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Green Synthesis of Copper Nanoparticles for Antimicrobial and Water Purification Applications

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Abstract: *The green synthesis of nanoparticles (NPs) has gained significant attention in nanotechnology due to its eco-friendly and cost-effective approach. Copper nanoparticles (Cu NPs) exhibit notable properties, including antimicrobial activity and disinfecting capabilities. Green-synthesized NPs are highly effective in heavy metal removal and wastewater treatment, addressing global water quality concerns. The plant-mediated synthesis of nanomaterials is advantageous as it utilizes naturally occurring biomolecules for metal ion reduction and stabilization. Silver nanoparticles were successfully synthesized within 10 minutes and demonstrated antibacterial effects. Similarly, green-synthesized Cu NPs have been employed as nano-adsorbents for the removal of pharmaceutical contaminants such as ibuprofen (Ibu), naproxen (Nab), and diclofenac (Dic) from wastewater. Optimal removal was achieved under conditions of 298 K, pH 4.5, and 60 minutes, with the adsorption process being endothermic. Additionally, copper-enriched paper sheets exhibited a bacterial reduction of log 8.8 against E. coli. The CuNP-infused paper filter presents a promising, cost-effective solution for water purification..*

Keywords: Wastewater Treatment, Nanoparticles, Copper, Green Synthesis, Applications, Characterization, Disinfection

I. INTRODUCTION

Domestic wastewater refers to water discharged from households due to daily activities such as cooking, bathing, washing, and sanitation. The composition and strength of domestic wastewater vary depending on factors like per capita water usage, dietary habits, lifestyle, and living standards. These variations are observed on an hourly, daily, and seasonal basis, with households in developed countries typically consuming more water than those in developing regions.

The application of green-synthesized nanoparticles (NPs) in water and wastewater treatment has gained significant attention due to their efficiency and eco-friendly nature. Green nanotechnology is an emerging field that focuses on synthesizing nanoparticles using biological methods, which are considered safer, more sustainable, and cost-effective compared to conventional physical and chemical approaches. Various biological sources, including plants, bacteria, algae, and fungi, have been employed for nanoparticle synthesis, with plant-mediated methods being the most widely explored due to their ease of use and sustainability. These green-synthesized NPs exhibit excellent stability and efficiency in removing heavy metals and organic pollutants from wastewater, enabling water purification for reuse and recycling. Their application in wastewater treatment presents a viable solution to global water quality challenges.

Copper nanoparticles (Cu NPs) have gained significant interest due to their distinctive physical and chemical properties, as well as their cost-effectiveness. Cu NPs are known for their antimicrobial and disinfecting capabilities, along with their high surface area-to-volume ratio, which enhances their stability and effectiveness. These nanoparticles facilitate chemical and biological reactions efficiently. Their small size and high specific surface area contribute to strong adsorption properties and high reactivity, making them effective in removing heavy metals, organic pollutants, inorganic anions, and bacteria from wastewater.

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II. OBJECTIVES

The primary goal of this study is to disinfect domestic wastewater using green-synthesized nanoparticles and explore its potential for reuse in various applications.

Green Synthesis of Copper Oxide Nanoparticles and Their Applications

1. Green Synthesis of Copper Oxide Nanoparticles and Their Role in Biginelli Reaction, BTB Photodegradation, and Antibacterial Activity

Copper oxide nanoparticles (CuO NPs) were synthesized through an environmentally friendly approach using *Cordia sebestena* flower extract. The synthesized nanoparticles, with a size range of 20–35 nm as confirmed by TEM and DLS analysis, demonstrated good crystallinity and stability, as indicated by the TEM-SAED pattern. These nanoparticles were tested for antibacterial properties against common waterborne pathogens, including *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, and *Klebsiella pneumoniae*. The results highlighted their potential for water disinfection. Additionally, CuO NPs exhibited promising applications in photolytic degradation, suggesting their effectiveness in breaking down contaminants in wastewater. Their antibacterial properties further validated their biological significance in wastewater treatment.

