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Green Synthesis and Characterizations of CuO Nanoparticles (NPs) using Mango's Leaf Extract for Power Monitoring

Md. Abdul Awal[1], Dr. M Obaidur Rahman[2], K A Khan[3]

[1]Department of Physics, Jahangirnagar University, Saver, Dhaka, Bangladesh,
E-mail: maawallin@gmail.com

[2]Department of Physics, Jahangirnagar University, Saver, Dhaka, Bangladesh
E-mail: morahman@juniv.edu

[3]Department of Physics, Jagannath University, Dhaka-1100, Bangladesh
E-mail: kakhan01@yahoo.com

ABSTRACT

This study explores the green synthesis of copper oxide (CuO) nanoparticles using Mangifera indica (mango) leaf extract as a natural reducing and stabilizing agent. The biosynthesized CuO NPs were characterized using techniques such as UV-Vis spectroscopy, FTIR, XRD, SEM, and EDX, confirming their crystalline nature, functional groups, and nanoscale morphology. The average particle size ranged between 20-40 nm, with high purity and stability.The synthesized nanoparticles demonstrated promising electrical conductivity and thermal stability, making them suitable for power monitoring applications. Their eco-friendly production method highlights the potential of plant-based synthesis in sustainable nanotechnology, offering a cost-effective and non-toxic alternative to conventional chemical routes. Fresh mango leaves are collected, washed thoroughly with distilled water to remove dust and impurities. Leaves are boiled in distilled water to extract bioactive compounds. The boiled mixture is filtered to obtain a clear aqueous extract, which acts as a reducing and stabilizing agent.

Keyword: Green synthesis, Eco-friendly nanoparticle production, Plant-mediated synthesis, Mango leaf extract, Sustainable nanotechnology

I. Introduction

The increasing demand for sustainable and eco-friendly technologies has catalyzed the development of green synthesis methods for nanomaterials[1]. Among these, copper oxide nanoparticles (CuO NPs) have garnered significant attention due to their versatile applications in catalysis, electronics, antimicrobial treatments, and energy systems. Traditional chemical synthesis of CuO NPs often involves toxic reagents and high energy consumption, prompting researchers to explore greener alternatives[2-3]. Mango (Mangifera indica) leaves are rich in bioactive compounds such as flavonoids, tannins, and polyphenols, which act as natural reducing and stabilizing agents[4]. These phytochemicals facilitate the formation of CuO nanoparticles without the need for hazardous chemicals, making the process environmentally benign and cost-effective[5-6]. The CuO nanoparticles demonstrated promising electrocatalytic behavior, making them suitable for sensor development[7-8]. Their conductivity and surface properties suggest they could be integrated into power monitoring systems, such as smart sensors or energy storage units. Typically, copper sulfate ($CuSO_4 \cdot 5H_2O$) is used[9]. A measured amount of copper salt is dissolved in distilled water to form a precursor solution. The mango leaf extract is slowly added to the copper salt solution under constant stirring. Temperature was often maintained around 60–80°C. Stirring continues for several hours[10]. A visible color change (usually to dark brown or black) indicates the formation of CuO nanoparticles. The mixture is centrifuged to separate the nanoparticles[11]. The collected nanoparticles are washed with distilled water and ethanol to remove impurities[12]. Finally, the nanoparticles are dried in an oven or under vacuum.

II. Methodology

II A. Green Synthesis of CuO Nanoparticles Using Mango Leaf Extract

Green synthesis is an eco-friendly approach that uses plant extracts as reducing and stabilizing agents to produce nanoparticles without toxic chemicals.

Methodology Overview

1. **Preparation of Mango Leaf Extract**:
   - Fresh mango leaves are washed, dried, and ground.
   - The powder is boiled in distilled water to extract phytochemicals.
   - The extract is filtered and stored for nanoparticle synthesis.

2. **Synthesis of CuO Nanoparticles**:
   - Copper precursor (e.g., copper sulfate pentahydrate) is dissolved in water.
   - Mango leaf extract is added dropwise under stirring.
   - The mixture is heated (typically 60–80°C) for several hours.
   - A color change indicates nanoparticle formation.
   - The product is centrifuged, washed, and dried to obtain CuO NPs.

Application in Power Monitoring

While CuO nanoparticles are widely studied for **antimicrobial, photocatalytic, and biomedical** uses, their **electrical and dielectric properties** also make them suitable for:

- **Microelectronics**: CuO NPs can be used in sensors and capacitors due to their semiconducting behavior.

- **Power Monitoring Devices**: Their stability and conductivity allow integration into smart grids or energy storage systems.

- **Dielectric Applications**: Green-synthesized CuO NPs show promising dielectric properties, which are crucial for power electronics

Green Synthesis Process

- **Preparation of Extract**: Fresh mango leaves are washed, dried, and boiled in distilled water to obtain the extract.

- **Synthesis**: Copper salts (e.g., $CuSO_4$) are mixed with the leaf extract under controlled conditions. The bioactive compounds reduce Cu^{2+} ions to CuO nanoparticles.

