

Eco-Friendly Fabrication of Metallic Nanoparticles via *Moullava spicata*: A Review on Therapeutic Potentials

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ABSTRACT

The growing concern over the environmental and biological hazards associated with conventional nanoparticle synthesis has led to the exploration of green nanotechnology. Biogenic synthesis using plant extracts offers a sustainable and non-toxic alternative, enabling the fabrication of metallic nanoparticles (MNPs) with significant biomedical potential. *Moullava spicata*, an underexplored medicinal plant, is rich in phytoconstituents such as flavonoids, tannins, and phenolic compounds, which serve as natural reducing and stabilizing agents in nanoparticle synthesis. This review presents a comprehensive overview of the phytochemistry of *Moullava spicata*, its role in the green synthesis of metallic nanoparticles, characterization methods, and their therapeutic applications particularly antimicrobial, antioxidant, anti-inflammatory, and anticancer properties. The review also highlights current challenges and future prospects for translating these nanoparticles into clinical and pharmaceutical applications.

Keywords: plant-mediated synthesis, green nanoparticles, metallic nanoparticles, phytochemicals, therapeutic activity, antimicrobial, antioxidant, anti-inflammatory, and anticancer

1. INTRODUCTION

Nanotechnology has become a transformative force in modern science and medicine, revolutionizing the way we approach diagnostics, therapeutics, and targeted drug delivery [1]. Among various nanomaterials, metallic nanoparticles (MNPs) such as silver (AgNPs), gold (AuNPs), zinc oxide (ZnONPs), and copper (CuNPs) have garnered significant attention due to their unique physical, chemical, and biological properties. These nanoparticles exhibit high surface area-to-volume ratios, tunable optical properties, and enhanced reactivity, making them ideal candidates for applications in biosensing, antimicrobial agents, cancer therapeutics, and gene delivery [2,3,4,5]. Conventional methods for synthesizing MNPs generally fall into two categories: physical and chemical methods [6]. Physical methods, such as laser ablation and evaporation-condensation, require expensive equipment and significant energy input. Chemical methods, including reduction with sodium borohydride or hydrazine, involve the use of hazardous chemicals, organic solvents, and surfactants [7]. These approaches not only raise concerns about environmental contamination and toxicity but also limit the biocompatibility and clinical translation of the resulting nanoparticles.

To overcome these challenges, researchers have turned toward green nanotechnology an emerging field that emphasizes the use of environmentally benign methods for nanoparticle synthesis. Among green approaches, plant-mediated synthesis, also known as biogenic or phytochemical synthesis [9], has shown great promise. This method utilizes plant extracts rich in secondary metabolites as natural reducing, stabilizing, and capping agents, eliminating the need for toxic reagents. It is cost-effective, energy-efficient, scalable, and aligned with the principles of green chemistry [10]. One such promising but underexplored plant species is *Moullava spicata*, a robust climbing shrub belonging to the Fabaceae family. Commonly found in parts of India, especially in the Western Ghats, *M. spicata* is traditionally known for its medicinal value [11]. Different parts of the plant leaves, flowers, seeds, and roots shown in fig. 1 are used in traditional practices for treating inflammation, skin disorders,

wounds, and microbial infections [12]. The therapeutic properties of *Moullava spicata* are attributed to its diverse phytochemical composition, including flavonoids, alkaloids, phenolic acids, tannins, saponins, and glycosides [13]. These phytochemicals not only provide therapeutic effects but also exhibit strong reducing and chelating abilities, which are critical for nanoparticle synthesis. In biogenic synthesis [14], these compounds donate electrons to metal ions (e.g., Ag^+ , Au^{3+} , Zn^{2+}), reducing them to their elemental state and subsequently capping the nanoparticles to enhance their stability and dispersion. The process is simple, does not require external reducing agents, and often occurs under ambient conditions. Biogenically synthesized nanoparticles using *Moullava spicata* extract are of particular interest due to the dual functionality imparted by the plant's inherent bioactivity and the nano-scale properties of the particles [15,16,17]. Studies have suggested that such nanoparticles may exhibit enhanced antimicrobial, antioxidant, anti-inflammatory, and anticancer properties compared to chemically synthesized counterparts. For instance, silver nanoparticles derived from *M. spicata* may be more effective against pathogenic bacteria due to synergistic effects between the metal core and surface-bound phytochemicals.

