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SYNTHESIS OF SILVER NANOPARTICLES: A PLANT EXTRACTS MEDIATED ECOFRIENDLY APPROACH

Review Article

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ABSTRACT

Background: Silver nanoparticles (AgNPs) have emerged as one of the most widely explored nanomaterials owing to their distinctive optical, chemical, and morphological properties. Their high stability, tunable surface characteristics, and broad-spectrum biological activities have positioned them as valuable tools in medicine, biosensing, imaging, and antimicrobial therapies. Recent advances in green nanotechnology, particularly plant-mediated synthesis, provide a cost-effective and eco-friendly alternative to conventional chemical approaches, minimizing toxicity and energy demands.

Objective: This review aims to highlight the therapeutic potential of plant-derived phytochemicals in the synthesis of silver nanoparticles and to emphasize the importance of optimizing reaction conditions for achieving desirable structural and functional properties.

Main Discussion Points: The review discusses general considerations of AgNP synthesis, including the influence of shape, size, and surface properties on biological activity. It outlines the role of various plant extracts as reducing and stabilizing agents, detailing how natural compounds such as flavonoids, tannins, and saponins enhance both synthesis and biomedical efficacy. Furthermore, the review examines spectrophotometric and morphological characterization techniques and evaluates how reaction influencers—such as pH, precursor concentration, incubation time, and temperature—directly affect yield, stability, and therapeutic potential.

Conclusion: Plant-mediated synthesis of AgNPs represents a promising frontier in nanomedicine, offering safe, sustainable, and versatile applications. However, standardization of protocols, mechanistic insights, and clinical validation are necessary to translate laboratory findings into reliable biomedical interventions.

Keywords: Silver nanoparticles, Green nanotechnology, Plant extracts, Nanomedicine, Reaction optimization, Characterization.

INTRODUCTION

Nanotechnology has emerged as one of the most transformative fields of modern science, offering unprecedented opportunities for advancements in medicine, industry, and environmental sustainability. The foundation of this concept can be traced back to Richard Feynman's visionary idea in 1959 of manipulating individual atoms and molecules to create new structures with tailored properties, an idea that later evolved into what is now termed "nanotechnology" (1). The term itself was introduced by Norio Taniguchi in the 1960s, while the invention of the scanning tunneling microscope in 1981 enabled researchers to visualize and manipulate atoms directly, laying the foundation for practical applications in nanoscience (1). Since then, nanotechnology has developed into a highly interdisciplinary domain, integrating physics, chemistry, biology, material science, and engineering to design nanoscale materials with unique physical and chemical properties (2). Nanoparticles, ranging in size from 1 to 100 nanometers, exhibit diverse morphologies such as spheres, rods, cubes, and complex architectures, which confer distinctive functional attributes (3). Their minute size not only facilitates deeper penetration into tissues but also enhances cellular uptake, making them promising candidates in drug delivery and antimicrobial therapies (4,5). Nanomedicine, in particular, has revolutionized therapeutic strategies by introducing drug carriers such as nanoparticles, liposomes, dendrimers, and solid lipid nanoparticles that provide targeted, sustained, and efficient delivery of drugs to specific sites in the body (6). This approach improves therapeutic efficacy, prolongs drug circulation time, and reduces the frequency of administration (6). Metal-based nanoparticles, particularly silver nanoparticles (AgNPs) and gold nanoparticles (AuNPs), have attracted considerable attention due to their catalytic, antimicrobial, and anticancer properties (7). Among these, AgNPs stand out because of their extensive physicochemical versatility and broad-spectrum biological activity, including antimicrobial effects against bacteria, fungi, and viruses through mechanisms such as membrane disruption, protein denaturation, DNA damage, and reactive oxygen species generation (8).

