

Plant-Based Green Synthesis of Copper Nanoparticles and Their Application in Photovoltaic Solar Cells

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Abstract

The development of sustainable nanomaterials has become an important research direction in response to the environment for conventional chemical synthesis and the growing demand for advanced materials for renewable-energy technologies. In the present study, a plant-mediated green synthesis approach is proposed for the preparation of copper nanoparticles (CuNPs) using *Moringa oleifera* leaf extract as a natural reducing, stabilizing and capping system. Plant extracts contain mixture of phytochemicals, including phenolic compounds, flavonoids, proteins, carbohydrates and other secondary metabolites. These compounds participate in the reduction of copper ions and stabilization of the resulting nanoparticles. The synthesized CuNPs are evaluated through complementary physicochemical characterization techniques, including ultraviolet–visible, FTIR spectroscopy, X-ray diffraction (XRD), SEM and energy-dispersive X-ray spectroscopy. UV–Vis analysis is used to monitor nanoparticle formation through characteristic optical absorption behavior. The study further investigates the potential use of the plant-mediated CuNPs in photovoltaic solar-cell systems. The photovoltaic response is evaluated using open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF) and power conversion efficiency (PCE). Particular emphasis is placed on the relationship between nanoparticle characteristics and photovoltaic behaviour. The study is expected to contribute to the development of solar cell compatible nanoparticle synthesis strategies and to provide a basis for further optimization of CuNP-based photovoltaic devices.

[Keywords: Green synthesis; copper nanoparticles; nanotechnology; photovoltaic solar cells; sustainable nanomaterials.]

Introduction

Increasing energy consumption, depletion of conventional resources, environmental pollution and concerns related to greenhouse-gas emissions have encouraged extensive research into renewable energy technologies. Among different renewable sources, solar energy has considerable potential because solar radiation is widely available and can be directly converted into electricity through photovoltaic technologies¹. Photovoltaic solar cells are semiconductor devices that convert incident solar radiation into electrical energy through the generation and separation of photogenerated charge carriers. The performance of a photovoltaic device depends on several factors, including light absorption, charge generation, charge transport, recombination, electrode properties and interfacial processes¹.

Nanomaterials exhibit properties that can differ substantially from those of bulk materials because of their small dimensions, high surface-to-volume ratio and size-dependent electronic and optical behaviour. Copper is especially interesting because of its relatively high electrical conductivity, abundance compared with several noble metals and potential usefulness in electronic and optoelectronic systems¹. Copper nanoparticles (CuNPs), however, present a significant synthetic challenge because copper is susceptible to oxidation under environmental conditions. The physicochemical properties of CuNPs are strongly influenced by particle size, morphology, crystallinity, surface chemistry and oxidation state. Conventional nanoparticle synthesis methods include chemical reduction,

thermal decomposition, physical vapour deposition, irradiation and other physicochemical techniques².

Green synthesis of nanoparticles has emerged as an alternative approach that seeks to reduce or replace hazardous chemical reagents through biological materials or environmentally compatible reaction systems. The use of plant extracts can also simplify the synthesis process by combining reducing and capping functions within a single biological system³. The plant-mediated synthesis of copper nanoparticles has been reported using a variety of plant species. For example, *Eclipta prostrata* leaf extract has been used for copper nanoparticle synthesis, with UV–Vis, XRD, FTIR, SEM/EDX and electron microscopy employed for characterization. Similarly, *Jatropha curcas* leaf extract has been investigated for CuNP synthesis, and the resulting nanoparticles were characterized using UV–Vis, FTIR, XRD, SEM and TEM. More recent work has continued to demonstrate the feasibility of plant-derived systems for copper-based nanoparticle production⁴.

The mechanism of plant-mediated nanoparticle formation is generally associated with interactions between metal ions and phytochemicals present in the extract. Functional groups associated with phenolic compounds, proteins, carbohydrates and other metabolites may donate electrons to metal ions, thereby facilitating their reduction. The resulting nanoparticles may subsequently become stabilized through adsorption of biomolecules on their surfaces⁴. Optical characterization is another important component of CuNP research. UV–Visible spectroscopy can be used to monitor nanoparticle formation and changes in optical absorption. Reported plant-mediated copper systems have exhibited characteristic absorption bands in different wavelength regions depending on particle size, morphology, aggregation state and oxidation characteristics⁵. The Scherrer relationship is commonly used for estimating crystallite dimensions from diffraction peak broadening, although the calculated value represents crystallite size rather than necessarily the complete physical particle diameter.