2. Green-Synthesized Copper Nano-Adsorbent for the Removal of Pharmaceutical Pollutants from Wastewater

Copper nanoparticles (Cu NPs) with high purity and stability were synthesized using extracts from *Tilia* leaves. Characterization studies revealed that these nanoparticles were well-dispersed, with spherical and semispherical shapes, and their sizes ranged between 4.7 and 17.4 nm. These nanoparticles were employed as nano-adsorbents for the removal of non-steroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen (Ibu), naproxen (Nab), and diclofenac (Dic) from wastewater. The adsorption process was spontaneous, endothermic, and physical in nature. Under optimal conditions (temperature: 298 K, pH: 4.5, Cu NP dosage: 10.0 mg, time: 60 minutes), the removal efficiencies for Ibu, Nab, and Dic were 74.4%, 86.9%, and 91.4%, respectively. The maximum monolayer adsorption capacities for these pharmaceuticals were calculated as 36.0 mg/g (Dic), 33.9 mg/g (Nab), and 33.9 mg/g (Ibu). These findings indicate that green-synthesized Cu NPs could be an efficient and sustainable alternative for removing pharmaceutical contaminants from wastewater.

3. Synthesis and Impregnation of Copper Oxide Nanoparticles on Activated Carbon for Water Pollutant Removal

Copper oxide nanoparticles were synthesized via a green method and impregnated onto vegetal activated carbon (VAC) using *Punica granatum* (pomegranate) leaf extract as a reducing and stabilizing agent. A methodology adapted from Wang et al. was followed to synthesize CuO NPs, which were then supported on activated coconut carbon. The CuO nanoparticles exhibited sizes between 104 and 165 nm, while those impregnated on activated carbon measured between 40 and 78 nm. Among the synthesized samples, carbon impregnated with 1.5% Cu for 24 hours demonstrated improved pollutant removal capacity. While the activated carbon effectively removed organic contaminants such as atrazine, diclofenac, caffeine, and nitrates, the addition of CuO nanoparticles enhanced nitrate ion removal efficiency by more than four times. The study suggests that the green-synthesized CuO-impregnated activated carbon offers a sustainable, cost-effective alternative for water purification, particularly for nitrate removal.

4. Disinfection of Drinking Water Using Algae-Mediated Green-Synthesized Copper Oxide Nanoparticles and Their Toxicity Evaluation

Copper oxide nanoparticles (CuO NPs) were synthesized using algal extracts under controlled conditions, with a particle size of approximately 3.6 nm. The characteristics of the synthesized nanoparticles were influenced by factors such as stirring speed, pH, extract concentration, and Cu^{2+} ion concentration. These nanoparticles exhibited strong antibacterial activity against *Escherichia coli* in surface water samples, with an optimal dosage of 50 mg/L for effective bacterial reduction.

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Toxicity assessments were conducted to evaluate the potential environmental and health risks of CuO NPs. Fish blood samples were analyzed for mononuclei formation, and cytotoxicity was tested on human gastric epithelium and Chinese hamster ovarian cell lines. Since surface water is frequently contaminated by industrial and domestic waste, leading to bacterial proliferation, the use of CuO NPs in water treatment offers an efficient alternative to conventional disinfection methods.

Currently, the activated sludge process is a widely used disinfection method, but its efficiency is often reduced due to bulking issues. Sequential Batch Reactors (SBRs) have demonstrated about 87% efficiency in Chemical Oxygen Demand (COD) removal. However, recent advancements in nanotechnology have introduced nanoparticle-based treatments, including nano-membranes and powders, which have shown promising results in removing heavy metals and biological contaminants.

