RESEARCH PAPER

Review on Green Fabrication Strategies of Silver Nanoparticles Using Lamiaceae Plants: Characterization and Bioactivities

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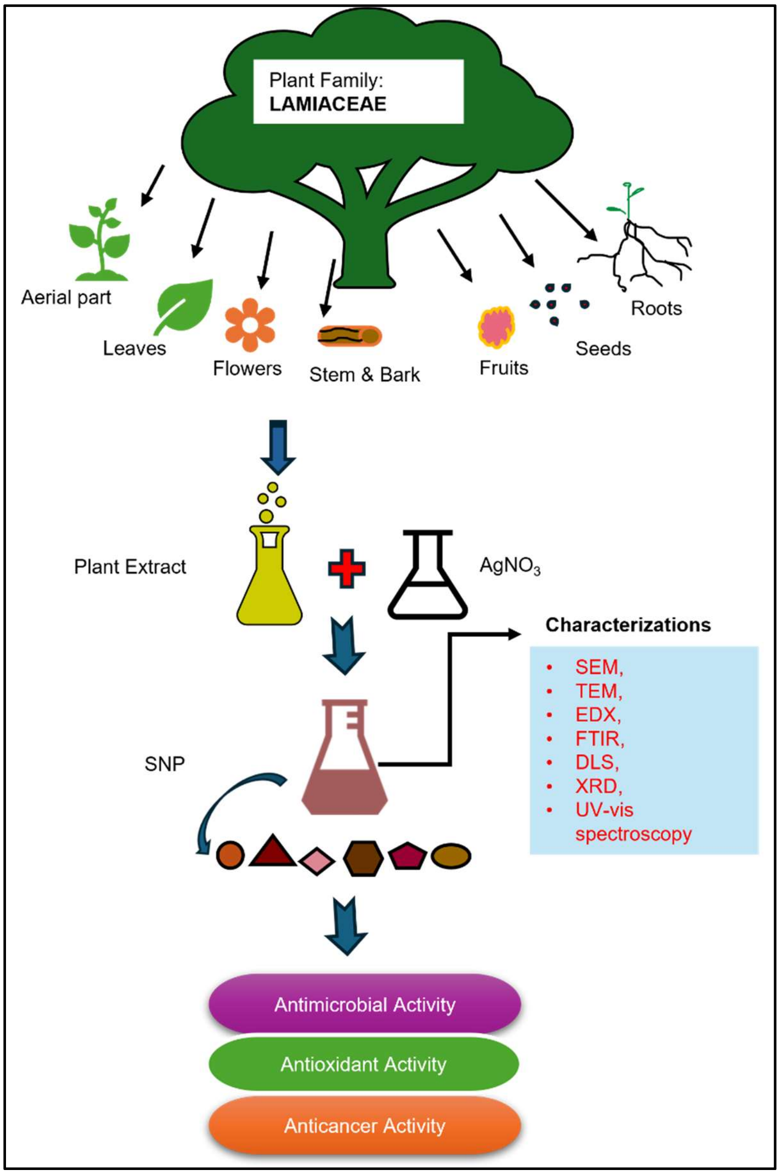
Abstract:
Silver nanoparticles (SNPs) have garnered much attention because of their multifunctional performance, especially in the pharmaceutical sector. The green synthesis of nanoparticles utilizing plants is thought to be less hazardous and more environmentally friendly than the synthesis of particles produced by chemical or physical means. The reduction, capping, and stabilization of nanoparticles depend on the phytochemicals present in the plant extracts. The Lamiaceae family, commonly known as the mint family, is a stockpile of phytometabolites, especially famous for essential oils. This article presents a systematic study of Lamiaceae-mediated synthesis of SNPs. All reliable factors related to manufacturing, including the plant parts used, the solvent employed, the concentration of plant material, silver salt, the pH, the temperature, and the reaction time, which are dependent on the nanoparticle size and corresponding biological activities, have been highlighted. The role of phytochemicals in the production of nanoparticles has been discussed. In addition, various characterization techniques utilized to detect the size, shape, and crystallinity of stable nanoparticles have been discussed. Studies of their biological activities have focused mainly on their antimicrobial, anticancer, and antioxidant properties. Overall, the novelty of the review included twenty-four genera belonging to the Lamiaceae family involved in SNP production and emphasized research gaps, possible challenges associated with this field of research, along with future perspectives in a precise and systematic way. This provides insightful information on recent developments in the sustainable synthesis of SNPs via plant-based resources.

Graphical abstract:



Keywords:

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Green fabrication, Silver nanoparticles, Lamiaceae, Bioactivities, Antimicrobial, Plant-mediated synthesis

Introduction:

The emergence of nanotechnology marked a momentous milestone in history. Nanotechnology involves the assembly, production, manipulation, control, and application of nanocompounds with diameters ranging from 1 to 100 nm, termed nanoparticles (NPs). This can be compared with the diameter of DNA, which is 2 nm, and a nanometer is equal to a thousand millionth of a meter, i.e., 10-9 m. The development of nanotechnology has created opportunities in many fields of science and technology, such as pharmaceuticals, agriculture, textiles, food technology, electronics, optics, and engineering (Kheiriabad et al. 2024; J et al. 2024). The concept of nanotechnology was first introduced by an esteemed American physicist, Richard Feynman, in 1959 in a lecture entitled “There’s plenty of room at the bottom.” Nanoparticles can be synthesized via three methods: physical, chemical, and biological. NPs can be synthesized via top-down and bottom-up approaches. In the first approach, bulky materials can be broken down into nanomaterials via mostly physical methods, whereas the second approach includes atomic interactions to produce nanoparticles, mostly via chemical and biological methods. The biological method is a sustainable method for synthesizing NPs by utilizing bacteria, algae, fungi, and plants. NPs are specialized for their unique features, such as a higher surface-to-volume ratio than bulk materials, and their unique surface properties make them useful in various fields (Ijaz et al. 2020). Green-synthesized metallic NPs have been reported to be useful for diverse biological activities (Salem and Fouda 2021). The term "green synthesis" refers to an environmentally benign method of producing NPs that uses biomaterials for the reduction, capping, and stabilization of NPs during synthesis rather than involving a green color. This preferred method is sustainable, affordable, devoid of chemical pollutants, and efficient for biological and medical applications (Hussain et al. 2016). SNP provides tremendous performance because of its high electrical and thermal conductivity potential (Joudeh and Linke 2022). Various studies have revealed the multifunctional activities of green-synthesized SNPs, such as antimicrobial (Roy et al. 2019), anticancer, wound healing, drug delivery, and agricultural applications (Eker et al. 2025).