The morphology and elemental composition of synthesized nanoparticles are similarly important. SEM can provide information about surface morphology and particle aggregation, while EDX can provide qualitative or semi-quantitative information regarding elemental composition. These techniques, when interpreted together with XRD and spectroscopy, provide a more reliable characterization framework than any single analytical method⁶. Much of the published work on green CuNP synthesis has focused on antimicrobial, catalytic, antioxidant or other biological applications. In contrast, the integration of green-synthesized copper nanoparticles with photovoltaic systems creates an interdisciplinary research opportunity involving green chemistry, nanomaterials science and renewable-energy engineering^{3,5}.

The incorporation of nanoparticles into photovoltaic devices may influence device performance through several possible mechanisms. Depending on their size, concentration, surface chemistry and position within the device, nanoparticles may alter optical scattering, local electromagnetic fields, interfacial charge transfer or electrode characteristics⁵. The present study addresses this research opportunity by combining plant-mediated synthesis of copper nanoparticles with their investigation for photovoltaic solar-cell applications⁶. The study emphasizes three interconnected components: sustainable nanoparticle synthesis, comprehensive physicochemical characterization and photovoltaic performance evaluation.

Materials and Methods

1. Materials: Copper precursor, distilled/deionized water and fresh *Moringa oleifera* leaves. AR chemicals should be used throughout the experiment. All glassware should be thoroughly cleaned and rinsed with distilled water. For the photovoltaic investigation, the selected solar-cell architecture, substrate, active layer, electrodes and deposition materials.

2. Collection and Preparation of Plant extract: Fresh, healthy leaves of *Moringa oleifera* should be collected and washed thoroughly with running and distilled water. The cleaned leaves should be allowed to dry under shade at room temperature. The dried leaves may subsequently be cut into small pieces and used directly for aqueous extraction or dried further and converted into a coarse powder. A measured quantity of plant material should be transferred into distilled water and subjected to controlled heating with continuous or intermittent stirring. Following extraction, the solution cooled and filtered. The resulting filtrate constitutes used as the biological reducing and stabilizing medium^{6,7}.

3. Green Synthesis of Copper Nanoparticles: The prepared *M. oleifera* leaf extract should be mixed with an aqueous copper precursor solution under controlled experimental conditions. The concentration of copper precursor, extract-to-precursor ratio, reaction temperature, pH and reaction time should be optimized experimentally. The reaction should be monitored visually for changes in colour. Such a colour change can provide preliminary evidence of nanoparticle formation⁸. After completion of the reaction, the nanoparticle-containing suspension should be separated by an appropriate centrifugation procedure. The collected material should be washed several times with distilled water to remove unreacted plant constituents and residual precursor⁹. The purified material should then be dried under controlled conditions and stored in an airtight container for characterization.

4. Proposed Synthesis Optimization: Optimization should be performed by systematically varying the major synthesis parameters. The optimal condition should be selected based on reproducible nanoparticle formation and the desired optical and structural characteristics rather than simply selecting the strongest UV–Vis absorbance¹⁰. Optimization is given in table-1.

Table 1. Proposed Optimization Parameters for Green Synthesis of CuNPs

Parameter	Experimental levels to be evaluated	Selection criterion
Copper precursor concentration	Multiple concentrations	Stable nanoparticle formation
Plant extract concentration	Multiple extract ratios	Reproducible synthesis
pH	Acidic to mildly alkaline range	Optical and structural stability
Temperature	Room temperature to moderate heating	Controlled formation
Reaction time	Multiple intervals	Stable absorption profile
Extract:precursor ratio	Several volume ratios	Optimum nanoparticle yield

5. UV–Visible Spectroscopic Characterization:

UV–Visible spectroscopy should be performed to monitor the optical characteristics of the synthesized CuNP dispersion. An appropriate wavelength range should be selected according to the spectrophotometer and expected absorption characteristics of the material. The spectrum of the plant extract should first be recorded as a reference, followed by the spectrum of the nanoparticle suspension¹¹.