The properties of green-synthesized CuO NPs are influenced by factors such as pH, temperature, Cu ion concentration, and incubation time. Unlike conventional physical and chemical synthesis methods, which often involve toxic chemicals and require extended processing times, green synthesis utilizes plant-derived reducing agents that facilitate nanoparticle formation in a safer and more eco-friendly manner. Polyphenols and phytochemicals in plant extracts act as capping agents during the synthesis process, ensuring stability and functionality. Algae, in particular, are rich in polyphenols, making them suitable for nanoparticle synthesis. The resulting CuO NPs are non-toxic, biodegradable, and environmentally sustainable. Due to their high growth rate and biomass productivity, algae-based nanoparticle synthesis provides an economically viable method for water disinfection and purification.

Green Synthesis of Copper Oxide Nanoparticles and Their Multifunctional Applications

Green Synthesis of CuO Nanoparticles Using Cordia Sebestena Flower Extract

Copper oxide nanoparticles (CuO NPs) were successfully synthesized through an eco-friendly approach using an aqueous extract of *Cordia sebestena* flowers. Characterization using TEM and DLS techniques confirmed that the nanoparticles ranged in size between 20 and 35 nm, with TEM-SAED analysis indicating crystallinity and stability. The synthesized CuO NPs were tested for antimicrobial activity against both Gram-positive (*Bacillus subtilis* and *Staphylococcus aureus*) and Gram-negative bacteria (*Escherichia coli* and *Klebsiella pneumoniae*), commonly found in household wastewater. The study suggests that these nanoparticles could serve as effective agents in photodegradation for water purification, as well as antibacterial applications.

Eco-Friendly Copper-Based Nano-Adsorbents for Pharmaceutical Pollutant Removal

High-purity copper nanoparticles (Cu NPs) were synthesized using *Tilia* leaf extracts and exhibited spherical to semi-spherical morphology with sizes between 4.7 and 17.4 nm. These nanoparticles demonstrated an ability to adsorb pharmaceutical pollutants, including ibuprofen (Ibu), naproxen (Nab), and diclofenac (Dic), from real wastewater. The adsorption process was found to be spontaneous, endothermic, and primarily physical in nature. Under optimal conditions (temperature: 298 K, pH: 4.5, Cu NP dosage: 10 mg, and contact time: 60 min), removal efficiencies for Dic, Nab, and Ibu were recorded at 91.4%, 86.9%, and 74.4%, respectively. The results indicate the potential of green-synthesized Cu NPs as cost-effective and efficient adsorbents for pharmaceutical wastewater treatment.

Copper Oxide Nanoparticle-Impregnated Activated Carbon for Pollutant Removal

A green approach was employed to impregnate CuO nanoparticles onto vegetal activated carbon (VAC) using *Punica granatum* (pomegranate) leaf extract as a reducing and stabilizing agent. The nanoparticles, synthesized following an adapted methodology, were supported on coconut-based activated carbon, with particle sizes ranging from 40 to 78 nm on the carbon surface and up to 165 nm in free form. Notably, CuO-impregnated carbon with a 1.5% Cu loading over 24 hours demonstrated enhanced nitrate ion removal while maintaining efficiency in organic pollutant adsorption (such as atrazine, diclofenac, and caffeine). The study highlights the potential of CuO nanoparticle-impregnated activated carbon as an eco-friendly and cost-effective alternative for water purification.

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Disinfection of Drinking Water Using Algae-Mediated CuO Nanoparticles

CuO nanoparticles synthesized via algal extracts exhibited a size of approximately 3.6 nm. Their properties were influenced by factors such as stirring speed, pH, extract concentration, and copper ion concentration. The nanoparticles displayed antimicrobial activity against *Escherichia coli*, with an optimum dosage of 50 mg/L required for effective bacterial inhibition in surface water. Toxicity assessments were conducted on fish blood and human cell lines, revealing minimal toxicity at appropriate concentrations. Given the limitations of conventional disinfection methods, these nanoparticles offer an efficient alternative for water treatment, with potential applications in nano-membrane technologies.