The mint family Lamiaceae contains approximately 227 plant genera with 7100 species (https://powo.science.kew.org/,. The family is renowned for its powerful phytochemical profile, which has beneficial effects on human health (Moshari-Nasirkandi et al. 2023). This aromatic plant family, which contains the highly diverse genus Plectranthus, is rich in essential oils and is responsible for antimicrobial, antioxidant, and anti-inflammatory effects (Ramos Da Silva et al. 2021). Common Lamiaceae members, including sage (*Salvia officinalis* L.), thyme (Thymus vulgaris L.), basil (Ocimum basilicum L.), and oregano (Origanum vulgaris L.), have strong antioxidant potential and cardio-protective effects (Chakrabartty et al. 2022). Members of the Lamiaceae plant family demonstrate remarkable antibacterial activity owing to the presence of important secondary metabolites, including linalool, thymol, eugenol, methyl chavicol, and carvacrol (Sahakyan 2023). The present review focuses on the plant-based synthesis of SNPs using members of the Lamiaceae family. Plant-mediated synthesis of SNPs has been documented in many studies; the effects of different parameters on the size and shape of green-synthesized silver nanoparticles and their antimicrobial activity have been explained (Vanlalveni et al. 2021). Basumatary et al. (2024) reviewed green-synthesized silver and gold nanoparticles of Lamiaceae and three other plant families (Basumatary et al. 2024). In contrast, there is still a lack of systematic research that focuses only on the Lamiaceae family. This review comprehensively highlights the role of Lamiaceae plants in the green synthesis of SNPs, with particular emphasis on mechanistic aspects, role of phytochemicals, the influence of reaction conditions on nanoparticle synthesis, toxicity studies, and biological activities. This review aims to summarize methods for synthesizing Lamiaceae-mediated NPs, their characterization, and their biological applications. Challenges of plant-mediated nanoparticle synthesis with sundry of research gap are still exist, which can help to make a concrete outline of the forthcoming research work.

Methodology:

Online databases such as Google Scholar, Academia, ResearchGate, and ScienceDirect were used to identify research publications on this topic. The data were collected via the keyword “green synthesis of silver nanoparticles using plants” from 2011 to 2025. Duplicated articles along with non-Lamiaceae plant-mediated articles were excluded, and full-text articles were selected for screening. The process of article selection for the study is represented by the PRISMA 2020 flow diagram for the new systematic review (Fig. 1). Overall, 63 articles that explored 24 genera of Lamiaceae involved in the green synthesis of SNPs have been documented.

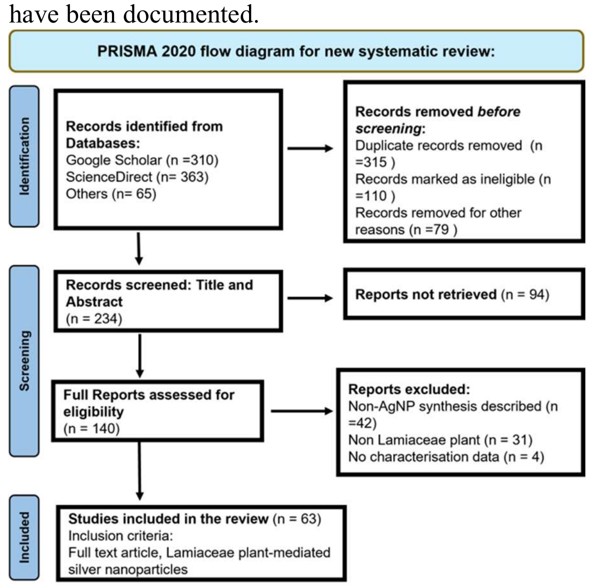

Fig. 1 Flow diagram showing the process of article selection for review

Mechanisms involved in plant-based nanoparticle synthesis:

A lot of studies on plant-mediated silver nanoparticle synthesis have been performed within the last few decades. The process of synthesis was explained hypothetically. Phytochemicals profile of the plant was studied, but direct participation of that phytochemical is unclear. Plants contain numerous phytochemicals, including proteins, carbohydrates, lipids, pigments, alcoholic compounds, alkaloids, vitamins, polysaccharides, and secondary metabolites (Dhir et al. 2023). The functional groups of these phytocompounds, such as -OH, -COOH, -C=C-, and -NH2, are essential for the redox potential to reduce silver nitrate salt from Ag+ to Ag0 (reduction). In the next step, Ag0 atoms aggregate to form small clusters (nucleation), followed by particle growth. Phytocompounds present in the extract stabilized SNPs with a specific size and shape (Fig. 2). Three phases are involved in the production of metal NPs: activation, development, and termination. The development phase increases the thermodynamic stability of the NPs through heterogeneous nucleation via the Ostwald ripening method, and finally, in the termination phase, NPs of specific size are developed (Deka et al. 2025).