Despite its potential, the use of *Moullava spicata* in green nanotechnology remains relatively unexplored in comparison to other well-studied medicinal plants. Systematic reviews and comprehensive evaluations are lacking, which limits the understanding and broader application of this plant in nanoparticle synthesis and biomedical research [20]. Additionally, optimization of synthesis parameters, detailed characterization of nanoparticles, mechanistic studies, and in vivo therapeutic evaluations are needed to validate and standardize its use for pharmaceutical applications. This review article aims to bridge that gap by providing a detailed overview of the biogenic synthesis of metallic nanoparticles using *Moullava spicata*, highlighting their physicochemical properties and therapeutic potentials. Furthermore, it outlines the current challenges and future perspectives in harnessing this plant-based nanotechnology for sustainable and impactful medical innovations.

2. PLANT PROFILE

Moullava spicata is a thorny climbing shrub belonging to the Fabaceae family [21], endemic to the Western Ghats of India. Traditionally used in folk medicine, the plant is known for its therapeutic properties attributed to a wide array of bioactive phytochemicals shown in table no. 1. Its rich content of flavonoids, phenolics, and alkaloids makes it a valuable candidate for green synthesis of metallic nanoparticles. The following table summarizes key botanical features, phytochemical constituents, and pharmacological potential of *Moullava spicata*.

Table 1: Taxonomical Classification and Phytoconstituents of *Moullava spicata*.

Parameter	Details	References
Scientific Name	<i>Moullava spicata</i> (Dalzell)	[21-22]
Synonyms	<i>Caesalpinia spicata</i>	[23-24]
Family	Fabaceae (Leguminosae)	[21-22]
Common Names	Waghati, Wakeri (Marathi), Kattukaranja (in Kannada), Spicate Moullava (English)	[23-24]
Plant Type	Robust woody, scandent shrubs; branches armed with numerous recurved prickles. Pinnae 4-6 pairs; leaflets ovate-elliptic, 5-7 pairs. Flowers nearly sessile, in dense spicate racemes. Petals orange-yellow. Pods torulose with thickened sutures. Seeds 3-4, brown, polished.	[25]
Habitat	Found in Western Ghats of India, especially in Maharashtra (Ajara, Bambavade, Borbet, Barki, Chandagad, Jotiba, Nivale, Panhala), Karnataka, and Kerala	[26]
Distribution	Endemic to India; primarily grows in tropical and subtropical forest regions	[23]
Morphology	- Leaves: Bipinnate, alternate, compound with small leaflets - Flowers: Bright yellow with orange-red markings, arranged in dense spikes - Fruits: Oblong pods with multiple seeds - Stems: Thorny and twining nature	[22]
Phytochemical	Rich in flavonoids (quercetin, kaempferol), phenolics, tannins,	[27]

Constituents	alkaloids, saponins, terpenoids, glycosides	
Traditional Uses	Used in Ayurvedic and folk medicine for treating inflammation, fever, wounds, and microbial infections	[27]
Pharmacological Properties	Antimicrobial, antioxidant, anti-inflammatory, hepatoprotective, anticancer potential	[28]
Part Used for Extract	Primarily leaves, bark, stems, and pods	[29]
Relevance in Nanotechnology	A promising bioresource for green synthesis of metallic nanoparticles due to its rich phytochemical content	[28-29]



A

B



CD E

Note: Figure 1 illustrates various parts of the *Moullava spicata* plant — (A) Whole plant, (B) Bark, (C) Flowers, (D) Pods, and (E) Seed.

3. METHODOLOGY

This review was conducted by systematically retrieving and analyzing scientific literature related to the green synthesis of metallic nanoparticles using *Moullava spicata* and their therapeutic applications. A comprehensive search was carried out across databases such as PubMed, ScienceDirect, SpringerLink, Scopus, and Google Scholar, using relevant keywords including *Moullava spicata*, plant-mediated synthesis, green nanoparticles, metallic nanoparticles, phytochemicals, therapeutic activity, antimicrobial, antioxidant, anti-inflammatory, and anticancer. Articles published in English between 2005 to 2024 were considered. Inclusion criteria involved peer-reviewed research and review articles focusing on the biosynthesis, characterization, and biological evaluation of nanoparticles derived from *Moullava spicata* or similar plant systems. Excluded were non-peer-reviewed publications, editorials, and papers lacking sufficient experimental data. Relevant information on synthesis mechanisms, phytochemical constituents, characterization techniques, and biological properties was extracted, validated, and synthesized into comparative tables and analytical summaries to provide an integrated understanding of the plant's potential in nanomedicine. Only scientifically credible and reproducible studies were included to ensure accuracy and quality of this review.

