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Multifunctional Green synthesized copper nanoparticles for environmental and biomedical applications

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Abstract

Green synthesis pathways play a vital role in the fabrication of metal nanoparticles. The present study focuses on an environmentally benign strategy for the synthesis of copper nanoparticles (CuNPs) using *Justicia adhatoda* leaf extract. The phytochemical constituents of the *J. adhatoda* extract effectively mediated the reduction of Cu²⁺ ions and also acted as stabilizing agents. The successful formation of CuNPs was confirmed by UV–Visible spectroscopy through the appearance of a surface plasmon resonance (SPR) band at 348 nm. Morphological analysis using SEM and TEM revealed predominantly spherical CuNPs with particle sizes in the range of 31–54.2 nm and 40–47 nm, respectively. AFM analysis further confirmed the smooth surface topography and effective bio-capping of the synthesized CuNPs. The biosynthesized CuNPs demonstrated excellent catalytic efficiency toward methylene blue dye, achieving more than 90% degradation. Furthermore, the synthesised CuNPs demonstrated notable cytotoxic effects on A-549 (human lung cancer) cells.

Keywords: Green synthesis, Copper nanoparticles, catalytic activity Methylene blue; anticancer activity.

Highlights

- Copper nanoparticles were synthesized using *Justicia adhatoda* leaf extract.
- The biosynthesized CuNPs exhibited effective catalytic degradation activity and cytotoxicity against A-549 lung carcinoma cells.
- The study demonstrates the eco-friendly and multifunctional potential of CuNPs for environmental and biomedical applications.

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3 **1. Introduction**
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5 Nanotechnology has transformed materials science by enabling the fabrication of
6 functional nanostructures with tailored physicochemical properties. Metal nanoparticles
7 (MNPs) are particularly attractive owing to their high surface-to-volume ratio and size-
8 dependent quantum effects, which impart remarkable catalytic, optical, and biomedical
9 activities [1–6].

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17 Copper nanoparticles are more preferred than silver nanoparticles because copper is more cost-
18 effective, exhibits good chemical and physical stability, and readily integrates with polymer
19 matrices.[7]. Owing to their favorable electrical, optical,, and catalytic properties, CuNPs have
20 found applications across diverse fields, including nanoparticle-based devices. [8,9].

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27 Additionally, copper exhibits ultraviolet sensitivity, high electrical and thermal conductivity,
28 malleability, and notable antibacterial and antifungal activities, along with appreciable
29 corrosion resistance.[10,11]
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34 The rapid growth of industrialization has increased the volume and complexity of effluent
35 discharge worldwide, resulting in water contamination and environmental disruption. When
36 industrial wastewater is released into water bodies without effective treatment, it alters the
37 physical, chemical, and biological properties of the receiving environment. Toxic components
38 such as heavy metals, organic pollutants, and dyes can accumulate in ecosystems, leading to
39 prolonged environmental contamination. The removal of industrial effluents remains a serious
40 environmental challenge due to the presence of toxic chemicals and dyes [12,13]. Although
41 numerous techniques have been developed for dye removal from industrial effluents, metal
42 nanoparticles have gained significant attention over the past decade because of their high
43 efficiency [14]. This study discusses the efficiency of copper nanoparticles in degrading dyes
44 from industrial wastewater [15–17]. Synthetic dyes, particularly methylene blue (MB), are
45 among the most commonly discharged pollutants into aquatic systems. MB is widely used in
46 the textile, leather, and paper industries and is considered potentially carcinogenic, thereby
47 posing serious ecological and human-health hazards [18-20].
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Another major global concern is cancer, which remains one of the leading causes of death worldwide. Medicinally valuable plants have long been used in cancer treatment, as plant-derived compounds offer several advantages, including reduced side effects, low cost, and easy availability [21,22]. Previous *in vitro* studies have reported the selective cytotoxicity of CuNPs against aggressive cancer cell lines such as A549 lung carcinoma and MDA-MB-231 triple-negative breast carcinoma cells [23–28]. Additionally, earlier studies have documented the medicinal properties of *Justicia adhatoda* [29]. The present study focuses on the green synthesis of CuNPs using *Justicia adhatoda* leaf extract and demonstrates their dual functionality: high catalytic efficiency in the degradation of methylene blue dye and potent anticancer activity against A549 lung cancer cells, thereby highlighting their potential in environmental and biomedical applications.

2. Materials and Methods

2.1. Chemicals and reagents

Copper nitrate [$\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$] was procured from Sigma-Aldrich (India). Methylene blue (MB). Dulbecco's Modified Eagle's Medium (DMEM), Fetal Bovine Serum (FBS), penicillin–streptomycin solution, and trypsin–EDTA were obtained from Sigma-Aldrich (USA). The A-549 human lung cancer cell line was purchased from the Cancer Institute, Chennai (India).

2.2. Preparation of *Justicia adhatoda* leaf extract

Fresh leaves of *Justicia adhatoda* were collected from local agricultural fields, washed thoroughly with DD water, shade-dried for 10–15 days, and ground into coarse powder. Approximately 10 g of the powdered leaves was mixed with 100 mL of DI water and heated at 60–70 °C for 20 min under constant stirring. The mixture was cooled to room temperature and filtered through Whatman No. 1 filter paper [30,31].

2.3. Green synthesis of copper nanoparticles

For the biosynthesis of CuNPs, 1 mL of *J. adhatoda* leaf extract was added dropwise to 20 mL of 1 mM aqueous $\text{Cu}(\text{NO}_3)_2$ solution at ambient temperature. The appearance of a dark brown color showed the reduction of Cu^{2+} ions and formation of CuNPs [32,33].