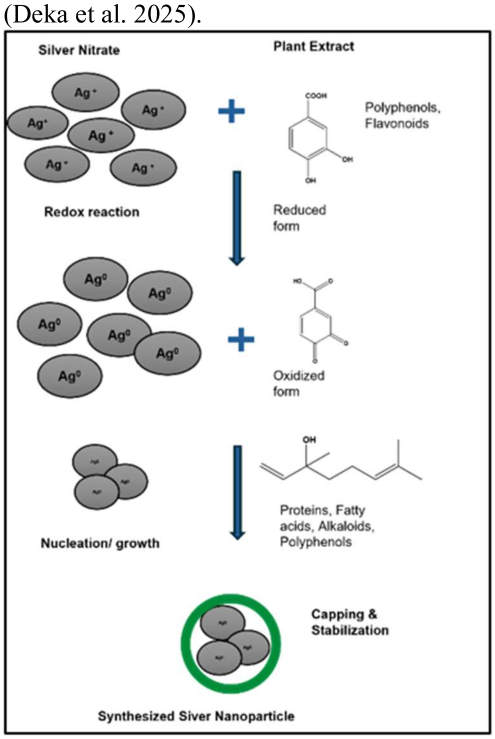

Fig. 2 Diagrammatic representation of the SNP synthesis mechanism

Lamiaceae-mediated synthesis of SNPs:

Numerous studies have shown that several genera of the Lamiaceae family, including Mentha, Ocimum, Origanum, Perilla, Salvia, and Rosmarinus, are involved in the environmentally friendly synthesis of SNPs. This is a terpenoid-rich plant family, rich in essential oils. Subsequent parts of the green synthesis mechanism using plants of Lamiaceae have been explored. But some aspects, like optimizations, mechanistic approach correlation with particle size, and phytochemical content, are still unclear. To effectively synthesize environmentally friendly SNPs, the extraction method and all the reaction parameters must be optimized to achieve functionally active nanoparticles with a specific diameter.

Plant extraction method:

The aerial parts, leaves, flowers, stems, bark, seeds, and roots of a plant species from Lamiaceae have been used in the green synthesis method (Fig. 3). Water has been selected as the primary solvent for dissolving phytochemicals (Hernández-Morales et al. 2019; Sivaramakrishnan et al. 2019). Unlike methanol and ethanol, it is a nontoxic and highly polar solvent. Shade-dried plant powders were soaked, macerated, or boiled with the solvent to produce extracts (Allafchian et al. 2016; Robles-martínez et al. 2020). Sometimes, organic solvent-driven plant extraction has also been accomplished (Balciunaitiene et al. 2021; Robles-martínez et al. 2020). Efficient, clear extracts of *Lavandula angustifolia* flowers were prepared via an ultrasonic bath with continuous stirring of the powder with a hydroalcoholic mixture (Șuică-Bunghez et al. 2024). During the synthesis of Lamiaceae-assisted SNPs, Leaves are the frequently used plant parts (Fig. 3). Leaves are the repository of metabolites, suitable for instant extraction, and can be collected without disturbing the ecosystem. The quantity of phytocompounds in the extract is dependent on the polarity of the solvent, the extraction process, duration, and above all, plant collection-related factors, which need to be standardized. The most commonly used extraction process in these studies was either soaking or boiling the plant powder with solvent. Without any tedious process, either soaking for longer duration or boiling for shorter duration of plant powder in the polar solvent can extract sufficient amount of phytocompound for nanoparticle production. So, the plant extraction method is also a cost-effective and time-saving process.

Fig. 3 The graphical presentation showing frequently utilized plant parts of the Lamiaceae family in SNPs synthesis

Phytochemicals involved:

Numerous studies proposed that Phytochemicals actively participate in redox reactions during the fabrication of nanoparticles. The proper size and shape of a particle are maintained by capping and stabilization. Bouhajeb et al. (2024) clearly demonstrated the involvement of phytochemicals via analysis before and after nanoparticle synthesis using the ^{1}HNMR technique (Bouhajeb et al. 2024). However, the contribution of isolated compounds in silver ion reduction or nanoparticle stabilization remains limited. Polyphenolic compounds play crucial roles in nanoparticle synthesis. This facilitates the reduction of silver ions and the nucleation of metallic silver atoms. In this reaction, phenolic compounds oxidize in the presence of silver nitrate ($AgNO_3$), converting Ag^+ ions to metallic silver (Ag^0) and producing stable phenoxy radicals (Tavan et al. 2023). UV–vis and FTIR studies have shown that phytoconstituents act as reducing and capping agents for SNPs (Șuică-Bunghez et al. 2024). Polyphenolic compounds, tannins, flavonoids, and terpenoids have shown promising effects (Ahmed and Mustafa 2019). Although the mechanisms of organic compounds are limited, phytochemical-dependent variations in nanosynthesis have been observed. Lamiaceae-mediated SNP production accompanied by phytochemical profiling of the plant extract used was assessed via chromatography–mass spectrometry-related analytical techniques (Table 1). Another important class of phytochemicals in the Lamiaceae family is terpenoids. Monoterpenes and sesquiterpenes found in species rich in essential oils may aid in the creation of nanoparticles and surface stability. However, there hasn't been as much experimental focus on their reducing capacity as phenolic chemicals. The finding raises the possibility that phenolic quantity and nanoparticle size are related (Dėnė et al. 2024; Hambardzumyan et al. 2020). However, the evidence that is now available is still primarily correlative rather than explanatory. The absence of standardized phytochemical characterization is a significant research restriction. Plant parts, extraction solvents, harvesting seasons, and geographic origins can all significantly change the phytochemical makeup. As a result, comparable species frequently produce nanoparticles that differ significantly in size and biological activity. This variability restricts reproducibility and makes direct comparisons between research more difficult.