Characterization and Applications of Green-Synthesized Copper Oxide Nanoparticles

Analysis of CuO Nanoparticles

The X-ray diffraction (XRD) pattern confirmed the highly crystalline nature of CuO nanoparticles, with an estimated crystallite size of 25–35 nm. Fourier transform infrared (FTIR) spectroscopy provided insights into the bonding nature of CuO. Particle size analysis indicated that the synthesized CuO nanoparticles ranged between 20 and 40 nm. Scanning electron microscopy (SEM) revealed their predominantly spherical and oval-shaped morphology. Additionally, energy-dispersive X-ray spectroscopy (EDAX) confirmed the elemental composition, ensuring the purity of the CuO nanoparticles with only copper (Cu) and oxygen (O) detected.

Phytochemical analysis identified the bioactive compounds in *Allium sativum* extract that contributed to the successful green synthesis of CuO nanoparticles. These nanoparticles demonstrated strong antimicrobial activity, effectively inhibiting the growth of both bacterial and fungal strains. Their antioxidant potential was also significant, exhibiting remarkable free radical scavenging properties. Given their environmentally friendly synthesis, CuO nanoparticles hold immense promise for wastewater disinfection in the 21st century.

II. CONCLUSION

In recent years, nanotechnology has emerged as a highly effective approach for water purification, owing to the distinctive properties of nanoparticles, such as high surface area, increased surface energy, and tunable size and volume. The physicochemical characteristics of nanoparticles can be tailored by adjusting parameters such as pH, temperature, and precursor concentration. Their multifunctionality makes them a superior alternative to traditional water treatment methods, which often rely on chemical disinfectants that may introduce toxicity into the water or prove costly in comparison to nanoparticle-based filtration. Additionally, chlorination can sometimes be ineffective due to the development of microbial resistance.

Among the various synthesis techniques, green synthesis stands out as the most sustainable and advantageous. Unlike physical methods, which require prolonged heating to achieve thermal stability, or chemical approaches that involve toxic reagents, green synthesis employs plant-based materials that are readily available and eco-friendly. The phytochemicals in plant extracts not only facilitate nanoparticle formation but also enhance their antimicrobial, catalytic, and antibacterial properties.

The properties of CuO nanoparticles synthesized using different plant extracts vary based on the phytochemical composition. Factors such as pH, copper ion concentration, stirring speed, and extract concentration significantly influence the size and morphology of the nanoparticles. Systematic experimental studies are essential to optimize these conditions for the most effective nanoparticle synthesis. Characterization techniques, including SEM and transmission electron microscopy (TEM), provide crucial insights into nanoparticle shape and size, while UV-Visible spectroscopy is used to confirm their formation through absorption spectra analysis.

A thin layer of plant-derived phytochemicals surrounding the nanoparticles was observed, which contributed to their enhanced antimicrobial properties. These CuO nanoparticles exhibited strong antibacterial effects against both *Escherichia coli* (Gram-negative) and *Staphylococcus aureus* (Gram-positive) by disrupting cell membranes and leading to bacterial cell death. Functionalization with EDTA further improved their surface area and porosity, significantly enhancing their ability to adsorb dyes, with a removal efficiency of up to 54%.

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The immobilization of CuO nanoparticles onto membranes and fabrics facilitated their application in filtration and water disinfection. These nanoparticle-coated membranes proved highly effective in removing dyes and preventing microbial contamination. Moreover, the amount of copper released into filtered water remained well below the permissible limit for drinking water, ensuring safety. Toxicity studies on humans and aquatic organisms helped establish an optimal concentration range within which the nanoparticles remained non-harmful.

The application of green-synthesized CuO nanoparticles for treating domestic wastewater proved to be both effective and sustainable. The treated water was suitable for secondary purposes such as cleaning and irrigation, helping reduce water consumption while providing an economical alternative to costly filtration methods like reverse osmosis (RO). Additionally, this approach eliminates the drawbacks associated with traditional disinfection techniques like chlorination, which can sometimes be ineffective and environmentally harmful.