In recent years, increasing emphasis has been placed on environmentally sustainable approaches to nanotechnology. Traditional methods of nanoparticle synthesis often involve hazardous chemicals, raising concerns about toxicity and ecological impact. In contrast, green nanotechnology has emerged as a safer and eco-friendly alternative, utilizing biological systems such as plants, fungi, algae, and bacteria for nanoparticle production (9,10). Plants, in particular, are rich sources of natural bioactive compounds including polysaccharides, phenolics, flavonoids, and alkaloids, which can act as reducing and stabilizing agents in the biosynthesis of nanoparticles (11). Plant-mediated synthesis of AgNPs is regarded as cost-effective, reliable, non-toxic, and sustainable, eliminating the need for external stabilizers and often requiring only mild conditions such as ambient temperature (12,13). Additionally, the vast availability of plant-based biomass, much of it originating from agricultural and food waste, presents an abundant and underutilized resource for nanoparticle synthesis (14). Such approaches not only reduce environmental waste but also contribute to the development of therapeutic agents with minimal ecological footprint. Given the rising global population, increasing biomedical demands, and mounting environmental challenges, the importance of safe, sustainable, and economically viable nanotechnological methods cannot be overstated. Green synthesis of nanoparticles represents a convergence of modern science and natural resources, providing innovative solutions for healthcare and environmental sustainability (15,16). Despite its promise, there remain gaps in understanding the optimization of biosynthetic pathways, the standardization of plant-based methods, and the long-term biomedical implications of such nanoparticles. Therefore, the present research is directed toward exploring plant-mediated synthesis of silver nanoparticles as an eco-friendly and efficient alternative to conventional chemical methods. The objective is to assess their biomedical potential, particularly in drug delivery and antimicrobial therapies, while highlighting their role in sustainable nanotechnology development.

THEMATIC DISCUSSION

General Considerations for Silver Nanoparticles

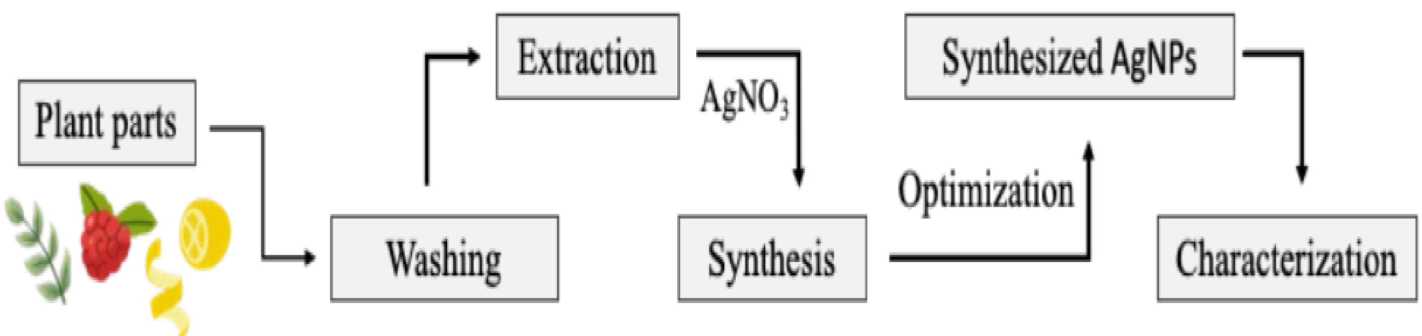
Silver nanoparticles (AgNPs) continue to attract significant attention due to their high surface-to-volume ratio and versatile properties that bridge atomic-scale phenomena with practical applications. Studies highlight that, key colloidal characteristics—such as color, stability, reduction potential, and optical behavior—are inherently tied to nanoparticle size and morphology (10). The shape and size govern surface plasmon resonance (SPR), which in turn affects functionality in antimicrobial, catalytic, and diagnostic contexts (11). Central synthesis factors include reaction kinetics, ion–reducing agent interactions, and the nature of stabilizing agents, which collectively influence nucleation and growth drives toward specific geometries (12). Chronologically, early green biosynthesis methods laid the groundwork, while recent research has focused on dissecting how synthesis parameters such as temperature, pH, extract concentration, and reduction potential can fine-tune AgNP properties (12,13).

Plant Extracts as Bulk Therapeutic Material for AgNPs Synthesis

Plant extracts serve as both reducing and capping agents in an eco-friendly and biocompatible fashion. A 2023 study using neem (Azadirachta indica) leaf extract demonstrated that plant phytochemicals such as polyphenols and flavonoids can effectively reduce Ag^+ to elemental silver while simultaneously stabilizing the nanoparticles (14). In a similar vein, the synthesis of AgNPs using Anzaroot (Anzaroot plant) aqueous extract exhibited well-defined SPR peaks at ~443 nm and an average particle size of 16 nm. Those nanoparticles displayed dose-dependent cytotoxicity against MCF-7 breast cancer cells, pointing to enhanced medicinal potential (15). Other plant-mediated syntheses likewise show antimicrobial promise; for instance, Hippophae rhamnoides berry extract–derived AgNPs yielded SPR around 450 nm and confirmed antioxidant and antimicrobial effects (16). These findings underscore the dual roles of plant extracts—not only as safe and abundant materials, but also as functionally enhancing agents for biomedical applications.