Table 1: Reported phytochemicals of the Lamiaceae family that are likely responsible for SNP production.

Sl. No.	**Plant name**	**Probable phytochemicals involved in SNP synthesis**	**Analytical techniques**	**Ref.**
1	*Clerodendrum serratum*	Serratin, lupeol, catechin, hispidulin, cleroflavone, luteolin, α-spinosteros, catechin, squalene	HPLC	(Vidyasagar et al. 2024)
2	*Coleus aromaticus*	Dimethylphosphine, 2-formylhistamine, 4-methylthiomorpholine-1,1-dioxide, Bicyclo, Heptacosanoic acid, octadecadienoyl chloride, 13-tetradece-11-yn-1-ol, 1-monooleoylglycerol trimethylsilyl ether, Dihydroartemisinin, Octasiloxane	GCMS	(Deepak et al. 2026)
3	*Lavandula angustifolia*	Eucalyptol, linalool, 2-bornanone, butanoic acid, endo-borneol, terpinen-4-ol, hexanedioic acid, bis(2-ethylhexyl) esters, linalyl acetate, caryophyllene, hexanedioic acid, dibutyl phthalate	GCMS	(Șuică-Bunghez et al. 2024)
4	*Perilla frutescens*	Rosmarinic acid, caffeic acid, ferulic acid, and rutin	HPLC	(Tavan et al. 2023)
5	*Rosmarinus officinalis*	Cineole, Borneol, acetic acid, rosmarinic acid, methional, linalool, oleic acid, palmitic acid, and taurolidine	GCMS	(Elmehalawy et al. 2025)
6	*Salvia mirzayanii*	Phenolic monoterpenes, linalool acetate,	GCMS	(Shaverdi et al. 2024)

		linalool, 1,8-cineol		
7	*Salvia rosmarinus* (Rosemary)	Thymol-beta-D-glucoside, dihydrogedunic acid methyl ester, melezitose, antimycin A, coumarin, eugenol, diosgenin, and 7-O-methylrosmanol	UPLC-HRMS	(Wahab et al. 2025)
8	*Teucrium ramosissimum*	Protocatechuicacid, gentisicacid, 4-hydroxybenzoate, gallicacid, phenylpropanoid1 &2, 3,4-dihydroxy-β-phenylethanoL, citricacid, malicacid, 2-hydroxyisovalerate, unsaturatedfattyacids	^{1}HNMR	(Bouhajeb et al. 2024)

HPLC- High-performance liquid chromatography, GCMS- Gas chromatography/Mass spectrometry, UPLC- Ultra performance liquid chromatography, HRMS- High-resolution mass spectrometry, 1 HNMR- Proton nuclear magnetic resonance.

Factors affecting the Lamiaceae-mediated synthesis of SNPs:

The green synthesis of silver NPs depends on various parameters, such as the quantity of plant extract and silver nitrate, the pH of the reaction mixture, the temperature, and the reaction time (Fig. 4). As phytochemicals respond to the formation of silver nitrate into silver NPs, the concentration and volume of plant extracts need to be optimized. Several studies have suggested that the concentration of plant extracts has a visible impact on NP synthesis. SNPs synthesized using aqueous leaf extracts of *Perilla frutescens* were optimized to 5% of the crude extract, which is within the studied range of 1–10% when mixed with 2 mM AgNO3 (Tavan et al. 2023). Larger concentrations of reducing and capping phytochemicals are provided by higher extract concentrations, which speed up the formation of nanoparticles and enhance colloidal stability. However, because of unregulated nucleation and growth processes, high extract concentrations may cause particle agglomeration. Numerous investigations involving Lamiaceae-mediated synthesis have documented this behavior, suggesting the presence of an ideal extract-to-silver ion ratio (Sharma et al. 2020). The production of nanoparticles seems to be most influenced by pH. In alkaline environments, where deprotonation of phenolic and flavonoid hydroxyl groups increases their electron-donating ability and facilitates the reduction of Ag^+ ions, the majority of studies found better nanoparticle synthesis. As a result, smaller and more evenly distributed nanoparticles are often produced at alkaline pH. Acidic circumstances, on the other hand, frequently lead to broader size distributions, slower reduction rates, and particle aggregation. The extraction volume of *Mentha aquatica* with a 100 mM silver nitrate mixing ratio ranging from 0.9:0.1 to 0.1:0.9 was optimized at a ratio of 1:1 at pH 9.5 and 25 °C, with smaller, potent synthesized SNPs (Nouri et al. 2020). Higher temperatures typically shorten synthesis times, speed up reaction kinetics, and facilitate the accelerated nucleation of smaller nanoparticles. However, thermolabile phytochemicals involved in reduction and stabilization may be broken down by overly high temperatures, which would lower the quality of the nanoparticles. In order to preserve both reaction efficiency and phytochemical integrity, moderate temperatures are typically favored. The increasing concentration of silver nitrate (1–5 mM) gradually blue-shifted the SPR peak, indicating a smaller nanoparticle size (Sharma et al. 2020). The SNPs were synthesized via the addition of 1 mM $AgNO_3$ to the *Coleus aromaticus* extract. Increasing the concentration of silver salt increased the agglomeration of the synthesized NPs (Deepak et al. 2026). Thus, the optimum silver salt concentration was estimated by studying the nature of the shift in the SPR peak in several studies (Ghojavand et al. 2020). The pH of the medium actively influences NP synthesis. The hydroxyl ion concentration promoted SNPs synthesis. Therefore, an alkaline reaction medium with a relatively high pH was preferable for this process. The SNP with *Salvia verticillata* showed a blue shift at pH 11 (Mihailovi et al. 2023). Both aqueous and hydroalcoholic NPs of *Teucrium ramosissimum* were smaller at pH 10.3 than at pH 9.5 (Bouhajeb et al. 2024). Temperature-dependent synthesis of SNPs from Lamiaceae plants has been reported in most cases, with the optimum size and yield of NPs found at room temperature (Ghojavand et al. 2020; Mihailovi et al. 2023; Gharari et al. 2023; Younis et al. 2023). A temperature above the optimum value broadens the UV–vis spectra, that is, a bathochromic shift, and reduces the SPR peak (Ihsan et al. 2024). The yield of silver NPs increases with time up to a certain period (Nouri et al. 2020; Sharma et al. 2020). The formation and stabilization of nanoparticles are also influenced by reaction time. While longer reaction times can promote particle development and aggregation, shorter reaction times may lead to partial silver ion reduction. Direct comparisons between research are still challenging despite significant improvements since synthesis conditions are rarely consistent. Standardized approaches should be used in future research to enable significant comparisons and enhance large-scale reproducibility.