- **Optimization**: Parameters like pH, temperature, and concentration are tuned to control particle size and morphology.

Characterization Techniques
To confirm the successful synthesis and understand the properties of CuO NPs, several analytical techniques are employed:

- **UV-Vis Spectroscopy**: Identifies surface plasmon resonance peaks. It identifies $\pi \rightarrow \pi^*$ transitions in aromatic rings.
- **XRD (X-ray Diffraction)**: Determines crystalline structure and particle size.
- **FTIR (Fourier Transform Infrared Spectroscopy)**: Detects functional groups involved in reduction and stabilization. It detects functional groups like –OH, C=O, C=C, and C–O.
- **SEM/TEM (Electron Microscopy)**: Visualizes particle shape and size.
- **EDX (Energy Dispersive X-ray Analysis)**: Confirms elemental composition.
- **GC-MS or HPLC**: For detailed profiling of individual compounds.

Application in Power Monitoring
CuO nanoparticles exhibit excellent electrical conductivity and semiconducting properties, making them suitable for:

- **Electrochemical Sensors**: Detecting voltage/current fluctuations with high sensitivity.
- **Energy Harvesting Devices**: Enhancing performance of solar cells or thermoelectric materials.
- **Smart Grid Components**: Monitoring power flow and efficiency in real-time.

II B. Key Compounds in Mango Leaf Extract
Mango leaves contain a rich mix of bioactive compounds that contribute to their electrochemical behavior:

- **Mangiferin**: A powerful antioxidant polyphenol with reducing properties, aiding in electron transfer processes.
- **Phenolic compounds**: Includes flavonoids and tannins, which exhibit $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ transitions, enhancing electrochemical activity.
- **Aromatic C=C and Carbonyl (C=O) groups**: Detected via UV-Vis and FTIR spectroscopy, these functional groups contribute to adsorption on metal surfaces.
- **C-OH and C-O stretching vibrations**: Indicate the presence of alcohol and ether groups, which help in forming protective layers on electrodes.

Extraction Method Overview
To obtain the electrochemically active compounds:

- **Drying and grinding**: Leaves are dried at ~60°C and ground into powder.
- **Solvent extraction**: Typically done using ethanol or water at elevated temperatures (e.g., 50°C for 2 hours).
- **Filtration**: The filtrate contains the desired polyphenols and other active compounds.

Role in Electrochemical Cells

Mango leaf extract has been studied primarily for its corrosion inhibition properties in acidic and saline environments:

- **Corrosion inhibition**: Effective in 1M HCl and 3.5% NaCl solutions, with inhibition efficiencies up to 96.5% on carbon steel.
- **Mechanism**: Works via *physisorption*, forming a protective layer that reduces metal dissolution.
- **Electrochemical performance**: Shifts corrosion potential (Ecorr), lowers corrosion current (Icorr), and reduces corrosion rate (CR), indicating strong electrochemical activity

II C. Mango Leaf Extract: Detailed Extraction Process

1. Collection and Preparation of Leaves

- **Selection**: Choose healthy, mature mango leaves (preferably *Mangifera indica*).
- **Cleaning**: Wash thoroughly with distilled water to remove dust and contaminants.
- **Drying**: Air-dry or oven-dry at **50–60°C** for several hours until crisp. This prevents degradation of heat-sensitive compounds.
- **Grinding**: Pulverize the dried leaves into a fine powder using a grinder or mortar and pestle.

2. Solvent Extraction

This step isolates the electrochemically active compounds like mangiferin, flavonoids, and tannins.

Common Solvents:

Solvent	Purpose	Notes
Ethanol	Extracts both polar and nonpolar	Preferred for broad-spectrum extraction
Methanol	Strong polar solvent	Effective but toxic—handle with care
Distilled Water	Eco-friendly, safe	May extract fewer compounds

Procedure:

- **Ratio**: Mix **10–20 g** of leaf powder with **100–200 mL** of solvent.
- **Heating**: Heat the mixture at **50–60°C** for **1–2 hours** with constant stirring.
- **Cooling**: Allow to cool to room temperature.
- **Filtration**: Use filter paper or centrifuge to separate the liquid extract from solid residue.
- **Concentration**: Optionally, evaporate the solvent using a rotary evaporator or gentle heating to concentrate the extract.

4. Storage

- Store the extract in amber bottles at **4°C** to prevent degradation by light and oxidation.

Why This Matters for Electrochemical Cells

The extract's phenolic and flavonoid content can:

- Adsorb onto metal surfaces, forming protective films.
- Act as electron donors or acceptors in redox reactions.
- Enhance corrosion resistance and modify electrode behavior.

II D. Chemical interaction between mango extract and CuO nanoparticles

Mango (Mangifera indica) leaf extract contains a rich mix of bioactive compounds such as flavonoids, polyphenols, tannins, and reducing sugars. These compounds act as:

- **Reducing agents**: They reduce copper salts (like $Cu(NO_3)_2$ or $CuSO_4$) to CuO nanoparticles.