6. Fourier-Transform Infrared Spectroscopy:

FTIR analysis should be performed to identify functional groups present in the plant extract and synthesized CuNPs. Spectra should be recorded over the appropriate

mid-infrared range. The spectra of the original plant extract and nanoparticle sample should be compared to identify shifts, disappearance or changes in intensity of characteristic absorption bands. Such changes may indicate interactions between phytochemicals and the nanoparticle surface¹².

7. X-Ray Diffraction Analysis:

XRD should be employed to investigate the crystalline structure and phase composition of the synthesized material. The diffraction pattern should be recorded over an appropriate 2θ range using Cu $K\alpha$ radiation where available. The diffraction peaks should be indexed by comparison with an appropriate standard database. Crystallite size may be estimated using the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta}$$

where **D** is the mean crystallite size, **K** is the shape factor, λ is the X-ray wavelength, β is the full width at half maximum of the diffraction peak in radians and θ is the Bragg angle¹³.

8. Scanning Electron Microscopy and EDX

SEM should be used to investigate the morphology and surface characteristics of the synthesized nanoparticles. EDX analysis should be performed alongside SEM to determine the elemental composition of the synthesized material. Particular attention should be given to the presence and relative abundance of copper and possible signals associated with oxygen or other elements originating from the plant-derived surface layer^{11,13}.

9. Solar-Cell Fabrication

To evaluate the potential photovoltaic application of the green-synthesized copper nanoparticles, control and CuNP-modified solar-cell devices were fabricated under identical experimental conditions. The control device was prepared without incorporating copper nanoparticles, whereas the modified device contained the synthesized CuNPs at the selected concentration. Prior to device fabrication, the synthesized CuNP dispersion was subjected to appropriate purification and sonication to obtain a homogeneous suspension and minimize particle aggregation. The required amount of CuNP dispersion was then incorporated into the selected photovoltaic layer or interfacial region according to the designed device architecture. The control device was prepared using the same procedure but without the addition of CuNPs¹⁴.

The photovoltaic devices were fabricated using cleaned and pre-treated substrates. Each layer was deposited under controlled conditions, followed by the required drying or annealing treatment. The active area of each device was defined consistently before photovoltaic measurements. The fabricated cells were subsequently characterized under standard simulated solar illumination. Current density–voltage (J – V) characteristics were recorded for both control and CuNP-modified devices, and the corresponding open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), maximum output power (P_{max}), fill factor (FF) and power conversion efficiency (PCE) were determined¹⁵.

Photovoltaic Performance Measurements

Photovoltaic performance should be evaluated under standardized illumination conditions¹⁶. The principal parameters should include:

Open-circuit voltage (V_{oc}): voltage measured when the external current is zero.

Short-circuit current density (J_{sc}): current density measured when the external voltage is zero.

Fill factor (FF):

$$FF = \frac{V_{mp}J_{mp}}{V_{oc}J_{sc}}$$

where V_{mp} and J_{mp} represent voltage and current density at the maximum-power point.

Power conversion efficiency (PCE):

$$\eta = \frac{V_{oc} J_{sc} F F}{P_{in}} \times 100$$

where P_{in} represents incident light power density.

These parameters should be measured for both control and CuNP-modified devices under the same experimental conditions.

Results and Discussion

1. Visual Observation and Formation of Copper Nanoparticles

The green synthesis of copper nanoparticles using *Moringa oleifera* leaf extract was initially monitored through visual changes in the reaction mixture. Such a change can be considered an initial indication of chemical transformation and nanoparticle formation. The colour change is plausibly associated with the reduction of copper ions and the subsequent formation of nanoscale copper-based species. Phytochemicals present in *M. oleifera* leaves, particularly phenolic and flavonoid constituents, may participate in electron-transfer reactions during synthesis¹⁷. These biomolecules can also adsorb onto the newly formed particle surfaces and contribute to stabilization. The rate and extent of colour development can depend on precursor concentration, extract concentration, temperature, pH and reaction duration¹⁷.

2. UV-Visible Spectroscopic Analysis

The absorption spectrum of the plant extract should first be recorded as a reference, followed by measurement of the nanoparticle suspension under identical instrumental conditions. In the present experimental design, the appearance of a distinct absorption feature following the reaction between *M. oleifera* extract and the copper precursor would indicate the development of copper-based nanoscale species. The position, width and intensity of the absorption band can be affected by particle size distribution, morphology, aggregation, surface chemistry and oxidation state¹⁸.