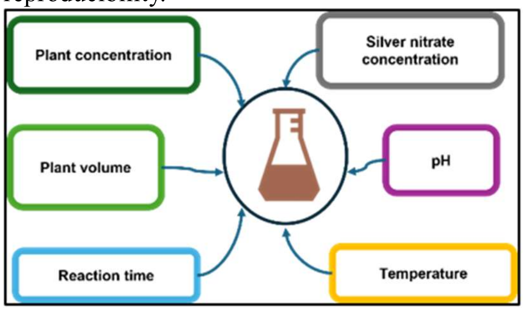

Fig. 4 Schematic representation of factors influencing Lamiaceae-based SNPs synthesis

Characterization of SNPs:

Several characterization approaches have been used to assess the size, shape, behavior, and properties of NPs. The analysis of NPs can be performed via a variety of methods. These techniques include SEM, TEM, EDX, FTIR, DLS, XRD, and UV–vis spectroscopy.

Ultraviolet-visible spectroscopy is a simple yet effective method for characterizing synthesized NPs. It is used to assess the characteristics of metallic NPs. Both the rate at which the NPs develop and their capacity to remain stable were tracked. The free electrons of metal NPs oscillate with the resonance of the light wave and produce a surface plasmon resonance band, which is detected by UV-vis spectroscopy as an SPR peak within 400-500 nm (Anandalakshmi et al. 2015; Dhir et al. 2023). Higher λmax values are linked to larger particle sizes and higher nanoparticle concentrations, whereas lower λmax values typically reflect smaller average sizes of SNPs. Furthermore, broad absorption peaks at higher wavelengths indicate larger particle sizes or potential nanoparticle aggregation, whereas narrow absorption peaks at lower wavelengths imply the formation of tiny and well-dispersed SNPs (Alharbi et al. 2022). *Salvia sclarea* flower-mediated synthesis of SNPs revealed that an increase in time, from 15-35 min, elevated the absorbance at 440 nm, resulting in the production of smaller-diameter spherical NPs (Zarei et al. 2024). The SPR peak depends on the chemical and physical conditions of the reaction media, as demonstrated by multiple studies (Ghojavand et al. 2020; Hambardzumyan et al. 2020; Bouhajeb et al. 2024; Deepak et al. 2026). Another important spectroscopic characterization method is Fourier transform infrared (FTIR) spectroscopy. The functional groups of the phytochemicals responsible for SNPs synthesis were investigated via FTIR spectroscopy. Stretching vibrations of different chemical bonds were detected when the transmittance was studied within the range of 4000 cm^{-1} to 500 cm^{-1} (Reddy et al. 2021). Infrared spectroscopic analysis of plant extracts and extract-mediated SNPs can reveal the functional groups responsible for capping and stabilizing the particles. *Salvia sclarea*-assisted SNP revealed N-H and O-H stretching vibrations in phytochemicals such as saponins, terpenoids, and phenolic compounds at 3780 and 3445 cm^{-1}, respectively (Zarei et al. 2024). The band at 860 cm^{-1} is attributed to C-H bending, which could be attributed to AgNO3 reduction in *Salvia leriifolia*-based SNPs (Baghayeri et al. 2018). FTIR analysis of the phyto-mediated SNPs using *Perilla frutescens* revealed functional groups such as hydroxyl, alkyne, amide C=O stretching, carbonyl, alcohol, and phenol groups in both the plant extract and the mediated SNPs. All the peaks were the same for both, with the observed peak shifts indicating the involvement of phytochemicals in the SNP production reaction. The comparative FTIR spectrum also confirmed the presence of an extra peak for SNPs at 1579.47 cm^{-1} for the notable Raman peak of SNPs (Tavan et al. 2023).

Two microscopic techniques are essential for studying nanoparticle morphology: scanning electron microscopy (SEM) and transmission electron microscopy (TEM). FESEM is a field emission SEM that involves the emission of electrons by a strong electric field. The secondary electrons produced by a sample after electron collisions in SEM can be used to reconstruct the surface topography of the sample and determine its size, shape, and size distribution. In contrast, quantitative measurements of the size, shape, and size distribution of NPs with high resolution can be obtained via the TEM imaging technique. The electrons emitted from the beam directly pass through the sample, and an internal image of the sample can be obtained; however, laborious sample preparation is needed (Alharbi et al. 2022). FESEM images of the SNPs revealed that they were primarily spherical in shape and monodisperse, with a size range of 31-58 nm, and were synthesized using *Scutellaria multicaulis* (Gharari et al. 2023). SEM images revealed that spherical, cylindrical, and deep hollow types of SNPs were generated by Salvia plebeian and *Salvia moorcroftiana* (Ihsan et al. 2024). An agglomeration of SNPs was observed in the SEM images but not in the TEM images of the same sample (Dėnė et al. 2024). The size and shape of the Lamiaceae-based SNPs determined via microscopic methods are tabulated in the supplementary data.