Plant-based Synthesis of AgNPs

Recent literature highlights the scalability and simplicity of plant-based AgNP synthesis. A study presents a comprehensive review of plant-mediated synthesis methods and key influencing factors (such as phytochemical profiles and extract types) that determine nanoparticle morphology and stability (17). A detailed methodological study with Curcuma longa flower extract demonstrated that uniform, homogenous, ~5 nm spherical AgNPs could be obtained, with potent antibacterial activity across several pathogens and defined minimum inhibitory concentrations (MICs) (18). These confirm that plant-based systems enable reproducible, controlled production while imparting functional benefits often absent in purely chemical methods.



Morphological and Spectrophotometric Characterization

Characterizing AgNPs is essential to establish correlations between structure and function. A study employed UV-Vis, TEM, XRD, and FT-IR to characterize Anzaroot-derived AgNPs, finding an SPR peak at 443 nm, a crystalline face-centered-cubic structure, and a ~16 nm mean size (19). Assessment of synthesis time-dependent absorbance (UV-Vis) in other studies revealed peak shifts, such as a strong maximum at 448 nm after 90 minutes, linking reaction kinetics to nanoparticle size (20). Collectively, these methods—including UV-Vis to track SPR, TEM or SEM for size and shape, XRD for crystallinity—enable quantitative mapping between synthesis conditions and morphological outcomes (21,22).

Optimization of Reaction Influencers

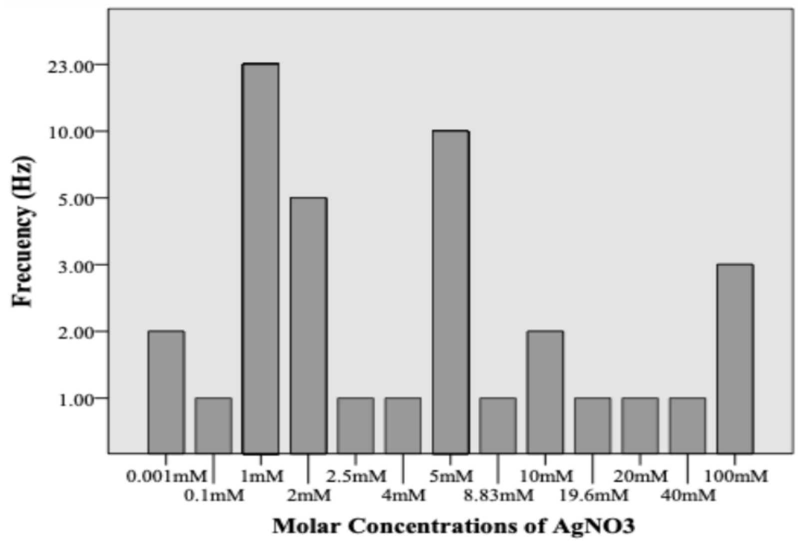
Optimizing synthesis conditions remains vital to control yield, size distribution, and stability. A study varied extract volume, $AgNO_3$ concentration, reaction time, and pH—finding optimized synthesis at 4 ml extract, 1–5 mM $AgNO_3$, pH 8-, and 300-min reaction time, producing well-defined AgNPs with anticancer activity (23). Another study reported that temperatures in the 60–80 °C range accelerated synthesis and yielded smaller-sized nanoparticles with blue-shifted SPR, indicating fine morphological tuning through thermal control (24). Collectively, these studies demonstrate that optimal pH (generally neutral to slightly basic), controlled precursor concentration (to avoid oversaturation), and moderate heating—balanced with sufficient reaction time—are crucial for monodispersity and desired morphology.

Despite extensive progress, inconsistency remains across plant species, extract preparation, and synthesis conditions, making cross-study comparisons difficult. Few studies systematically dissect the mechanistic roles of individual phytochemicals, leading to gaps in standardization (25). Moreover, long-term stability, in vivo biodistribution, and potential toxicity of plant-derived AgNPs remain underexplored—highlighting the need for standardized methodologies and in-depth biomedical assessments. Therefore, this thematic review aims to synthesize recent (last five years) evidence on plant-mediated silver nanoparticle synthesis, focusing on how general physicochemical considerations, phytochemical contributions, synthetic methodologies, characterization approaches, and reaction optimizations interact to define nanoparticle properties. It seeks to clarify mechanistic underpinnings, identify standardization gaps, and guide future research toward reproducible, safe, and efficacious nanomedicine applications.