2.4. Characterization of CuNPs

The optical properties of the synthesized CuNPs were analyzed using UV–visible spectroscopy (PerkinElmer Lambda 45) in the wavelength range of 200–800 nm. The surface plasmon resonance (SPR) peak confirmed nanoparticle formation. Morphological and structural features were characterized using scanning electron microscopy (SEM, Hitachi S-3400N), Transmission electron microscopy (TEM, JEOL 1200EX), and atomic force microscopy (AFM, Bruker Dimension Icon). [34–36].

2.5 Cell culture:

2.5.1 MTT Assay

The MTT assay was employed to evaluate the cytotoxic and anticancer activity of copper nanoparticles (CuNPs) against A549 human lung cancer cells. The cells were cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 1% penicillin–streptomycin, and maintained at 37 °C in a humidified atmosphere containing 5% CO_2 . A549 cells were seeded into 96-well microtiter plates at a density of 1×10^5 cells/mL and incubated for 24 h to allow cell attachment. After incubation, the cells were treated with varying concentrations of CuNPs and further incubated for an additional 24 h. Subsequently, 10 μL of MTT solution was added to each well, and the plates were incubated for 5 h to facilitate the formation of formazan crystals. The culture medium was then carefully removed, and 200 μL of dimethyl sulfoxide (DMSO) was added to each well to dissolve the formazan crystals. Absorbance was measured at 570 nm using a microplate reader. Cell viability and percentage cytotoxicity were calculated from the absorbance values, and the half-maximal inhibitory concentration (IC_{50}) was determined from the dose–response curve using GraphPad Prism version 6.0 (GraphPad Software, USA) [37].

2.5.2 Morphological study

Morphological changes in A549 lung cancer cells following CuNP exposure were examined using an inverted light microscope. Briefly, A549 cells were seeded into 6-well culture plates at a density of 5×10^5 cells/mL and incubated under standard culture conditions (37 °C, 5% CO₂). After cell attachment, the cells were treated with CuNPs at their IC₅₀ concentration and incubated for 48 h. Untreated cells maintained under identical conditions served as the control group. Following treatment, cellular morphology was observed and compared with control cells to evaluate CuNPs induced cytotoxic effects, including changes in cell shape, adhesion, and confluency [38,39]. Cell viability was calculated using the following equation:

$$\text{Cell viability} = \frac{\text{A sample}}{\text{A Control}} \times 100$$

3. Result and discussion

3.1 Role of plant extract in nanoparticle formation

The plant extract plays a crucial role in the synthesis and stabilization of the nanoparticles. The presence of phytochemicals such as polyphenols, flavonoids, and proteins facilitates the reduction of metal ions and simultaneously acts as capping agents, thereby preventing aggregation. This results in nanoparticles with smaller size, improved dispersion, and enhanced stability. Additionally, these bioactive compounds may remain adsorbed on the nanoparticle surface, contributing to enhanced biological activity. The improved surface functionality and high surface area of the plant-mediated nanoparticles also promote enhanced catalytic performance, as evidenced by their efficient dye degradation activity. In contrast, nanoparticles synthesized without plant extract are typically associated with poor size control, aggregation, and reduced stability due to the absence of natural stabilizing agents, which can adversely affect their catalytic and biological efficiency. Although a direct comparative study was not performed in the present work, the observed properties strongly suggest the significant contribution of the plant extract [6,40].

3.2. UV–Visible Spectroscopy

The formation of copper nanoparticles (CuNPs) was confirmed by UV–visible spectroscopic analysis. A distinct color change of the reaction mixture from blue to dark brown was observed upon the addition of *Justicia adhatoda* leaf extract to the aqueous $\text{Cu}(\text{NO}_3)_2$ solution, indicating the reduction of Cu^{2+} ions (Figure 1). This visual transformation is a characteristic signature of surface plasmon resonance (SPR), which arises from the collective oscillation of conduction electrons in metallic nanoparticles. The UV–Vis absorption spectrum of the biosynthesized CuNPs displayed a prominent SPR band at 348 nm (Figure 1b), confirming the successful formation of stable colloidal copper nanoparticles. Similar SPR absorption peaks in the range of 340–360 nm have been reported for CuNPs synthesized using various plant extracts, including *Aloe vera* and *Azadirachta indica* [41,42]. The phytochemicals

present in *J. adhatoda*, such as flavonoids, alkaloids, and phenolic compounds, functioned as both reducing and stabilizing agents. These biomolecules contain functional groups, including hydroxyl ($-\text{OH}$) and carbonyl ($-\text{C}=\text{O}$) groups, which can chelate copper ions, thereby facilitating nanoparticle formation and enhancing colloidal stability [43].

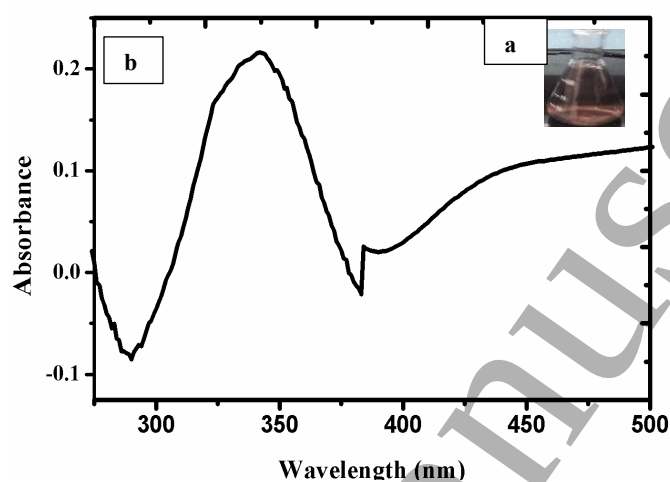


Figure 1 : a)Inset digital photograph of synthesized copper nanoparticles. b)UV-Vis absorption spectrum of CuNPs synthesized from *J. adhatoda* leaf extract.