4. PHYTOCHEMICAL PROFILE OF MOULLAVA SPICATA

Moullava spicata, a plant native to India and traditionally used in various herbal remedies, is a reservoir of phytochemicals

mentioned in table no 2, with significant pharmacological and biotechnological relevance. Recent phytochemical investigations reveal the presence of numerous secondary metabolites, including flavonoids, phenolics, alkaloids, terpenoids, saponins, and glycosides [30]. These constituents not only impart therapeutic properties but also serve as natural reducing and stabilizing agents in the biogenic synthesis of metallic nanoparticles. Flavonoids such as quercetin and kaempferol are abundant in *M. spicata*. These compounds exhibit strong antioxidant activity by scavenging free radicals and preventing oxidative stress [31]. They also possess anticancer properties by modulating key signaling pathways involved in cell proliferation and apoptosis [32]. In nanoparticle synthesis, flavonoids act as electron donors, reducing metal ions to elemental forms and contributing to nanoparticle stability through capping [33]. Phenolic compounds and tannins are key contributors to the plant's antioxidant and antimicrobial effects [34]. Their polyhydroxy structures facilitate strong metal-chelating activity, making them excellent candidates for the green synthesis of nanoparticles [36]. Phenolics help control particle size and prevent aggregation through effective surface binding. Alkaloids and terpenoids, also present in the extract, provide antimicrobial, anti-inflammatory, and analgesic benefits. These compounds are known to interfere with bacterial cell membranes and inflammatory mediators [37]. In nanoparticle synthesis, they serve as both reducing and capping agents, enhancing the biological functionality of the synthesized nanomaterials. Saponins and glycosides improve nanoparticle dispersity and biocompatibility. They contribute to the colloidal stability of nanoparticles by preventing clumping, while also adding to the bioactive potential, particularly in immunomodulatory and cytotoxic applications [38].

The dual functionality of these phytochemicals as bioreducing agents for nanoparticle synthesis and as bioactive agents in therapeutic contexts highlights the holistic value of *Moullava spicata* in nanomedicine. Their involvement ensures the eco-friendly formation of nanoparticles with embedded therapeutic properties, making the plant an ideal candidate for green nanotechnology.

Table 2: Major Phytochemicals in *Moullava spicata* and Their Roles

Phytochemical Class	Examples	Therapeutic Role	Function in Nanoparticle Synthesis	References
Flavonoids	Quercetin, Kaempferol	Antioxidant, anticancer	Reducing agent, nanoparticle stabilizer	[30-31]
Phenolics & Tannins	Gallic acid, Catechins	Antioxidant, antimicrobial	Metal ion reduction, capping agent	[35]
Alkaloids	-	Antimicrobial, anti-inflammatory	Reducing agent, enhances bioactivity	[36]
Terpenoids	Monoterpenes, Diterpenes	Antimicrobial, anti-inflammatory	Stabilization, bioactive enhancer	[37]
Saponins & Glycosides	Saponin derivatives	Immunomodulatory, cytotoxic	Improves dispersion and biocompatibility	[38]

5. GREEN SYNTHESIS OF METALLIC NANOPARTICLES USING *MOULLAVA SPICATA*

5.1 Mechanism of Synthesis:

The green synthesis of metallic nanoparticles using *Moullava spicata* is primarily governed by the redox capabilities of its phytochemical constituents [40]. The process involves the transformation of metal ions (such as Ag^+ , Au^{3+} , or Zn^{2+}) from precursor salts like silver nitrate (AgNO_3), chloroauric acid (HAuCl_4), or zinc sulfate (ZnSO_4) into stable, nanoscale metallic particles. This transformation is mediated by plant-derived biomolecules that act as both reducing and capping agents. Phytochemicals such as flavonoids, phenolics, tannins, alkaloids, and terpenoids possess functional groups like hydroxyl ($-\text{OH}$), carboxyl ($-\text{COOH}$), and amine ($-\text{NH}_2$), which play a critical role in nanoparticle synthesis. These functional groups donate electrons to the metal ions, reducing them to their zero-valent metallic state. This reduction initiates the nucleation phase, where small clusters of metal atoms are formed [41].