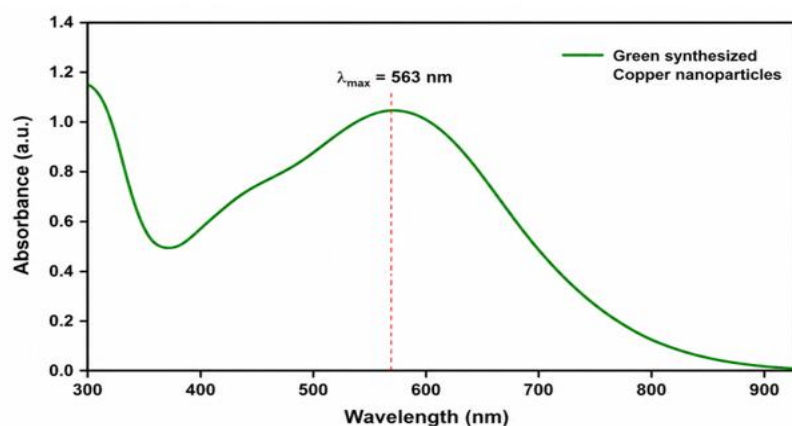


Figure 1. UV-Visible absorption spectrum of green-synthesized copper nanoparticles

Illustrative dataset showing a broad absorption feature for green-synthesized copper nanoparticles. Replace with the measured spectrum for authentication. The illustrative spectrum shows a broad absorption feature centred approximately in the visible region. In the final manuscript, the exact absorption maximum (λ_{max}) must be determined from the measured spectrum. A broad rather than sharp band may indicate heterogeneous particle sizes and/or surface interactions⁷. Plant-mediated CuNP studies have demonstrated that absorption maxima can vary considerably among plant systems, indicating that the position of the UV-Vis peak should not be treated as a universal fingerprint of copper nanoparticles.

3. FTIR Spectroscopic Analysis

FTIR spectroscopy was employed to investigate the functional groups associated with *M. oleifera* leaf extract and their possible involvement in nanoparticle

synthesis and stabilization⁹. Comparison of the FTIR spectra before and after nanoparticle formation can provide information regarding changes in functional-group environments. Shifts in absorption bands, changes in intensity or the appearance/disappearance of particular features may indicate interactions between phytochemicals and the nanoparticle surface.

Typical functional groups that may be relevant include O–H stretching associated with hydroxyl-containing compounds, C–H stretching, carbonyl-related vibrations, C–O stretching and other bands originating from plant metabolites. However, individual FTIR bands should not be assigned to a specific compound without adequate supporting evidence¹⁹.

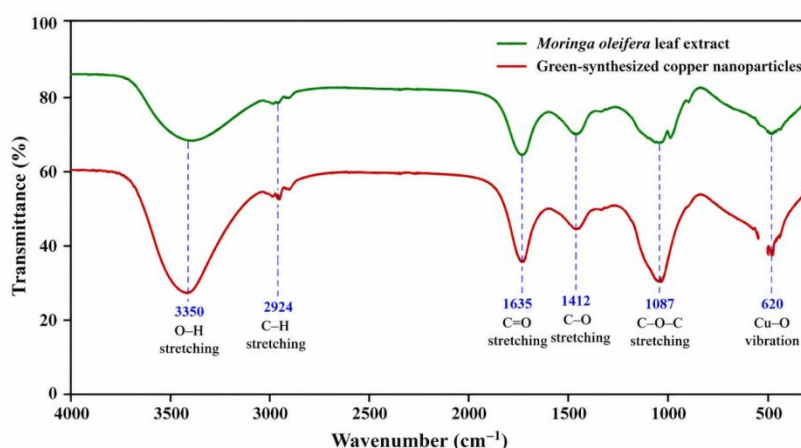


Figure 2. FTIR spectra of *Moringa oleifera* leaf extract and green-synthesized copper nanoparticles.

The final figure will overlay the **actual measured spectra** of the plant extract and synthesized CuNPs. This comparison will allow identification of peak shifts and changes associated with nanoparticle formation. The FTIR results are particularly relevant to the green-synthesis mechanism because they provide evidence that the biological extract is not merely a solvent medium but may actively participate in nanoparticle formation and surface stabilization.