It is important to note that CuNPs are metallic in nature and therefore do not exhibit a well-defined optical bandgap like semiconductor materials. Hence, bandgap estimation using methods such as Tauc plot analysis is not applicable in the present study. The optical response of CuNPs is primarily governed by surface plasmon resonance rather than interband transitions [44,45].

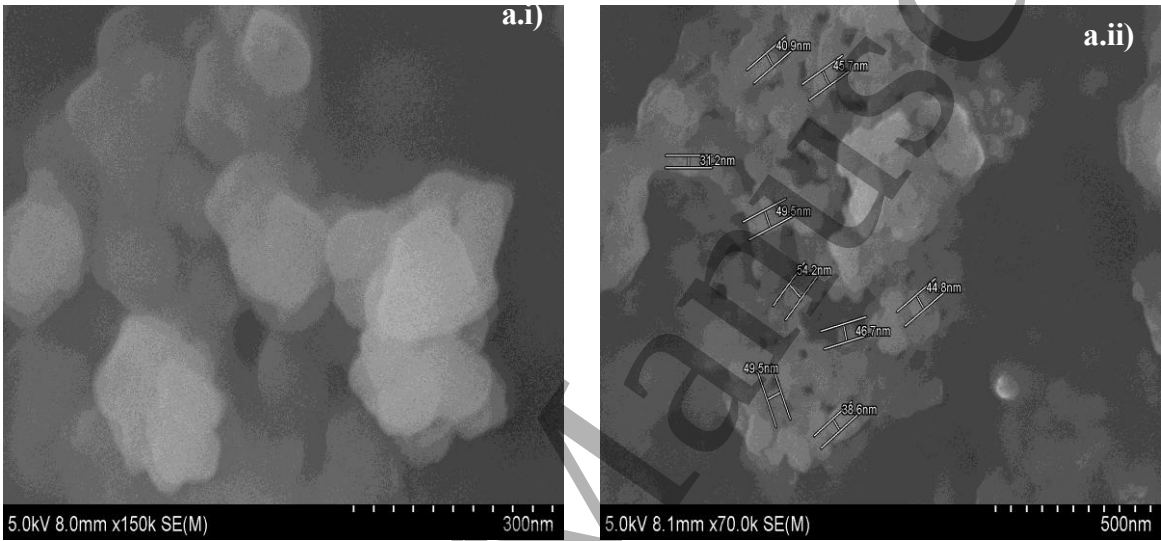


Figure 2 :a)SEM images of CuNPs synthesized by using *J. adhatoda* leaf extract with different magnifications

3.3. Scanning Electron microscopy (SEM)

The surface morphology of the biosynthesized CuNPs was examined using Scanning Electron Microscopy (SEM). The SEM images revealed predominantly spherical-shaped nanoparticles, as shown in Figure 2. The average particle size was found to be in the range of approximately 31–54.2 nm. The nanoparticles exhibit relatively uniform morphology with moderate dispersion, although slight agglomeration is observed. These observations confirm the successful formation of CuNPs via the green synthesis approach [46,47].

3.4. Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) was employed to examine the surface morphology and size distribution of the synthesized Copper nanoparticles. The TEM micrographs revealed predominantly spherical nanoparticles with well-defined boundaries, as shown in Figure 3. The average particle size was found to be in the range of 40–47 nm, indicating a relatively narrow size distribution and a homogeneous nucleation process. The particle size distribution is consistent with SEM analysis, with slight variations attributed to differences in sample–electron interactions and measurement resolution inherent to each technique.

A slight to moderate degree of agglomeration is observed, which may be attributed to interparticle interactions such as van der Waals forces and drying effects during TEM sample preparation. Despite this, individual nanoparticles remain clearly distinguishable, indicating relatively good dispersion. Furthermore, the nanoparticles appear to be reasonably stabilized, likely due to the capping action of phytochemical constituents present in the *Justicia adhatoda* leaf extract. Biomolecules such as polyphenols and flavonoids may contribute to partial stabilization, reducing excessive aggregation and enhancing colloidal stability [48,49].

