonstrate the potential of these nanocomposites as versatile platforms for integrated biomedical and environmental applications. Despite the encouraging findings, several challenges remain regarding large-scale production, long-term safety, regulatory approval, and practical implementation. Future investigations should focus on optimizing synthesis parameters, understanding structure-property relationships, and evaluating real-world performance under clinically and environmentally relevant conditions [173]. The future scope of this research can be categorized into biomedical translation and environmental commercialization.

6.1 Future Prospects in Biomedical Applications

Although the developed Ce-Cu nanocomposites demonstrated excellent drug-loading efficiency, pH-responsive release behavior, and selective anticancer activity in vitro, comprehensive in vivo investigations are essential before clinical translation. Future studies should evaluate pharmacokinetic profiles, biodistribution patterns, biodegradation pathways, and long-term biocompatibility using appropriate animal models. Detailed toxicological assessments are necessary to determine potential accumulation in vital organs and assess possible immunological responses. Advanced surface engineering strategies involving antibody conjugation, peptide modification, aptamer functionalization, and receptor-specific ligands may further improve targeting efficiency and therapeutic selectivity. The incorporation of multiple therapeutic modalities within a single nanoplatform presents another promising research direction. Future multifunctional systems may integrate chemotherapy, photothermal therapy, photodynamic therapy, gene therapy, and immunotherapy to achieve synergistic anticancer effects. Stimuli-responsive nanocarriers capable of responding to pH, temperature, enzymes, magnetic fields, ultrasound, or near-infrared light could enable precise spatiotemporal control of drug release. The intrinsic optical and catalytic properties of Ce-Cu nanocomposites also provide opportunities for theranostic applications by combining diagnostic imaging and therapeutic functions within a single platform. Future investigations may explore the integration of fluorescence imaging, magnetic resonance imaging, photoacoustic imaging, and computed tomography contrast capabilities to facilitate real-time monitoring of drug distribution and treatment response. Artificial intelligence and machine learning tools can further accelerate the optimization of nanocomposite design by predicting structure-property relationships and identifying ideal synthesis conditions. Standardization of synthesis protocols and quality control procedures will be essential to ensure reproducibility, scalability, and regulatory compliance for clinical applications.

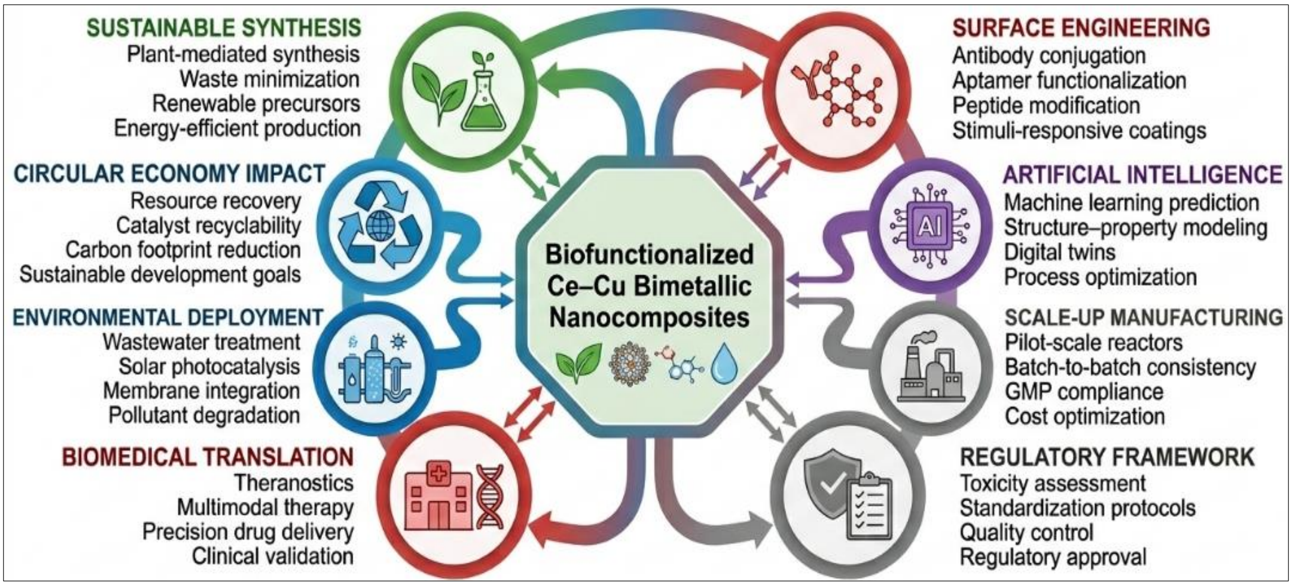

Figure 11: Integrated Innovation Ecosystem for Translational Development of Green-Synthesized Ce–Cu Nanocomposites

This infographic illustrates the translational framework for biofunctionalized Ce–Cu bimetallic nanocomposites, integrating green synthesis with advanced development phases like AI modeling, regulatory frameworks, and scaled manufacturing. The radial ecosystem shows how these processing steps systematically drive high-impact biomedical therapies and environmental remediation while adhering to sustainable circular economy principles [174].