By harnessing the potential of green nanotechnology, CuO nanoparticles offer a promising solution for sustainable water purification, contributing to a cleaner environment and improved public health.

Enhancing Methylene Blue Dye Adsorption Using Functionalized CuO Nanoparticles

Copper oxide nanoparticles were synthesized through a co-precipitation method using copper nitrate as a precursor. A comparative analysis was conducted between functionalized and non-functionalized CuO nanoparticles in their ability to enhance chitosan's adsorption of methylene blue dye. The nanoparticles had a crystallite size of approximately 10 nm. Functionalization with EDTA-silane significantly increased surface area and porosity, leading to improved dye adsorption and photocatalytic degradation under sunlight. When combined with chitosan, the functionalized nanoparticles achieved a dye removal efficiency of 54%. Despite some variability in particle size, the cost-effectiveness of the co-precipitation method makes it suitable for large-scale wastewater treatment applications.

Green Synthesis of Copper Nanoparticles Using *Punica granatum* Extract and Their Antibacterial Properties

Copper nanoparticles were synthesized using a green chemistry approach with pomegranate fruit rind extract as a reducing and stabilizing agent. A 10 mM copper sulfate solution mixed with 50% concentrated extract yielded medium-sized nanoparticles within 1.5 to 2 hours. UV-Visible spectroscopy confirmed the stability of the synthesized nanoparticles, with SEM analysis revealing a size range of 56-59 nm. The nanoparticles exhibited significant antibacterial activity against *Staphylococcus aureus*, making them a promising alternative for antimicrobial applications, particularly in combating drug-resistant bacterial strains.

Copper Nanoparticles in Paper-Based Point-of-Use Water Purification

To provide a low-cost alternative to silver-based filters, an environmentally friendly approach was developed for embedding copper nanoparticles into paper filters for water purification. The in situ reduction of sorbed copper ions using ascorbic acid led to the rapid formation of CuNPs within 10 minutes, with uniform distribution on paper fibers. Characterization using XRD, SEM, EDX, and AAS confirmed the presence of copper nanoparticles. When tested against *Escherichia coli*, the CuNP-infused paper exhibited a high bacterial reduction (log 8.8), while the copper release remained below the permissible limit of 1 ppm for drinking water. These findings suggest that CuNP-integrated paper could serve as an affordable and effective solution for point-of-use water filtration.

Optimization and Application of Bioflocculant-Passivated Cu Nanoparticles in Wastewater Treatment

Nanotechnology plays a crucial role in pollutant and microbial removal from wastewater. In this study, copper nanoparticles were synthesized using a polysaccharide-based bioflocculant and assessed for their flocculation activity, removal efficiency, and antimicrobial effects. The nanoparticles were characterized through multiple techniques, including TGA, UV-Vis spectroscopy, FT-IR, XRD, SEM, and TEM. The optimal flocculation activity (96%) was achieved at a nanoparticle concentration of 0.2 mg/mL, with stable performance across neutral to alkaline pH conditions and high thermal resistance (91% flocculation at 100°C). These nanoparticles demonstrated excellent pollutant removal capabilities, achieving over 89% COD and BOD reduction in coal mine and river water samples.

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Additionally, they exhibited antimicrobial activity against both Gram-positive and Gram-negative bacteria at concentrations as low as 3.13 mg/mL, indicating their potential for wastewater disinfection and dye effluent removal.

Green Synthesis of CuO Nanoparticles Using *Allium sativum* Extract and Their Biological Applications

Copper oxide nanoparticles were synthesized using *Allium sativum* (garlic) extract, leveraging the phytochemicals as natural reducing agents. The resulting CuO NPs exhibited antimicrobial, antioxidant, and antilarvicidal properties. The study highlights how synthesis parameters, such as pH, temperature, copper ion concentration, and incubation time, influence nanoparticle characteristics. Given their biocompatibility and eco-friendly nature, these nanoparticles hold promise for applications in biomedical and environmental sectors.

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