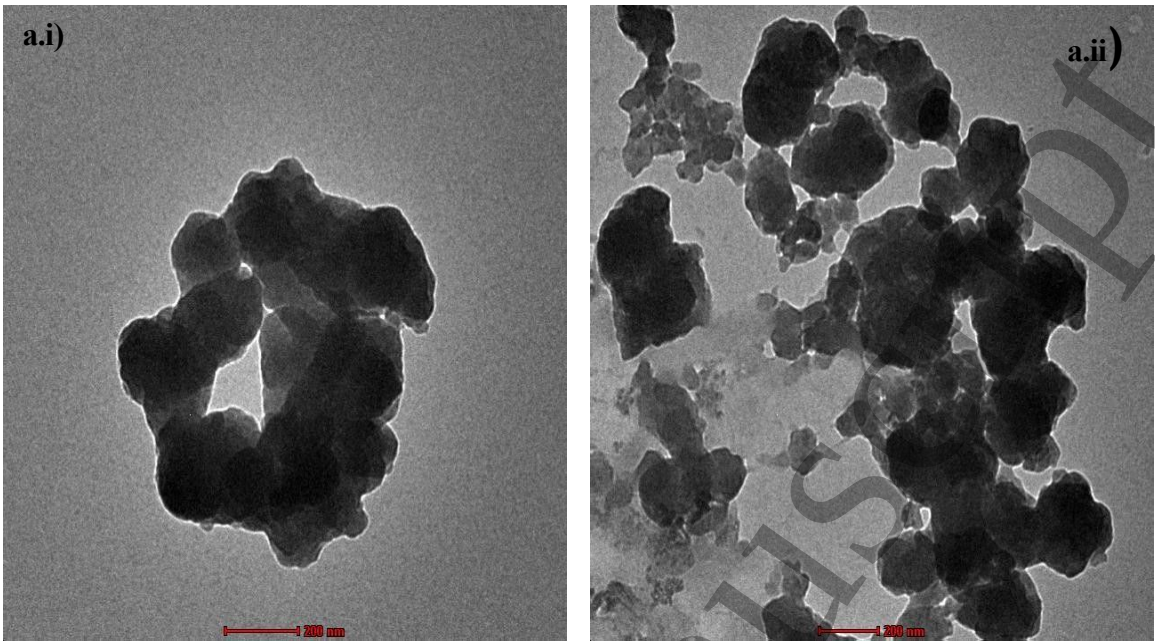


Figure 3 :a)TEM images of CuNPs synthesized by using *J. adhatoda* leaf extract with different magnifications

3.5. Topographical analysis by AFM

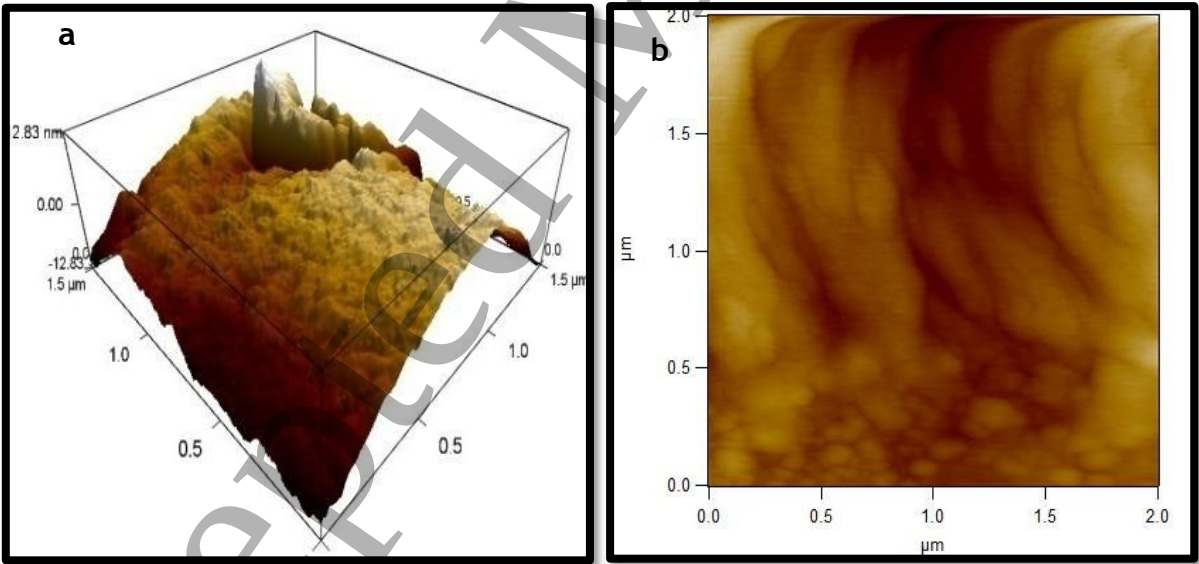


Figure 4.AFM images of CuNPs

Atomic force microscopy (AFM) was employed to investigate the surface morphology of the CuNPs. The AFM micrographs revealed uniformly distributed, predominantly spherical nanoparticles with minimal surface roughness shown in Figure 4. Such nanoparticles roughness can be ascribed to the adsorption of phytochemical like alkaloids, phenolic compounds, and flavonoids onto the CuNPs surface [50,51]. Topographical features such as surface smoothness and uniform particle size play important roles in influencing catalytic reactivity and anticancer behaviors[52,53].

3.6. Catalytic activity

The catalytic efficiency of *Justicia adhatoda*-mediated CuNPs was evaluated using methylene blue (MB) as a model organic pollutant. MB is a cationic thiazine dye extensively used in textile and paper industries and is commonly employed as a standard probe molecule for assessing catalytic degradation performance. The degradation process was monitored by UV-visible spectrophotometry. When MB was treated with sodium borohydride (NaBH_4) alone, negligible degradation was observed, as the characteristic absorbance peak at 664 nm remained almost unchanged even after 25 min, indicating the absence of significant catalytic activity (Figure 5a). In contrast, the addition of CuNPs to the MB- NaBH_4 reaction system resulted in a rapid decrease in the absorbance intensity at 664 nm, accompanied by a visible decolorization of the solution[54]. The UV-Vis absorption spectra (Fig. 5b) demonstrated a continuous and pronounced reduction in MB absorbance, confirming efficient dye degradation within 16 min.