Following nucleation, these metal clusters undergo growth through aggregation or coalescence, leading to the formation of nanoparticles [42]. Simultaneously, the same phytochemicals (or their oxidation products) adsorb onto the nanoparticle surface, acting as capping agents that prevent agglomeration and ensure colloidal stability. The capping also imparts biological functionality to the nanoparticles, improving their therapeutic potential. This green synthesis pathway is favored over conventional methods due to its simplicity, low energy requirement, and environmental sustainability. It enables the

production of monodispersed, size-controlled nanoparticles under ambient conditions without toxic by-products, making it a valuable approach for biomedical and pharmaceutical applications [43].

5.2 Synthesis Parameters:

The successful green synthesis of metallic nanoparticles using *Moullava spicata* extract depends heavily on a variety of experimental parameters. Each parameter influences the physicochemical characteristics of the resulting nanoparticles, including size, shape, dispersity, surface charge, and stability factors critical to their biological performance [45]. Temperature and pH are key determinants of reaction kinetics and nanoparticle morphology [46, 47]. Elevated temperatures typically accelerate the reduction of metal ions, resulting in faster nucleation and smaller particle sizes. However, excessively high temperatures may lead to uncontrolled growth and polydispersity. Similarly, the pH of the reaction mixture affects the ionization state of phytochemicals [48]. Alkaline conditions often enhance the reducing power of phenolics and flavonoids, promoting smaller and more uniform nanoparticles, whereas acidic pH may reduce stability due to protonation of functional groups. Extract concentration plays a dual role in nanoparticle formation. Higher concentrations of plant extract provide more reducing and capping agents, which can favor rapid nucleation and prevent agglomeration. However, overly high extract levels can lead to excessive capping, which may hinder growth and alter surface functionality. Optimal extract-to-metal ratios must be carefully standardized [49, 50].

Metal precursor concentration determines the availability of metal ions for reduction. Low concentrations may result in incomplete nanoparticle formation, while high concentrations can lead to larger particles or irregular shapes due to secondary nucleation or particle aggregation [51]. Reaction time influences the completion of the reduction process and the stability of nanoparticles. Prolonged reactions may lead to further growth or secondary aggregation unless effectively capped. Optimizing these parameters ensures reproducible, monodispersed, and biofunctional nanoparticles suitable for therapeutic applications.

6. CHARACTERIZATION OF SYNTHESIZED NANOPARTICLES

Characterization of metallic nanoparticles synthesized via *M. spicata* extract is essential to confirm their formation, assess their physicochemical properties shown with observation in table no. 3, and understand their biomedical relevance. A combination of spectroscopic, microscopic, and analytical techniques is typically employed to evaluate size, shape, surface chemistry, and crystalline structure [52]. UV-Visible Spectroscopy (UV-Vis) is one of the earliest and most rapid tools for confirming nanoparticle formation [53]. Metallic nanoparticles, especially silver and gold, exhibit characteristic surface plasmon resonance (SPR) bands in the visible range (e.g., 400–450 nm for AgNPs). Changes in absorbance intensity and peak position can indicate particle size, shape, and dispersion [54].

Fourier Transform Infrared Spectroscopy (FTIR) is used to identify functional groups from phytochemicals involved in reduction and capping [55]. Peaks corresponding to hydroxyl (–OH), carbonyl (C=O), and amine (–NH) groups confirm their role in nanoparticle stabilization [56]. X-Ray Diffraction (XRD) provides insight into the crystalline nature of the nanoparticles [57]. Distinct diffraction peaks matching standard JCPDS data indicate the face-centered cubic (fcc) structure typical of metals like silver and gold [58]. Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) offer direct visualization of nanoparticle morphology and size distribution [59]. TEM, in particular, can reveal particle uniformity and lattice fringes, confirming crystallinity at the nanoscale [60]. Dynamic Light Scattering (DLS) assesses hydrodynamic diameter and polydispersity index (PDI) [61, 62], while Zeta Potential measurement evaluates surface charge, which is indicative of colloidal stability [63–66].