Table 1: Various plant parts used in AgNPs synthesis along with their spectrophotometric and magnified imagining properties.

Plants	Extract	Absorption peak	Particle size distribution	Particle Morphology	References
Thymus vulgaris	Whole plant	400nm	44-62nm	Spherical	(Ejaz et al., 2024)
Parthenium	Leaves	474nm	30-80nm	Irregular	(PARASHAR et al., 2009)
Moringa oleifera	Leaves	419nm	10-25nm	Spherical	(Asif et al., 2022)
Rhopalomyia capitata	Leaves	400nm	2-60nm	Spherical	(Zahoor et al., 2023)
Mangifera indica	Leaves	448nm	50-75nm	Spherical	(Raza et al., 2023)
Melia azedarach	Leaves	434nm	12-46nm	Spherical	(Ashraf et al., 2020)
Azadirachta indica	Leaves	406nm	20-50nm	Triangular and cuboidal	(Asimuddin et al., 2020)
Musa balbisiana, Azadirachta indica, Ocimum tenuiflorum	Leaves	425-475nm at various dilutions	------	Triangular and cuboidal	(Banerjee et al., 2014)
Cycas circinalis, Ficus amplissima, Commelina benghalensis and Phyla Nodiflora L.	Leaves	423-452nm at various dilutions	13-51nm	Spherical	(Johnson and Prabu, 2015)
Azadirachta indica	Leaves	350-365nm at various dilutions	<10-40nm	Triangular and Irregular	(Tahir et al., 2011)
Ficus palmata	Leaves	1st reaction 451nm 2nd reaction 457nm	28-33nm	Semi-irregular	(Nasar et al., 2017)
Ziziphus joazeiro	Leaves	400nm	5-50nm	Spherical	(Guimarães et al., 2020)
Citrullus colocynthis	Fruit pieces	420nm	17-40nm	Spherical	(Rasool et al., 2022)
Annona squamosa	Fruit and Leaves	Fruit: 410nm Leaf: 430nm	Fruit: 15-50nm Leaf: 35-90nm	Spherical	(Malik et al., 2022)
Azadirachta indica	Leaves	412-416nm	12-24nm	Spherical	(Rasool et al., 2020)
Citrullus colocynthis	Fruit	416-431nm	20-36nm	Spherical	
Megaphrynium macrostachyum	Leaves	400-450nm	------	-----	(Meva et al., 2016)
Hagenia abyssinica	Leaves	430nm	-----	-----	(Melkamu and Bitew, 2021)
Smyrnium cordifolium	Aerial parts	360-580nm	77.8-93 nm.	Spherical	(Rashidi et al., 2024)
Allium cepa	Peel	438.90nm	8.44–19.93 nm	Spherical	(Baran et al., 2023)