Visual observation was shown in Figure 5.b.i. This enhanced catalytic performance can be attributed to the large specific surface area of the biosynthesized CuNPs, which provides abundant active sites for electron transfer during the reduction process.

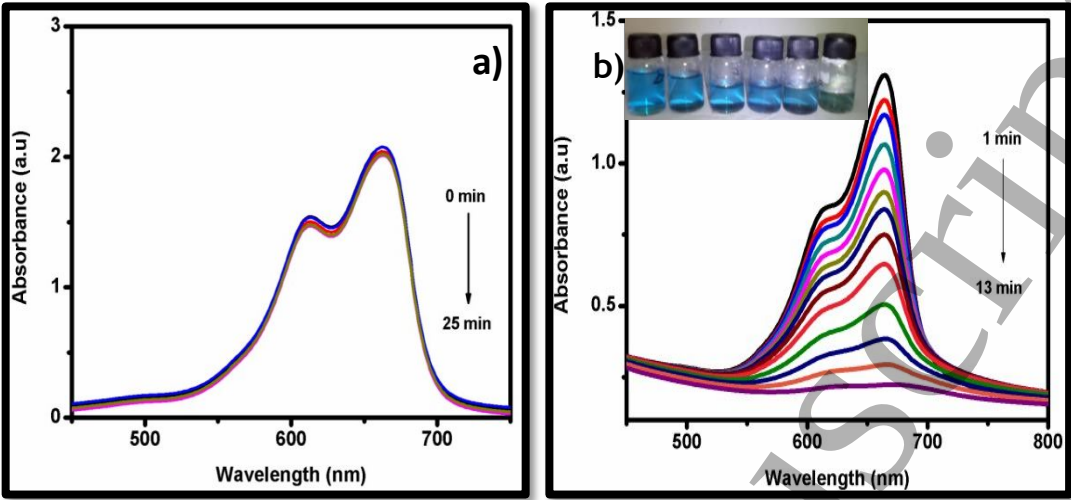
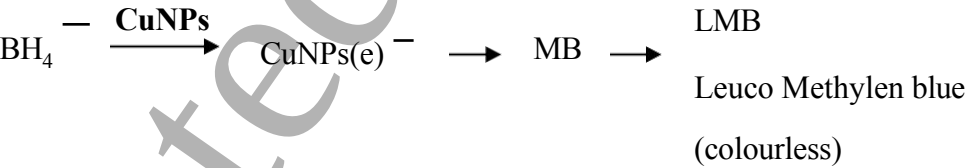


Figure 5: UV-Visible absorption spectra of dye degradation by a)NaBH₄ alone b) in the presence of CuNPs . i)Visual observation

These results indicate that CuNPs effectively catalyzed the transfer of electrons from BH₄⁻ ions to MB molecules, thereby facilitating the reduction and degradation of the dye [55]. Figure 6 was exhibited the mechanism of the catalytic activity of CuNPs against MB dye degradation. The proposed reaction mechanism is outlined below:



Mechanism of Catalytic Activity of CuNPs toward MB Degradation

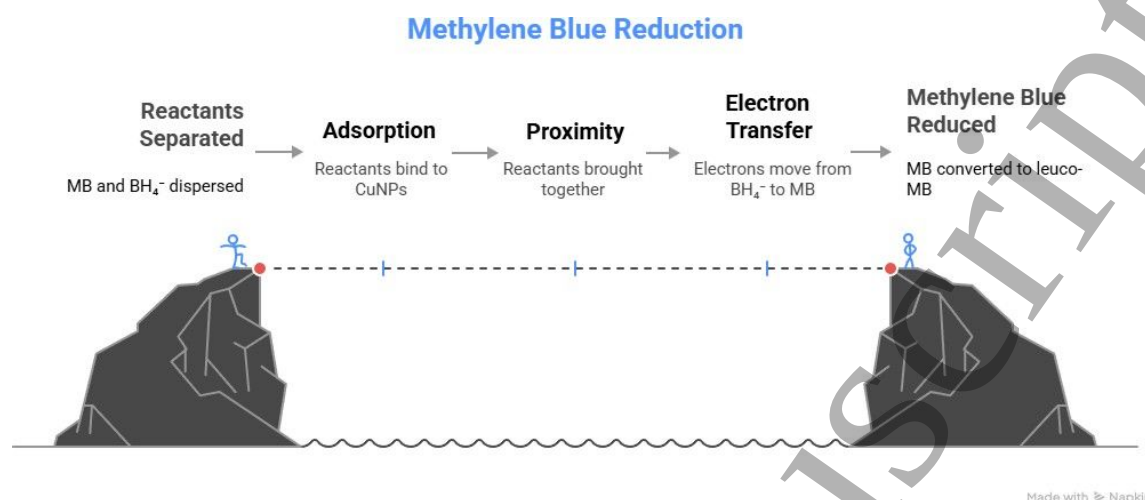


Figure 6. Mechanism of catalytic activity of CuNPs against MB

Comparable catalytic efficiencies have been reported for green-synthesized copper and silver nanoparticles prepared using *Centella asiatica* and *Diospyros montana* leaf extracts [56]. The percentage of dye degradation was calculated using the following equation:

$$\% \text{ of dye degradation} = \frac{A_0 - A_t}{A_0} \times 100$$

A_0 = Initial absorbance; A_t = Absorbance at time

A plot of $\ln(A/A_0)$ versus reaction time exhibited a strong linear relationship, confirming that the reduction of MB follows pseudo-first-order kinetics shown in Figure 7. The corresponding rate constants and percentage degradation values are summarized in Table 1. The high catalytic efficiency and elevated reaction rate constants can be attributed to the enhanced electron-transfer capability of the CuNPs, which promote efficient charge transfer from borohydride ions (electron donors) to MB molecules (electron acceptors). This redox process, commonly

described as the “electron relay effect,” is a characteristic feature of transition-metal nanoparticles, which provide abundant active surface sites for effective charge exchange.