Table 3: Characterization Techniques for *Moullava spicata*-Mediated Metallic Nanoparticles

Technique	Purpose	Key Observations/Outcomes	References
UV-Visible Spectroscopy (UV-Vis)	Confirms nanoparticle formation via Surface Plasmon Resonance (SPR)	SPR peaks (e.g., 400–450 nm for AgNPs); peak intensity and position indicate size, shape	[52–54]
FTIR (Fourier Transform Infrared)	Identifies functional groups involved in reduction and capping	Peaks for –OH, C=O, –NH ₂ groups confirm involvement in nanoparticle stabilization	[55–56]
XRD (X-ray Diffraction)	Assesses crystalline structure and phase purity	Sharp diffraction peaks match face-centered cubic (fcc) patterns typical for metallic NPs	[57–58]
SEM/TEM (Electron)	Visualizes morphology, shape,	SEM shows surface texture; TEM reveals particle size, shape, and lattice	[59–60]

Microscopy)	and size distribution	fringes	
DLS (Dynamic Light Scattering)	Measures hydrodynamic diameter and polydispersity	Provides average nanoparticle size in colloidal solution and size distribution	[61-62]
Zeta Potential	Evaluates surface charge and colloidal stability	High zeta potential (± 30 mV or more) indicates good nanoparticle stability	[63]

7. THERAPEUTIC APPLICATIONS OF MOULLAVA SPICATA-MEDIATED NANOPARTICLES:

7.1 Antimicrobial Activity:

The table 4 emergence of multidrug-resistant microbial strains has intensified the need for alternative antimicrobial agents, with metallic nanoparticles (MNPs) synthesized via green methods offering a promising solution. Among these, silver (AgNPs) and zinc (ZnONPs) nanoparticles synthesized using *M. spicata* extract have demonstrated potent antimicrobial activity against a range of pathogenic microorganisms, including *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans* [67, 68, 69]. The phytochemicals present in *M. spicata*, such as flavonoids, phenolics, and terpenoids, not only facilitate the bioreduction and stabilization of nanoparticles but also enhance their intrinsic antimicrobial properties. The antimicrobial mechanism of these biogenic nanoparticles involves multiple pathways. One of the primary actions is membrane disruption, where nanoparticles attach to the microbial cell wall, alter its permeability, and lead to leakage of cellular contents. Additionally, the generation of reactive oxygen species (ROS) induces oxidative stress within microbial cells, damaging essential biomolecules like DNA, proteins, and lipids. Silver ions released from AgNPs further interfere with enzyme function and metabolic pathways. ZnONPs contribute through their photocatalytic ROS generation and ability to destabilize microbial membranes. Studies have reported dose-dependent inhibitory zones and minimum inhibitory concentrations (MICs) comparable to conventional antibiotics. Moreover, the nanoscale size and high surface-to-volume ratio of the particles facilitate effective interaction with microbial cells, even at low concentrations. These findings indicate that *Moullava spicata*-mediated MNPs are promising antimicrobial agents with potential applications in wound healing formulations, antimicrobial coatings, and drug delivery systems.

Table 4: Antimicrobial Activity of Moullava spicata-Mediated Nanoparticles

Organisms Targeted	Nanoparticles Used	Mechanism of Action	Reference
<i>E. coli</i> , <i>S. aureus</i> , <i>Candida albicans</i>	AgNPs, ZnO NPs	Membrane disruption, ROS generation, protein denaturation	[68-70]
<i>P. aeruginosa</i> , <i>B. subtilis</i>	AgNPs	DNA damage and inhibition of respiratory enzymes	[71]

7.2 Antioxidant Activity:

The antioxidant potential of metallic nanoparticles synthesized using *Moullava spicata* extract has been widely studied through radical scavenging assays such as DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid). These assays are effective for evaluating the ability of nanoparticles to neutralize free radicals, which are implicated in oxidative stress-related cellular damage. The high antioxidant activity of these green-synthesized nanoparticles is primarily attributed to the presence of surface-bound phytochemicals like flavonoids, phenolics, and tannins from the *Moullava spicata* extract. During the synthesis process, these bioactive compounds not only reduce metal ions but also cap the nanoparticle surfaces, thereby retaining their functional groups. These groups contribute directly to free radical scavenging by donating hydrogen atoms or electrons, stabilizing unpaired electrons in reactive species. As a result, the nanoparticles exhibit potent antioxidant behavior, significantly reducing the absorbance of DPPH and ABTS radicals in spectrophotometric assays.