The TEM images exhibited spherical, monodispersed SNPs with an average diameter of 12.1 nm, 27 nm, and 60.5 ± 1.38 nm, using *Salvia leriifolia* (Baghayeri et al. 2018) and *Lavandula intermedia* (Elemike et al. 2017). The TEM images revealed a flower-shaped arrangement of SNPs by the plant materials, along with NPs shaped like quasi-spheres, quasi-pyramids, or polygons with an average diameter of 50 nm, which was not clear in the SEM image (Grigoras and Grigoras 2024).

Energy-dispersive X-ray (EDX) analysis uses a low-noise preamplifier to detect X-rays on the basis of the photon energy that produces detectable voltage pulses. A multichannel analyzer counts and digitally records these pulses to create an X-ray spectrum (Kokila et al. 2016). EDX was used to analyze the chemical composition of the silver NPs. Qualitative and quantitative profiling of the elements involved in the plant-based synthesis of SNPs, including the intense Ag signal, was performed using EDX, confirming SNP formation. The presence of carbon, chlorine, oxygen, or other elements in the EDX spectrum indicates the elemental composition of plant metabolites (Gharari et al. 2023).

X-ray diffraction (XRD) analysis is an essential method for characterizing SNPs. This helps to qualitatively and quantitatively determine the crystal structure and degree of crystallinity of the NPs. This method generates a unique diffraction pattern for the sample, which can be compared with the standard database to analyze the crystallinity. Face-centered cubic SNPs synthesized by *Rosmarinus officinalis* presented XRD Bragg diffraction peaks of 111, 200, 220, and 311 at 2θ° of 38. 28°, 44. 45°, 64. 39°, and 77. 27°, respectively, supported by the Joint Committee on Powder Diffraction Standards (JCPDS) file number 04-0783 (Elmehalawy et al. 2025). The size of the SNP crystal structure was calculated via the Scherrer formula, as per the study by Dar et al. (2025), and the particle diameter was estimated to be 16.7 nm (Dar et al. 2025). The purity of the particles was also revealed by XRD spectra through sharp, intense crystalline peaks (Vidyasagar et al. 2024). Diffraction peaks of plant metabolites were also observed in the XRD pattern, confirming the involvement of phytometabolites in NP synthesis (Pirtarighat et al. 2019).

Dynamic light scattering (DLS) or photon correlation spectroscopy (PCS) was used to estimate the hydrodynamic size of the NPs and the polydispersity index (PDI) of the colloidal NP sample. It determines fluctuations in the scattered light of spherical particles dispersed by Brownian motion through diffusion rates over very short times. The instrument measures the diffusion coefficient, and the particle size is calculated via the Einstein–Stokes equation. The zeta potential of NPs is a significant parameter for determining the electrical potential difference between the surface and aggregation of the particles. The stability of the colloidal solution of SNP can be determined by studying the surface charge. DLS analysis of SNPs synthesized via *Salvia officinalis* revealed monodispersed particles with a PDI value of 0.43, and the hydrodynamic size was larger than that reported by electron microscopy because of the nonspherical shape of some particles in the solution (Grigoras and Grigoras 2024). *Origanum vulgare* collected from different regions was used to generate SNPs, and DLS analysis revealed different sizes of polydisperse particles with a PDI range of 0.291–0.536. The recorded zeta potentials of the four types of SNPs were ± 0–10 mV, ± 10–20 mV, and ± 30 mV, which were considered unstable, relatively stable, and highly stable, respectively (Hambardzumyan et al. 2020). DLS analysis of *Perilla frutescens*-mediated SNPs revealed a small hydrodynamic particle size (44±14.4 nm) monodispersed in water, but the large standard deviation implies variation in size (Hou et al. 2023).

Table 2: SNPs synthesized using 24 genera of Lamiaceae (full table in the supplementary information)

	Genus	**No. Species (Studied)**	**Plant parts**	**Particle size range (nm)**	**Activities**	**Ref.**
1	*Callicarpa*	1	Bark	9 to 15	N/A	(Shameli et al. 2012)
2	*Clerodendrum*	2	Leaves	5.5 to 35	Antimicrobial, Antioxidant	(Khan and Shahid 2020; Vidy

						asagar et al. 2024)
3	*Coleus*	2	Leaves, Roots	20 to 44	Antimicrobial, Antioxidant, Larvicidal	(Vanaja and Annadurai 2013; Deepak et al. 2026)
4	*Hyptis*	1	Leaves	40 to 55	Antimicrobial	(Muthamil et al. 2018)
5	*Hyssopus*	1	Leaves and Flower	11.5 to 21.5	Antimicrobial	(Balciunaitiene et al. 2022)
6	*Lavandula*	2	Leaves and Flower	4.6 to23	Antimicrobial, Antioxidant	(Elemike et al. 2017; Şuică-Bunghez et al. 2024)
7	*Leonuri*	1	Whole plant	9.9 to 13	Antimicrobial	(Im et al. 2011)
8	*Leucas*	1	Leaves	20 to 40	Antimicrobial, Catalytic	(Sivaramakrishnan et al. 2019)
9	*Mentha*	5	Leaves	5 to 90	Antimicrobial, Antioxidant, Anticancer, Catalytic, Cytotoxicity	(MubarakAli et al. 2011; Abd Kelkawi et al. 2017; Erci et al. 2018; Ahmed and Mustafa 2019; Nouri