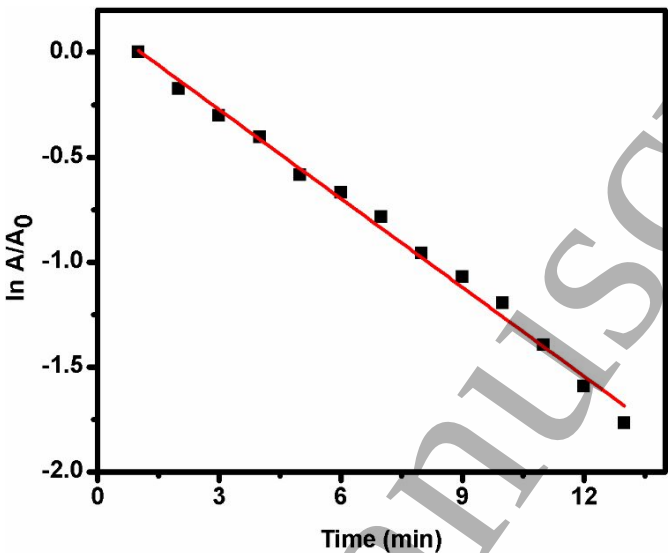


Figure 7 : Linear plot of $\ln A/A_0$ vs time

Table 1: The rate constant (min^{-1}) and percentage of dye degradation

S.No	Dye	R^2	Rate constant	% of dye degradation
1.	MB	0.9929	0.1498	83

Overall Reaction Pathway

The catalytic degradation of methylene blue (MB) in the presence of CuNPs and sodium borohydride (NaBH_4) occurs via an electron-transfer-mediated redox pathway, commonly referred to as the electron relay effect. Various biosyntheses of copper nanoparticles using different biological sources are shown in Table 2.

Table 2: Biosynthesis of copper nanoparticles using various biological sources

Synthesis Method	Nanoparticle	Bioactivity	Key Quantitative Results	Study (Ref)
Passiflora flower extract (green)	CuNPs	Anticancer & antibacterial	IC ₅₀ ~47.01 µg/ml vs MCF-7; normal cells & IC ₅₀ ~128.35 µg/ml; broad-spectrum activity	Sahib <i>et al.</i> (2025)[57]
Wrightia tinctoria extract (green)	CuNPs	Anticancer & larvicidal	MCF-7 IC ₅₀ ~119.23 µg/ml; Vero cells IC ₅₀ ~898.75 µg/ml	Rajagopal <i>et al.</i> (2021) [58]
Impatiens chinensis Leaf extract (green)	CuNPs	Anticancer + antioxidant	~65.34 % inhibition in MCF-7 cells	Kirubakaran <i>et al.</i> , (2024) [59]
Quinoa seed extract (green)	CuNPs	Antibacterial (wastewater focus)	Confirmed crystalline CuNPs with small size	Hassan <i>et al.</i> (2023) [60]
Microbial biosynthesis	CuNPs	Cytocompatible, low toxicity	Excellent stability, low cytotoxicity toward lung cells	El-Sayed <i>et al.</i> , (2025) [61]

3.7. Anticancer activity of *J. adhatoda*-mediated CuNPs

The anticancer potential of green-synthesized copper nanoparticles (CuNPs) was evaluated against human lung carcinoma (A549) cells using the MTT assay. Cells were exposed to increasing concentrations of CuNPs (20–120 $\mu\text{g/mL}$) for 24 h. Untreated cells served as the control and exhibited no significant change in cell viability. Schematic diagram for anticancer activity of CuNPs was shown in Image 3. A clear dose-dependent decrease in cell viability was observed with increasing CuNP concentration (Figure 8). The half-maximal inhibitory concentration (IC_{50}) was estimated to be approximately 60 $\mu\text{g/mL}$, corresponding to ~40.6% inhibition of A549 cell growth. At higher concentrations (≥ 100 $\mu\text{g/mL}$), cytotoxicity increased markedly, suggesting enhanced intracellular accumulation of CuNPs, which may elevate oxidative stress and activate apoptotic pathways. The schematic diagram illustrating the anticancer activity of CuNPs is shown in Figure 9.