This antioxidant capability is crucial in therapeutic applications, as oxidative stress is a key contributor to chronic diseases such as cancer, cardiovascular disorders, and neurodegeneration. Hence, *Moullava spicata*-mediated nanoparticles hold promise as antioxidant agents in drug delivery, wound healing, and anti-aging formulations.

Table 5: Antioxidant Activity of *Moullava spicata*-Mediated Nanoparticles

Assays Used	Observed Effects	Role of Phytochemicals	Reference
DPPH Radical Scavenging	High radical scavenging (up to 80–90% inhibition)	Quercetin, kaempferol capping enhances antioxidant activity	[72, 73]
ABTS Assay	Strong inhibition of ABTS radicals	Flavonoid-coated NPs scavenge ROS in vitro	[74]
FRAP and reducing power	Elevated electron transfer activity	Phenolics and tannins enhance reducing power	[75]

7.3 Anti-inflammatory Effects:

Metallic nanoparticles synthesized using *Moullava spicata* extract have shown significant anti-inflammatory effects in both in vitro and in vivo models [76]. This therapeutic activity is primarily due to the presence of phytochemicals such as flavonoids, saponins, and terpenoids, which are known for their immunomodulatory properties. When these bioactive compounds cap and stabilize the nanoparticles during the green synthesis process, they retain their functional potential, enhancing the overall biological efficacy of the nanoparticles. These green-synthesized nanoparticles exert their anti-inflammatory effect by modulating key pro-inflammatory mediators and pathways. Notably, they have been observed to downregulate the expression of cytokines such as Tumor Necrosis Factor-alpha (TNF- α) [77], Interleukin-6 (IL-6), and the cyclooxygenase-2 (COX-2) enzyme [78]. These mediators play a crucial role in the initiation and propagation of the inflammatory response. By suppressing their expression, the nanoparticles help reduce tissue damage, swelling, and pain associated with inflammation.

The mechanism is often linked to the inhibition of nuclear factor-kappa B (NF- κ B) and mitogen-activated protein kinase (MAPK) pathways, which are central to inflammatory signal transduction. Experimental studies using cell lines and animal models of inflammation have shown reduced edema, leukocyte infiltration, and oxidative stress upon treatment with these nanoparticles [79]. Such findings highlight the promise of *Moullava spicata*-mediated nanoparticles as safe, plant-based alternatives to synthetic anti-inflammatory drugs, with potential applications in treating chronic inflammatory diseases.

7.4 Anticancer Potential:

Metallic nanoparticles synthesized via *Moullava spicata* extract have demonstrated considerable anticancer potential, particularly silver (AgNPs) and gold nanoparticles (AuNPs). These nanoparticles exhibit potent cytotoxic activity against a variety of human cancer cell lines, including breast, lung, liver, and colon cancers [80,81]. The anticancer mechanisms are largely attributed to the synergistic effect of the metal core and the bioactive phytochemicals capping the nanoparticles. A key anticancer mechanism involves the induction of apoptosis, or programmed cell death. The nanoparticles penetrate cancer cell membranes and localize within the cytoplasm and mitochondria, where they disrupt the mitochondrial membrane potential [82]. This disruption leads to the release of cytochrome c and activation of caspases critical steps in the apoptotic cascade. Additionally, the nanoparticles elevate reactive oxygen species (ROS) levels within cancer cells, triggering oxidative stress that damages cellular components like DNA, proteins, and lipids, ultimately leading to cell death [83]. The selectivity of these nanoparticles towards cancer cells is also notable, as they often exhibit lower toxicity toward normal cells. This selective cytotoxicity may be due to the higher metabolic rate and weaker antioxidant defense in cancer cells, making them more susceptible to oxidative stress.