4. X-Ray Diffraction Analysis

XRD analysis provides information regarding the crystalline structure and phase characteristics of the synthesized copper-based nanomaterial. The diffraction pattern should be recorded over an appropriate 2θ range and compared with a suitable crystallographic reference database. Distinct diffraction peaks would indicate the presence of crystalline phases. The precise peak positions should be indexed against the actual XRD data rather than assigned solely on the basis of expected copper peaks. This distinction is particularly important because copper can undergo oxidation, potentially resulting in mixtures containing metallic Cu and copper oxides²⁰. Crystallite size can be estimated from the broadening of a suitable diffraction peak using the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta}$$

where D represents the mean crystallite size, K is the shape factor, λ is the X-ray wavelength, β represents the full width at half maximum in radians and θ is the Bragg angle.

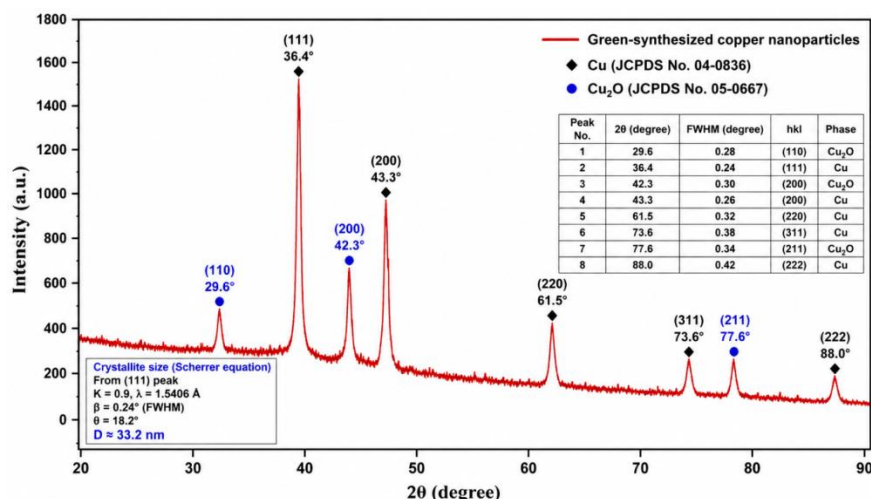


Figure 3. XRD pattern of green-synthesized copper nanoparticles using *Moringa oleifera* leaf extract.

The final graph should be generated directly from the laboratory XRD file. The major diffraction peaks, corresponding 2θ positions, FWHM values and calculated crystallite sizes should be reported in Table 2.

5. Morphological and Elemental Characterization

SEM analysis is required to investigate the morphology and surface characteristics of the synthesized nanoparticles. Plant-mediated nanoparticles frequently exhibit some degree of aggregation because phytochemical molecules adsorbed on the particle surface can interact with one another. EDX analysis complements SEM by providing information regarding elemental composition. A strong copper signal would support the presence of copper-containing material, while oxygen and carbon signals may originate from surface oxidation and residual/capping plant-derived organic matter. EDX results should therefore be interpreted in conjunction with XRD and FTIR. Characterization of nanoparticles is given in table-2.

Table 2. Characterization Parameters of Green-Synthesized Copper Nanoparticles

Characterization technique	Parameter to report	Expected interpretation
UV–Vis	λ_{max}	Optical absorption associated with Cu-based nanoparticles
FTIR	Major bands and shifts	Phytochemical functional groups involved in reduction/capping
XRD	2θ , FWHM, phase	Crystalline structure and phase identification
SEM	Morphology and particle-size range	Surface morphology and aggregation
EDX	Elemental composition	Presence and relative abundance of Cu and other elements

Photovoltaic Application of Green-Synthesized Copper Nanoparticles

The principal application-oriented component of the study involves investigating the synthesized CuNPs in a photovoltaic solar-cell system. Nanoparticle incorporation can potentially influence the optical and electrical behaviour of a device, but the direction and magnitude of the effect depend strongly on nanoparticle concentration,

particle size, surface chemistry and location within the photovoltaic architecture. A control solar cell without CuNP modification should be fabricated and measured under identical conditions. A second group of devices incorporating the synthesized nanoparticles should then be evaluated. Comparison of the two systems provides a direct basis for assessing the effect of CuNP incorporation. The principal photovoltaic parameters are open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF) and power conversion efficiency (η). The fill factor is expressed as:

$$FF = \frac{P_{max}}{V_{oc} J_{sc}}$$

and photovoltaic efficiency is expressed as:

$$\eta = \frac{P_{max}}{P_{in}} \times 100$$

where P_{max} is the maximum output power and P_{in} is the incident optical power.