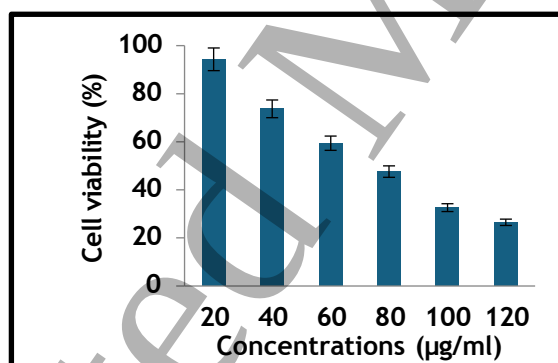


Figure 8: *In vitro* cytotoxicity of Synthesized CuNPs on A-549 cell line

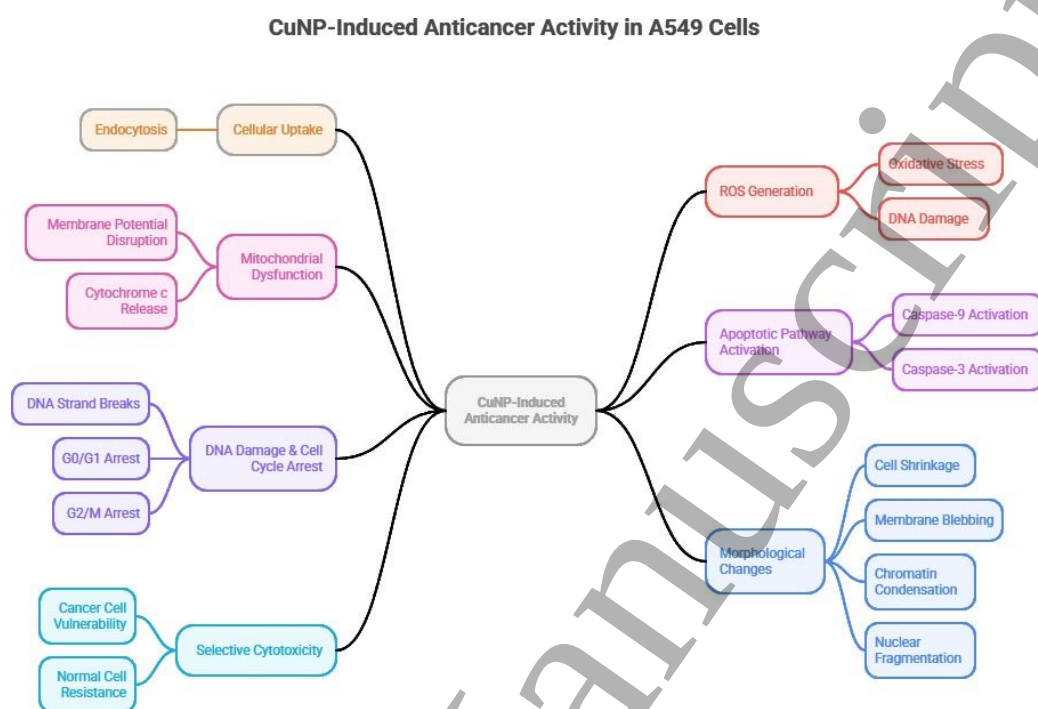


Figure 9 schematic diagram for anticancer activity of CuNPS

Mechanism of action of biosynthesized CuNPs in cancer cells

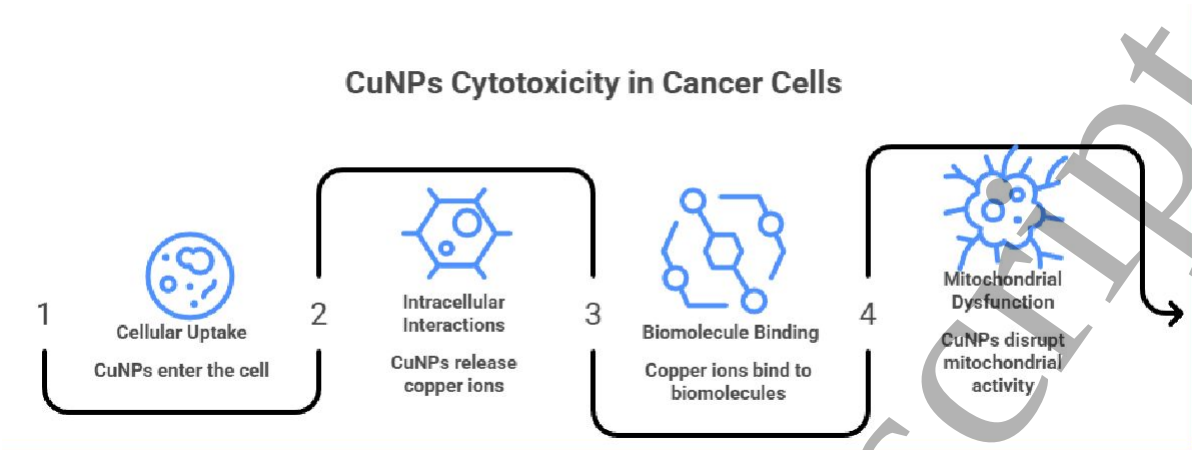


Figure 10: schematic diagram for anticancer activity of CuNPS

1. The plant-mediated copper nanoparticles (CuNPs) are localized within endosomal and lysosomal compartments.
2. In the acidic intracellular environment, the nanoparticles partially dissolve, releasing Cu^+ and Cu^{2+} ions.
3. Released copper ions disrupt cellular functions by interacting with proteins, nucleic acids, and membranes, and by binding to thiol-containing enzymes, thereby altering their activity and metabolic processes.
4. Intracellular copper accumulation disrupts mitochondrial function, reduces ATP production, and triggers apoptotic pathways, ultimately leading to cell death; severe damage may result in necrosis.

Phytochemical capping agents enhance nanoparticle stability and cellular interaction, thereby increasing cytotoxicity. The anticancer activity of the green-synthesized CuNPs is likely due to copper ion-mediated cellular dysfunction and apoptosis, although detailed mechanisms were

not explored. Both Cu^{2+} ions and CuNPs show anticancer activity by inducing cell damage and apoptosis; however, nanoparticles are more effective than copper ions this is due to their small size, high surface area, and enhanced cellular uptake[62].