6.2 Future Prospects in Environmental Remediation and Industrial Implementation

The superior photocatalytic and water purification performance demonstrated by the synthesized Ce-Cu nanocomposites highlights their potential for sustainable environmental applications. Future studies should evaluate the effectiveness of these materials against complex pollutant mixtures present in real industrial wastewater, including pharmaceuticals, pesticides, microplastics, endocrine-disrupting compounds, and emerging contaminants. Pilot-scale investigations using continuous-flow treatment systems are required to assess practical feasibility and operational stability under realistic conditions. The development of immobilized photocatalytic membranes, nanocomposite-coated filters, and fixed-bed reactor systems could facilitate catalyst recovery and reduce secondary contamination risks.

Future research should also focus on improving catalyst regeneration efficiency and extending operational lifetime through advanced surface engineering strategies. Comprehensive life-cycle assessments are necessary to evaluate the environmental impact, energy requirements, and economic feasibility of large-scale production and deployment. The integration of Ce-Cu nanocomposites with renewable energy technologies such as solar-driven photocatalytic reactors may enhance treatment efficiency while reducing operational costs. Furthermore, hybrid treatment systems combining adsorption, membrane filtration, photocatalysis, and biological processes could provide comprehensive solutions for wastewater remediation. Detailed investigations into the environmental fate, transport mechanisms, and ecotoxicological impacts of nanocomposites are essential to ensure safe implementation. Collaboration among researchers, industrial stakeholders, environmental agencies, and regulatory organizations will play a critical role in accelerating commercialization and establishing standardized guidelines for nanomaterial-based water treatment technologies. Overall, future advancements in green synthesis, surface functionalization, and multifunctional integration are expected to transform biofunctionalized Ce-Cu nanocomposites into next-generation platforms capable of addressing global healthcare and environmental challenges simultaneously.

7. CONCLUSION

This study successfully demonstrated the design and development of bioactive natural ligand-functionalized cerium-copper (Ce-Cu) bimetallic nanocomposites through an environmentally sustainable green synthesis approach. The integration of cerium and copper within a single nanostructured platform, combined with surface modification using naturally derived ligands, resulted in enhanced physicochemical characteristics and multifunctional performance suitable for both biomedical and environmental applications. Comprehensive characterization analyses confirmed the successful formation of highly crystalline and uniformly distributed Ce-Cu nanocomposites with excellent colloidal stability, increased surface area, reduced bandgap energy, and improved visible-light absorption capability. The synergistic interaction between cerium and copper promoted efficient charge separation and suppressed electron-hole recombination, contributing to superior photocatalytic activity and enhanced therapeutic performance. The biofunctionalized nanocomposites exhibited high drug encapsulation efficiency and controlled pH-responsive release behavior, enabling selective delivery of anticancer agents within acidic tumor microenvironments. In vitro investigations demonstrated significant cytotoxic effects against cancer cell lines while maintaining acceptable biocompatibility toward normal cells, highlighting the potential of these nanocomposites as effective targeted drug delivery systems. Furthermore, the synthesized Ce-Cu nanocomposites achieved remarkable visible-light-driven degradation of organic pollutants and demonstrated efficient removal of heavy metal ions and pathogenic microorganisms from contaminated water. The excellent reusability and operational stability observed during repeated treatment cycles further support their practical applicability in sustainable environmental remediation. The key findings of this work emphasize that the combination of green synthesis, bimetallic heterojunction engineering, and natural ligand functionalization provides a versatile strategy for developing next-generation multifunctional nanomaterials. The resulting nanocomposites offer an integrated solution for targeted cancer therapy, photocatalytic degradation, and environmental water purification while minimizing the environmental impact associated with conventional synthesis methods. Overall, this research establishes biofunctionalized Ce-Cu bimetallic nanocomposites as promising candidates for advanced theranostic and environmental technologies. Future studies focusing on large-scale production, in vivo validation, long-term safety assessment, and pilot-scale implementation will further facilitate their translation from laboratory research to real-world applications.

Key Takeaways:

- Green synthesis enabled the eco-friendly fabrication of Ce-Cu bimetallic nanocomposites without hazardous chemicals.
- Natural ligand functionalization improved colloidal stability, biocompatibility, and targeting capability.
- Ce-Cu heterojunction formation enhanced visible-light absorption and charge separation efficiency.
- The nanocomposites exhibited high drug-loading capacity and pH-responsive anticancer drug release.
- Significant photocatalytic degradation, heavy metal removal, and antimicrobial performance were achieved.
- The multifunctional platform demonstrated strong potential for integrated biomedical and environmental applications.

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