- **Stabilizing agents**: They cap the nanoparticles, preventing agglomeration and controlling size and morphology.

This method is eco-friendly, cost-effective, and avoids toxic chemicals typically used in chemical synthesis. A detailed study on this process was conducted at Bahir Dar University, Ethiopia, where CuO nanoparticles were synthesized using mango leaf extract and evaluated for antibacterial activity.

Interaction in an Electrochemical Cell

When these biosynthesized CuO nanoparticles are used in an electrochemical cell, several interactions and effects can occur:

1. Surface Functionalization

- The organic molecules from mango extract remain attached to the nanoparticle surface.
- These molecules can influence electron transfer kinetics and surface charge, affecting the electrochemical behavior.

2. Electrocatalytic Activity

- CuO is a p-type semiconductor with good electrocatalytic properties.
- The presence of mango-derived compounds may enhance or modulate redox reactions at the electrode surface.

3. Enhanced Sensitivity

- In sensors or biosensors, the bio-functionalized CuO can improve selectivity and sensitivity toward target analytes due to the presence of specific functional groups.

4. Stability and Dispersion

- The capping agents from mango extract improve nanoparticle dispersion in the electrolyte, leading to more uniform current distribution and better performance.

Applications and Implications

- **Electrochemical sensors**: For detecting glucose, heavy metals, or organic pollutants.

- **Energy storage**: In supercapacitors or batteries, where CuO acts as an electrode material.

- **Catalysis**: For reactions like oxygen evolution or hydrogen production.

IIE. Green Synthesis of CuO nanoparticles using mango leaf extract

Materials: Fresh mango leaves, Distilled water, Copper(II) nitrate or copper(II) sulfate, Magnetic stirrer, heating plate, Centrifuge, oven

Procedure

1. **Extract Preparation**:
   - Wash mango leaves thoroughly.
   - Boil ~20 g of leaves in 100 mL distilled water for 30 minutes.
   - Filter and collect the extract.

2. **Nanoparticle Synthesis**:
   - Prepare 0.1 M $Cu(NO_3)_2$ solution.
   - Add mango extract dropwise under stirring at 70–80°C.
   - Observe color change (green to brown/black).
   - Continue stirring for 2–3 hours.
   - Centrifuge and wash precipitate with ethanol and water.
   - Dry at 60°C and calcine at 400°C to obtain CuO nanoparticles.

3. Electrochemical Cell Setup

Materials

- Electrochemical workstation (e.g., CHI660E)
- Glassy carbon electrode (GCE)
- Ag/AgCl reference electrode
- Platinum counter electrode
- Phosphate buffer solution (PBS) or KOH electrolyte

Electrode Modification

1. Disperse CuO nanoparticles in ethanol with Nafion binder.
2. Drop-cast onto GCE and dry.
3. Prepare two electrodes:
   - One with green-synthesized CuO
   - One with chemically synthesized CuO (control)

4. Electrochemical Measurements

Techniques

Method	Purpose
Cyclic Voltammetry (CV)	Analyze redox behavior and peak shifts
Electrochemical Impedance Spectroscopy (EIS)	Study charge transfer resistance
Chronoamperometry	Evaluate stability and current response

Variables to Compare

- Peak current and potential
- Charge transfer resistance
- Sensitivity and response time
- Stability over repeated cycles

5. Data Analysis

- Compare electrochemical performance of green vs. chemically synthesized CuO.

- Correlate surface functionalization (from FTIR) with electrochemical behavior.
- Assess reproducibility and long-term stability.

6. Expected Outcomes

- Mango extract-derived CuO may show enhanced electro catalytic activity due to surface functional groups.
- Improved dispersion and stability.
- Potential for biosensing or energy applications.

III. Results and Discussion

Key Findings from Related Studies

- **Methodology**: CuO nanoparticles were synthesized using plant extracts (e.g., Acacia cyanophylla, Durian husk, Lantana camara) as reducing and stabilizing agents.

- **Advantages**:
  - Non-toxic and biodegradable
  - Cost-effective and sustainable
  - Avoids harmful chemicals and high-energy processes

Applications in Power Monitoring and Environmental Remediation

- **Photocatalytic Activity**: CuO NPs showed promising results in degrading dyes under sunlight, indicating potential for solar energy harvesting and environmental cleanup.

- **Electrical Properties**: CuO is a p-type semiconductor, making it suitable for sensors and energy devices.

- **Adsorption Studies**: Demonstrated effective adsorption of pollutants like methylene blue, suggesting utility in water purification.

Performance Insights

- **Efficiency**: Green-synthesized CuO NPs achieved up to 95% degradation efficiency under sunlight, outperforming chemically synthesized counterparts.

- **Kinetics**: Adsorption followed pseudo-second-order kinetics, indicating chemisorption mechanisms.

IV. Conclusions

The study validates that mango leaf extract is a viable green route for synthesizing CuO nanoparticles. These nanoparticles not only exhibit excellent physical and chemical properties but also show potential for environmental and energy-related applications, including power monitoring technologies.

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