Table 3: Comparative Evaluation of Phytogenic various metal NanoparticleMediated Apoptosis in A549

S. No.	Plant Source	NPs	Cell Line	Observed Anticancer Mechanism/Effect	Reference
1.	<i>Gloriosa superba</i>	CuNPs	A549	ROS generation, apoptosis induction	Thounaojam et al., 2011 [63]
2.	<i>Terminalia arjuna bark extracts</i>	CuNPs AgNPs	MDA-MB-231, HeLa, SiHa, and Hep-G2	Dose dependent	Yallappa et al., 2014 [64]
3.	<i>Schisandra chinensis</i>	CuNPs	A549	Membrane damage, mitochondrial dysfunction	Dario et al., 2024 [65]
4.	<i>Eclipta prostrata</i>	CuNPs	A549	Nuclear condensation, apoptosis	Ill-min chung et al., 2017[66]
5.	<i>Syzygium aromaticum</i>	CuNPs	A549	Dose-dependent cytotoxicity, ROS elevation	Venugopal et al., 2017 [67]
6.	<i>Derris trifoliata</i>	AgNPs	A-549	Dose-dependent apoptosis	Neethu Cyril et al., 2019[68]
7.	<i>Azadirachta indica</i>	AgNPs	A549	ROS generation, caspase activation	Ahmed et al., 2016 [69]
8.	<i>Centella asiatica</i>	AgNPs	A549	Mitochondrial dysfunction, oxidative stress	Usharani et al., 2023[70]
9.	<i>Moringa oleifera</i>	AuNPs	A549	DNA damage, apoptosis	Dawei Qian et al., 2025 [71]
10.	<i>Camellia sinensis</i>	Graphene Oxide NPs	A549	ROS-dependent apoptosis	Farkhunda Fatima et al., 2021 [72]
11.	<i>Aloe vera</i>	AgNPs	A549	Apoptotic morphology, ROS generation	Nida et al., 2022[73]
12.	<i>Phyllanthus emblica</i>	AuNPs	A549	Mitochondrial membrane disruption	Akkulanna et al., 2024 [74]
13.	<i>Justicia adhatoda</i>	CuNPs	A549	Cell apoptosis, cell shrinkage	Present study
14.	<i>Zingiber officinale</i>	ZnO NPs	A549	Cell cycle arrest, apoptosis	Premanathan et al., 2011 [75]
15.	<i>Curcuma longa</i>	AuNPs	A549 and PC3 cell lines	Dose dependent	Mamta Sharma et al., 2020 [76]
16.	<i>Ocimum americanum</i>	Ag–CuO NCs	A-549	Oxidative DNA damage, membrane blebbing	DineshBabu Manikandan et al., 2023 [77]
17.	<i>Tridax procumbens</i>	AgNPs	A549	ROS generation, apoptosis	Rohini Pungle et al., 2022 [78]
18.	<i>Punica granatum</i>	AgNPs	A549	Dose-dependent cytotoxicity, apoptotic morphology	Ramesh et al., 2019 [79]
19.	<i>Musa paradisiaca</i>	AgNPs	A549	ROS-induced cell death	Kumar et al., 2020 [80]
20.	<i>Solanum nigrum</i>	AgNPs	A549	Caspase-3 activation, nuclear fragmentation	Vijilvani, et al., 2020 [81]

3.7.1. Cytomorphological assessment of CuNPs-treated cells

The effect of *Justicia adhatoda*-mediated CuNPs on the morphology of A549 lung carcinoma cells was systematically evaluated after 24 h of exposure at different concentrations. The cells were categorized into three groups: untreated control cells, IC₅₀-treated cells (60 µg/mL), and cells treated with the maximum concentration (120 µg/mL). Representative morphological changes are shown in Figure 11 a–c. Control cells exhibited a typical polygonal morphology with intact cell membranes, strong substrate adhesion, and uniform cytoplasmic distribution. Cells treated with the IC₅₀ concentration displayed early apoptotic features, including cell shrinkage, rounding, and partial detachment from the culture surface. In contrast, exposure to the highest CuNP concentration (120 µg/mL) resulted in pronounced cytotoxic effects, characterized by extensive cell death, membrane blebbing, and severe disruption of cellular architecture.



Figure 11: Cytotoxic effect of CuNPs treated cells A-549

i) Control cell ii) IC₅₀ (60 µg/mL) iii) 120 µg/mL

These morphological alterations are consistent with previously reported apoptotic responses in HepG2 liver carcinoma cells treated with *Eclipta prostrata*-mediated CuNPs [66]. A comparative evaluation of apoptosis induced by phytogetic metal nanoparticles in A549 cells is presented in Table 3. Similar cytomorphological changes have also been observed in plant-mediated CuNP studies involving lung cell lines [74-79].

4. Conclusion

Overall, this study establishes *J. adhatoda* as a medicinally valuable and sustainable bioresource for the green synthesis of copper nanoparticles (CuNPs) and introduces a versatile nanoplatform capable of addressing both environmental and therapeutic challenges. The developed synthesis route is innovative, eco-friendly, and cost-effective. The superior dual functionality of the CuNPs is attributed to their nanoscale dimensions, large specific surface area, and bioactive phytochemical capping, which collectively enhance both catalytic efficiency and anticancer activity. The successful integration of green synthesis with environmental remediation and biomedical applications represents a meaningful contribution to the advancement of sustainable nanotechnology and multifunctional nanomaterial research.

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Declaration of Competing Interest : The authors declare no conflict of interest.

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