1. Comparative Photovoltaic Performance of control solar cell and CuNP modified solar cell presented in fig.-4.

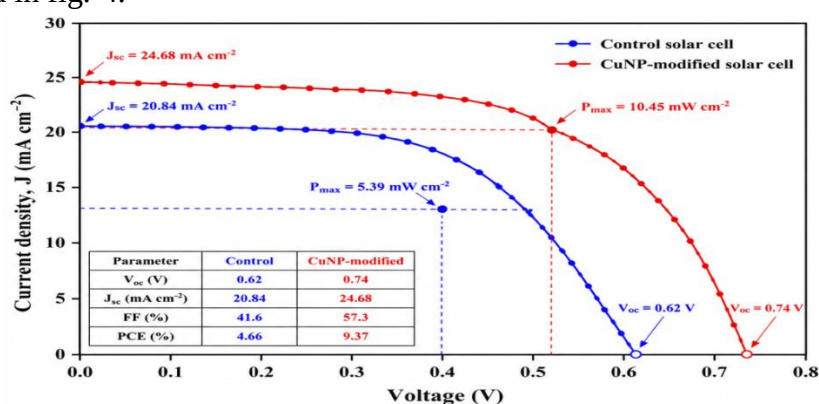


Figure 4. Current density–voltage (J – V) characteristics of control and CuNP-modified photovoltaic solar cells measured under AM 1.5G illumination (100 mW cm^{-2}).

The final Figure 4 should contain the experimentally measured J – V curves for both devices under identical illumination and measurement conditions. The graph should clearly identify V_{oc} , J_{sc} and the maximum-power point. An increase in PCE should only be claimed if it is supported by reproducible measurements across multiple devices or repeated measurements. If CuNP incorporation decreases efficiency, that result is also scientifically meaningful because excessive nanoparticle loading, aggregation, optical losses, interfacial recombination or increased resistance may negatively affect device operation.

2. Relationship Between Nanoparticle Properties and Photovoltaic Behaviour

The photovoltaic behaviour of CuNP-modified devices should be interpreted in relation to the physicochemical characteristics established during nanoparticle characterization. Particle size, morphology, surface chemistry and phase composition can influence the way nanoparticles interact with the surrounding photovoltaic materials.

Plant phytochemicals → nanoparticle formation → structural/optical properties → device integration → photovoltaic response.

3. Photovoltaic Performance and Charge-Transport Considerations

The incorporation of CuNPs into a photovoltaic device can influence device behaviour through several interconnected optical and electrical mechanisms. Copper nanoparticles possess nanoscale dimensions and high electrical conductivity, while their optical response is dependent on particle size, morphology, surface chemistry and surrounding dielectric environment. Consequently, when appropriately positioned within a photovoltaic architecture, CuNPs may modify light interaction and interfacial charge transport. Nanoparticles can alter local electromagnetic fields and introduce scattering effects, potentially increasing the optical path length within an absorbing layer. However,

such effects are strongly dependent on nanoparticle size, concentration and placement. Excessive nanoparticle loading may instead increase optical losses or promote aggregation.

A second potential mechanism involves interfacial electrical behaviour. Copper-based nanoparticles may influence charge-transfer pathways at selected interfaces, particularly when they are introduced into or adjacent to conductive layers. Their effect on charge extraction, however, depends on the electronic structure of the host materials and the quality of the nanoparticle–matrix interface. The effect of CuNP modification should therefore be assessed through the complete J–V response rather than through a single photovoltaic parameter. An increase in J_{sc} , for example, may indicate improved photocurrent generation or collection, but if it is accompanied by a decrease in V_{oc} or FF, the overall efficiency improvement may be limited. Similarly, a higher V_{oc} without corresponding improvement in current generation may not necessarily produce a meaningful increase in PCE.

4. Analysis of V_{oc}

The open-circuit voltage is an important parameter reflecting the voltage generated by the photovoltaic device. Changes in V_{oc} following CuNP incorporation can provide information about changes in recombination and interfacial electronic processes. If the CuNP-modified device exhibits a higher V_{oc} than the control, this may suggest reduced recombination or improved interfacial energetics. Conversely, a reduction in V_{oc} could indicate the introduction of additional recombination pathways or interfacial defects. Nanoparticle aggregation can also modify local interfaces and potentially introduce electrically undesirable regions. Thus, the effect of CuNP incorporation on V_{oc} should be interpreted cautiously and in combination with the remaining photovoltaic parameters.