Table 6: Cytotoxic and Apoptotic Effects of *Moullava spicata*-Derived Metallic Nanoparticles Against Cancer Cells

Cancer Cell Line	Nanoparticles Used	Mechanism of Cytotoxicity	Reference
MCF-7 (breast cancer)	AgNPs, AuNPs	Apoptosis induction, mitochondrial disruption, caspase activation	[84-85]
A549 (lung carcinoma)	AgNPs	ROS generation, DNA fragmentation	[86-87]
HeLa (cervical cancer)	AuNPs	Cell cycle arrest, oxidative stress	[88-89]

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8. FUTURE PERSPECTIVES:

The green synthesis of metallic nanoparticles (MNPs) using *Moullava spicata* represents a promising frontier in sustainable nanomedicine. However, several critical challenges remain before these bioengineered nanoparticles can be transitioned from bench to bedside. Addressing these gaps will be essential for optimizing their biomedical utility, regulatory approval, and commercial viability. A primary consideration is the standardization of plant extract composition and synthesis protocols. *Moullava spicata*, like many medicinal plants, contains a complex and variable array of phytochemicals depending on factors such as geographic origin, harvesting season, extraction method, and plant part used. These variations can significantly influence the size, shape, and stability of synthesized nanoparticles. Establishing standardized protocols for extract preparation including solvent choice, concentration, and temperature along with optimized synthesis parameters such as pH, metal ion concentration, and reaction time, will help ensure reproducibility and batch-to-batch consistency. Incorporating chemometric tools and metabolomic profiling may further aid in correlating specific phytochemicals with synthesis efficiency and nanoparticle properties.

Toxicity assessment remains another pressing issue. While many in vitro studies have reported biocompatibility and bioactivity of green-synthesized nanoparticles, comprehensive in vivo evaluations are still limited. Understanding the biodistribution, metabolism, immunogenicity, and long-term toxicity of *Moullava spicata*-mediated MNPs is vital for clinical translation. Rigorous preclinical testing using animal models followed by controlled clinical trials will be required to establish safety profiles and therapeutic indices. Such studies should also investigate potential cytotoxicity to normal tissues and assess organ-specific accumulation of nanoparticles. Another area for advancement lies in mechanistic studies to elucidate the molecular pathways modulated by these nanoparticles. While several biological effects—such as antimicrobial, antioxidant, anti-inflammatory, and anticancer activities have been reported, the underlying mechanisms remain poorly understood. Omics-based approaches, including transcriptomics, proteomics, and metabolomics, could be utilized to identify cellular targets and signaling cascades influenced by nanoparticle treatment. Additionally, studying the interaction between surface-bound phytochemicals and cellular receptors may reveal synergistic or novel modes of action.

The final step toward real-world application involves scalability and formulation into drug delivery systems. The green synthesis process must be adapted for large-scale production without compromising nanoparticle quality. Approaches such as bioreactor-based synthesis or lyophilized extract formulations could enhance yield and stability. Furthermore, integrating these nanoparticles into targeted delivery platforms such as liposomes, hydrogels, or polymeric carriers could enhance bioavailability, site-specific delivery, and therapeutic efficacy. Their surface functionalization with ligands, antibodies, or aptamers may also enable active targeting of specific disease sites such as tumors or inflamed tissues. Future research should integrate computational modeling, targeted delivery systems, and clinical collaborations to realize the translational potential of these nanoparticles.

9. CONCLUSION

Biogenic synthesis of metallic nanoparticles using *Moullava spicata* offers a green, sustainable, and efficient route for developing next-generation therapeutic agents. The plant's rich phytochemical profile including flavonoids, phenolics, and saponins not only facilitates nanoparticle formation but also imparts significant biological activities such as antimicrobial, antioxidant, anti-inflammatory, and anticancer effects. These green-synthesized nanoparticles exhibit enhanced bioavailability, reduced toxicity, and targeted action, making them highly suitable for diverse biomedical applications. Furthermore, the environmentally friendly synthesis process aligns with the principles of green chemistry, reducing dependence on hazardous reagents and high-energy methods. However, despite promising in vitro and in vivo results, extensive pharmacological validation, toxicity profiling, and mechanistic studies are crucial for translating these nanomaterials into clinical settings. Standardization of extraction and synthesis protocols, along with scalability assessments, will also be vital. With further research and regulatory support, *Moullava spicata*-mediated nanoparticles could emerge as valuable tools in modern pharmaceutical and therapeutic development.

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