Plants	Extract	Absorption peak	Particle size distribution	Particle Morphology	References
Brillantaisia patula,	Leaves	434nm	45nm	Roughly Spherical	(Kambale et al., 2020)
Crossopteryx febrifuga		489nm	47nm		
Senna siamea		522nm	115nm		
Glycine max	Seeds	430nm	5-50nm	Spiral	(Kumar et al., 2024)
Trigonella foenum-graecum	Seeds	443nm	82nm	Spherical	(Awad et al., 2021)
Glycine max	Seeds	425nm	87nm	Spherical	(Hosamani et al., 2020)
Trigonella foenum-graecum	Seeds	343nm	8.932-33.50nm	Irregular spherical	(Hassan et al., 2024)
Glycine max	Seeds	434nm	25-50nm	Spherical	(Prasad et al., 2014)
Picea	Spruce needles	-------	1st batch 61nm	Spherical and Rod	(Okonov and Ovsuk, 2024)
			2nd batch 8nm	Irregular	
Citrus reticulat	Peel extract	423nm	10-35nm	Spherical	(Jaast and Grewal, 2021)
Cucumis prophetarum	Leaves	420nm	30-50nm	irregularly granulated, ellipsoidal	(Hemlata et al., 2020)
Ananas comosus	Fruit pulp	430nm	5-30nm	Spherical, Oval, Elliptical	(Ahmed and Sharma, 2012)
Impatiens balsamina	Leaves	450-420nm	1-5mM: 12-20nm	Spherical	(Aritonang et al., 2019)
Lantana camara		450-440nm	1-5mM: 3.2-12nm		
Paullinia cupana	Flower	440-460nm	48.85nm	Irregular spherical	(Lima et al., 2024)
	Leaves	410-420nm	40.72nm		
Ribes uva-crispa	Leaves	408-420nm	4-24nm	Spherical	(Stozhko et al., 2024)
Lonicera caerulea,			4-29nm		
Fragaria vesc			3-20nm		
Hippophae rhamnoides			2-15nm		
Uvaria narum	Leaves	427nm	7-25nm	Spherical	(Ajaykumar et al., 2023)
Acacia ehrenbergiana	Plant cortex	435nm	1-40nm	Spherical	(Alamier et al., 2023)
Eugenia roxburghii	Leaves	417nm	19-39nm	Spherical	(Giri et al., 2022)
Diospyros kaki	Leaves	453nm	8.13–38.5 nm	Spherical	(Keskin et al., 2023)
Lysiloma acapulcensis	Leaves	400nm	1.2-62nm	Quasi-spherical	(Garibo et al., 2020)
Citrus limon	Zest	535.5nm	7-28nm	Spherical	(Khane et al., 2022)
Tectona grandis	Seeds	440nm	10-30nm	Spherical	(Rautela et al., 2019)
Viburnum opulus	Fruit pulp	415nm	7-26nm	Spherical	(David and Moldovan, 2020)



CRITICAL ANALYSIS AND LIMITATIONS

The existing body of literature on plant-mediated synthesis of silver nanoparticles (AgNPs) demonstrates significant promise in terms of biomedical and environmental applications; however, several critical limitations temper the strength and generalizability of these findings. Many of the reviewed studies rely on small sample sizes, particularly in experimental validations involving antimicrobial or anticancer assays, which restricts statistical power and weakens the reliability of conclusions (14). Few investigations extend beyond in vitro models, and the absence of well-structured randomized controlled trials (RCTs) or in vivo studies substantially limits translation to clinical contexts (15). Additionally, follow-up durations are often short, providing little insight into the long-term stability, toxicity, and biodistribution of plant-derived AgNPs (16). These methodological shortcomings highlight the need for more rigorous experimental designs to substantiate early findings. Methodological biases also permeate much of the available literature. Selection bias is evident where specific plant species or extracts are preferentially studied, often due to regional availability, rather than standardized comparative analyses across a wider botanical spectrum (17). Performance bias further complicates interpretation, as most studies lack blinding or independent replication, raising questions about reproducibility. Moreover, confounding factors such as varying extract preparation techniques, solvent systems, and silver precursor concentrations lead to inconsistencies in reported outcomes (18). This variability creates difficulty in determining whether observed therapeutic effects arise from the intrinsic properties of AgNPs, the phytochemicals in the extract, or synergistic interactions between them.

Publication bias is another concern. The literature disproportionately emphasizes positive outcomes, including enhanced antimicrobial or anticancer activity, while negative or inconclusive findings are underreported. This selective dissemination inflates perceived efficacy and undermines balanced evaluation of green-synthesized nanoparticles (19). Similarly, variability in outcome measurement—such as reliance on surface plasmon resonance (SPR) peaks, particle size distribution, or zones of inhibition—creates challenges in cross-study comparisons. Differences in methodological endpoints and analytical tools contribute to inconsistencies in reported nanoparticle size, morphology, and bioactivity (20). Finally, the generalizability of existing findings remains limited. Most studies employ extracts from locally accessible plants, leading to geographically skewed data that may not reflect broader biodiversity. Additionally, bioactivity assessments often focus on selected bacterial or cancer cell lines, which restricts applicability across diverse populations or clinical conditions (21). Without cross-cultural, multi-species, and multicenter investigations, it is premature to assume universal therapeutic efficacy. Collectively, these limitations underscore the need for standardized protocols, robust clinical trials, and comprehensive toxicity evaluations to ensure that plant-mediated AgNPs transition from promising experimental entities to reliable biomedical tools.