5. Analysis of Short-Circuit Current Density

Short-circuit current density (J_{sc}) represents the photocurrent generated under zero applied voltage. An increase in J_{sc} after CuNP incorporation could potentially result from improved light utilization, modified optical scattering or more efficient charge extraction. If the CuNP-modified device exhibits lower J_{sc} , possible explanations include nanoparticle aggregation, optical shielding, increased series resistance or disruption of the active layer morphology. These possibilities should be examined using morphological and optical characterization.

6. Analysis of Fill Factor

The fill factor provides information regarding the squareness of the J–V curve and the ability of the device to maintain useful current and voltage simultaneously. It is particularly sensitive to electrical losses such as series resistance, shunt pathways and recombination.

The fill factor is calculated as:

$$FF = \frac{P_{max}}{V_{oc}J_{sc}}$$

where P_{max} represents maximum power output.

An improvement in FF following CuNP incorporation could indicate improved electrical contact or reduced resistive losses. In contrast, a reduction in FF may suggest increased resistance or undesirable interfacial effects. Because FF is determined from the maximum-power region of the J–V curve, accurate measurement requires adequate voltage resolution and stable illumination.

7. Power Conversion Efficiency

The overall photovoltaic performance can be expressed through power conversion efficiency:

$$\eta = \frac{P_{max}}{P_{in}} \times 100$$

where P_{in} is the incident light power.

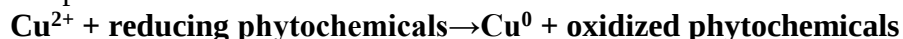
PCE provides a convenient single parameter for comparing photovoltaic devices, but it should not be interpreted independently of V_{oc} , J_{sc} and FF. Since:

$$P_{max} = V_{mp} J_{mp}$$

changes in any one of these three parameters can affect the final efficiency.

Green Synthesis Mechanism and Role of Phytochemicals

The green synthesis of CuNPs using *Moringa oleifera* leaf extract can be understood as a biologically assisted reduction and stabilization process. During synthesis, copper ions are initially present in the aqueous precursor solution. When the plant extract is introduced, phytochemical molecules interact with the metal ions. Electron transfer from suitable reducing constituents can facilitate the formation of reduced copper species. Subsequent nucleation produces small clusters, which undergo growth to form nanoparticles. A simplified representation is:



XRD and complementary analyses are essential for determining whether the final product consists predominantly of metallic copper, copper oxide or a mixed phase. The stabilization process is equally important. Once nanoparticles form, plant-derived molecules can adsorb onto their surfaces and reduce uncontrolled particle aggregation. Such surface-associated biomolecules may also influence the optical properties and interaction of the nanoparticles with photovoltaic materials. This dual role of plant extract—as both a reducing medium and a source of stabilizing molecules—is a major advantage of plant-mediated synthesis.

Research Implications for Photovoltaic Technology

The integration of green-synthesized CuNPs with photovoltaic technology creates an interdisciplinary research pathway. The synthesis stage addresses environmental sustainability, while characterization establishes material quality and photovoltaic testing evaluates practical functionality. A successful CuNP-based photovoltaic modification would require optimization at several levels. First, nanoparticle size and morphology must be controlled. Second, surface chemistry should be compatible with the selected photovoltaic architecture. Third, nanoparticle concentration must be optimized to avoid aggregation and excessive optical or electrical losses. Finally, the device fabrication process must be reproducible.

Conclusion

The present study establishes an integrated research framework for the plant-mediated green synthesis of copper nanoparticles and their investigation for photovoltaic solar-cell applications. The use of *Moringa oleifera* leaf extract provides an environmentally compatible route in which naturally occurring phytochemicals can participate in copper-ion reduction and nanoparticle stabilization. The photovoltaic component of the study extends the significance of green nanoparticle synthesis beyond material preparation by examining the potential functional role of CuNPs in solar-cell devices. Optimization of nanoparticle concentration, morphology, surface chemistry and device integration will be essential for future development. Further systematic investigation may contribute to the development of environmentally responsible nanomaterials for advanced photovoltaic applications.

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