IMPLICATIONS AND FUTURE DIRECTIONS

The growing body of evidence on plant-mediated silver nanoparticles highlights substantial implications for clinical practice, particularly in the development of novel antimicrobial and anticancer therapies. The capacity of plant-derived AgNPs to enhance drug delivery, improve bioavailability, and exert synergistic therapeutic effects provides clinicians with potential alternatives to conventional treatments, especially in the face of rising antimicrobial resistance and the limitations of synthetic drugs (22). Their biocompatibility and eco-friendly synthesis further enhance their appeal for integration into future medical applications, including wound dressings, targeted drug delivery systems, and adjuncts in cancer therapy (23). However, the absence of standardized formulations and rigorous clinical validation currently prevents their widespread adoption in patient care, underlining the necessity of translating in vitro promise into safe, clinically applicable nanomedicines. From a policy perspective, the evidence underscores the urgent need for regulatory guidelines addressing the synthesis, characterization, and biomedical application of green-synthesized nanoparticles. At present, the lack of unified standards creates variability in outcomes and raises concerns regarding long-term safety and toxicity (24). Policies that establish quality control benchmarks, safety thresholds, and standardized reporting protocols could facilitate reproducibility and clinical translation. Furthermore, international guidelines should promote eco-friendly nanotechnology as part of sustainable healthcare, encouraging interdisciplinary collaboration between clinicians, nanotechnologists, and regulatory bodies (25).

Several unanswered questions and research gaps remain. There is limited understanding of the mechanisms underlying plant-extract mediated reduction and stabilization of silver ions, particularly the role of individual phytochemicals in determining particle morphology and therapeutic efficacy (26). Equally underexplored are the long-term in vivo effects of AgNPs, including biodistribution, clearance pathways, and potential toxicity to non-target tissues (27). Additionally, most current evidence stems from localized plant species, restricting generalizability across different populations and ecological settings. These gaps highlight the need for systematic investigations that explore diverse botanical sources, standardized extract preparation methods, and reproducible synthesis protocols. Future research should prioritize methodological improvements through the design of randomized controlled trials, multi-center collaborations, and longitudinal studies that assess both efficacy and safety profiles (28). Advanced in vivo models are required to elucidate pharmacokinetics and pharmacodynamics, while clinical trials should focus on well-defined patient populations to establish therapeutic benefits and adverse event profiles. Incorporating omics-based technologies, such as proteomics and metabolomics, could help uncover molecular pathways involved in nanoparticle–host interactions, providing mechanistic clarity (29,30). Furthermore, comparative studies that evaluate plant-based synthesis against conventional chemical and microbial approaches would contribute to identifying optimal strategies for large-scale, safe, and cost-effective nanoparticle production. Overall, the evidence positions green-synthesized silver nanoparticles as a promising frontier in nanomedicine, yet their clinical and translational potential can only be realized through standardized methodologies, rigorous safety evaluations, and supportive policy frameworks that ensure responsible integration into healthcare.

CONCLUSION

Green nanotechnology has emerged as a promising and sustainable approach for the synthesis of silver nanoparticles, offering advantages over conventional chemical methods by utilizing plant-derived phytochemicals as natural reducing and stabilizing agents. This review highlighted how bioactive compounds in plants not only contribute therapeutic benefits but also enhance nanoparticle stability, with their size, morphology, and optical properties being strongly influenced by reaction parameters such as pH, temperature, precursor concentration, and incubation time. While existing studies provide encouraging evidence of antimicrobial and anticancer potential, much of the literature is limited by small-scale experimental models and lacks mechanistic clarity, which restricts the strength of evidence. For clinicians and researchers, these findings suggest that plant-mediated AgNPs may hold future relevance in drug delivery, wound healing, and antimicrobial therapies, provided that standardization and safety assessments are established. Moving forward, further research is urgently needed to explore precise mechanistic pathways, optimize synthesis conditions, and conduct robust preclinical and clinical trials to ensure reproducibility, safety, and translational applicability of these eco-friendly nanomaterials.

AUTHOR CONTRIBUTION

Author	Contribution
Mnahil Baig*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Ghozeel Fatima	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Fatima Jamil	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Komal Ajmal	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Hira Mumtaz	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Ayesha Aslam	Substantial Contribution to study design and Data Analysis Has given Final Approval of the version to be published
Amna Shahid	Contributed to study concept and Data collection Has given Final Approval of the version to be published

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