						et al. 2020; Robles-Martínez et al. 2020; Moosavy et al. 2023)
10	*Ocimum*	5	Leaves	3.5 to 95	Antimicrobial, Cytotoxicity	(Singhal et al. 2011; Patil et al. 2012; Ramteke et al. 2013; Brahmachari et al. 2014; Gudadh
						e et al. 2014; Logeswari et al. 2015; Tailor et al. 2020; Sharma et al. 2020; Abdelsattar et al. 2022; Nwabunwanne et al. 2023)
11	*Origanum*	2	Leaves	1 to 146	Antimicrobial, Anticancer	(Sankar et al. 2013; Hambardzumy

						an et al. 2020; Yassin et al. 2022)
12	*Perilla*	1	Leaves	20 to 70	Antimicrobial, Antioxidant, Anticancer, Cytotoxicity	(Reddy et al. 2021; Hou et al. 2023; Tavan et al. 2023)
13	*Phlomis*	1	Aerial parts	19 to 30	Antimicrobial	(Alafchian et al. 2016)
14	*Premna*	1	Leaves	9 to 35	Antimicrobial, Antioxidant, Cytotoxicity	(Singh et al. 2019)
15	*Rosmarinus*	1	Leaves	10 to 61	Antimicrobial, Antidiabetic, Antioxidant, Anticancer	(Ghaedi et al. 2015; Elme
						halawy et al. 2025)
16	*Salvia*	12	Leaves, Flower, Seed, Aerial part, Whole plant	1 to 60	Antimicrobial, Antioxidant, Anti-giardial, Scolicidal, Cytotoxicity	(Baghayeri et al. 2018; Hernández-Morales et al. 2019; Balčiūnaitienė et al. 2022; Mihailović et al. 2023; Mehdi Zabihi et al. 2024; Ihsan et al.

						2024; Dėnė et al. 2024; Grigoras and Grigoras 2024; Shaverdi et al. 2024; Zarei et al. 2024; Wahab et al. 2025)
17	*Satureja*	1	Leaves	2.9 to 3.4	Antimicrobial	(Rasaee et al. 2018)
18	*Scutellaria*	2	Leaves	22 to 58	Antimicrobial, Antioxidant, Cytotoxicity	(Veeraraghavan et al. 2021)
19	*Stachys*	3	Leaves, Flower, Aerial part	12 to 78	Antimicrobial, Antioxidant, Anticancer, Catalytic, Cytotoxicity	(Ghahari et al. 2023)
20	*Tectona*	1	Leaves, Seeds	10 to 30	Antimicrobial, Antioxidant	(Zanganeh et al. 2019; Dar et al. 2025)
21	*Teucrium*	2	Leaves, Flower, Stem, Aerial parts	8 to 100	Antimicrobial, Antioxidant, Cytotoxicity, catalytic	(Devadiga et al. 2015; Rautela et al. 2019; Younis et al. 2023)
22	*Thymbra*	1	Leaves	25.1	Antimicrobial, Cytotoxicity	(Erci et al. 2018)
23	*Thymus*	1	Whole plant	48	Antimicrobial, Antioxidant	(Balciunaitiene et

						al. 2021)
24	*Vitex*	1	Leaves	5 to 47	Anticancer	(Prabhu et al. 2013)

Biological application of Lamiaceae SNPs:

Antimicrobial activity of Lamiaceae-mediated SNPs:

Owing to the inappropriate overuse of antibiotics, a variety of human pathogenic bacteria, including *Staphylococcus, Salmonella, Pseudomonas, and Escherichia*, are becoming more resistant to antibiotics. Effective alternative antimicrobial techniques are urgently needed, as the development of multidrug resistance has become a serious worldwide health concern. Several studies have been performed to inhibit the growth of pathogenic bacteria by synthesizing Lamiaceae-mediated SNPs (Balciunaitiene et al. 2021; Mehdi et al. 2024). *Phlomis*-mediated SNPs inhibited the growth of Gram-negative (*S. typhimurium* and *E. coli*) and Gram-positive bacteria (*S. aureus* and *B. cereus*), whereas the plant extracts did not have antibacterial effects. Compared with Gram-negative bacteria, Gram-positive bacteria presented a lower zone of inhibition. This may be due to the presence of a thick peptidoglycan layer that impedes the entry of SNPs into the cell (Allafchian et al. 2016). P. frutescens-based SNPs have a relatively small diameter and positive zeta potential, which have been explored for their antimicrobial effects because of their high permeability within microbial cells (Tavan et al. 2023). The SNP made with *Rosmarinus officinalis* demonstrated strong antibacterial activity against Pseudomonas aeruginosa, with a minimum inhibitory concentration (MIC) of 32.5 µg/mL, which was significantly lower than that of the antibiotic chloramphenicol (250 µg/mL). The most likely reasons for the antibacterial activity were the easy penetration of SNPs in gram-negative bacteria due to the thinner peptidoglycan cell wall. The cytosolic contents of organisms can leach through porous membranes. Moreover, SNPs bind and fragment genetic material, degenerate enzymes, and destabilize the 70S ribosomal subunit, causing bacterial cell death (Reddy et al. 2021). The production of reactive oxygen species (ROS) is one of the main processes resulting in the ability of SNPs to combat bacteria. Research has demonstrated that SNPs dramatically increase intracellular ROS levels in bacteria, and this effect intensifies as the concentration of NPs increases. Bacterial membranes are damaged by oxidative stress caused by an overabundance of ROS. A confocal laser scanning microscopy study revealed that SNPs triggered membrane damage in *Pseudomonas aeruginosa*. The degree of membrane destruction was increased by increasing the dose and duration. The results also demonstrated that the release of bacterial protein and DNA increased after exposure to high concentrations of SNP. SNPs can destroy bacteria by blocking bacterial respiration. A study revealed that the levels of lactate dehydrogenase, a respiratory enzyme, and glutathione, an antioxidant enzyme in bacteria, were reduced in a concentration-dependent manner by SNP, thereby increasing bacterial susceptibility to oxidative stress. Biofilms are organized bacterial populations that lead to chronic illnesses and strong resistance to antimicrobial medications. According to previous studies, Pseudomonas aeruginosa biofilms can be considerably inhibited and disrupted by silver NPs (SNPs) in a concentration-dependent manner. SNPs impede both the formation of new biofilms and the survival of existing biofilms by penetrating the biofilm matrix, damaging bacterial membranes, blocking exopolysaccharide synthesis, and interfering with bacterial adhesion (Wahab et al. 2025). A schematic representation of the antibacterial activity of SNPs is given in Fig. 5. Lamiaceae-mediated SNPs have significant effects on plants as antifungal agents. *Salvia officinalis*, *Hyssopus officinalis*, *Teucrium polium* and *Lavandula intermedia*-based SNPs inhibit some plant pathogenic fungi, such as *Fusarium oxysporum* and *Aspergillus niger* (Elemike et al. 2017; Ghojavand et al. 2020; Dėnė et al. 2024). Compared with ethanolic plant extracts, SNPs synthesized using *Mentha piperita* ethanol extracts resulted in an 80% increase in the anti-biofilm activity. The synergistic effects of silver with plant metabolites include antibiofilm effects against *Candida albicans*, which can cause catheter-related infection (Robles-martínez et al. 2020). *Salvia mirzayanii* contains monoterpenes, which have antiparasitic activity. SNPs synthesized using essential oils exhibit anti-Giardia activity (Shaverdi et al. 2024). SNPs produced from Lamiaceae have been shown in antimicrobial investigations to have broad-spectrum activity against both Gram-positive and Gram-negative bacteria as well as fungi. However, variations in the physicochemical characteristics of nanoparticles, such as their size, shape, and surface chemistry, as well as variable experimental methods, have been observed in reported antibacterial effectiveness across the literature. Because of their higher surface area-to-volume ratio and improved ability to interact with membranes, evidence consistently indicates that smaller nanoparticles provide superior antibacterial activity. Gram-negative bacteria are frequently more vulnerable to SNPs than Gram-positive bacteria, according to some studies, potentially due to variations in cell wall morphology. Beyond the silver core itself, it is believed that phytochemical components obtained from Lamiaceae plant extracts and retained on the surface of the nanoparticle enhance antimicrobial effects through complementary mechanisms such as oxidative stress induction, membrane destabilization, and enzymatic inhibition. However, given the vast variation in MIC determination techniques, nanoparticle concentrations, microbial strain selection, and evaluation parameters, meaningful cross-study comparisons continue to be challenging. The tendency to solely attribute demonstrated bioactivity to silver nanoparticles without taking into consideration the independent or synergistic contributions of surface-bound phytochemicals is another prevalent shortcoming in the field. Because of this, the exact mechanistic functions of phytochemical action, reactive oxygen species production, and silver ion release are still not well understood. Future studies should use detailed mechanistic analyses and standardized antimicrobial testing frameworks to further develop the therapeutic potential of these nanomaterials.

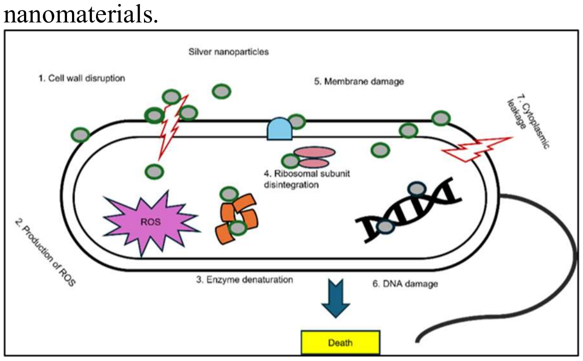

Fig. 5 Possible antimicrobial mechanisms of Lamiaceae-based SNPs

Antioxidant activity of Lamiaceae-mediated SNPS:

Many chronic illnesses are associated with oxidative stress, which is caused by excessive levels of free radicals and reactive oxygen species (ROS). Medicinal plants contain natural antioxidants that shield biological systems from oxidative damage. The plant-mediated synthesis of silver NPs can scavenge free radicals (Bedlovičová et al. 2020). Studies on Lamiaceae-mediated SNPs have demonstrated antioxidant capacities via DPPH (2,2-diphenyl-1-picryl-hydrazyl) and ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) radical scavenging assays. However, research has shown that due to the presence of phytochemical capping with two states of silver ions, plant-based SNPs have stronger antioxidant effects than plant extracts do (Balciunaitiene et al. 2022; Dar et al. 2025). Compared with the CA-SNP extract, the aqueous extract of *Coleus aromaticus* (CA) had a lower DPPH scavenging effect. A hydroxyl radical scavenging assay and ferric reducing power assay of CA-SNPs confirmed a concentration-dependent increase in antioxidant activity compared with that of the plant itself (Deepak et al. 2026). Some studies have shown that the increase in the radical scavenging effects of phytosynthesized SNPs is due mainly to the presence of antioxidant phenolic compounds such as flavonoids (baicalein, wogonin and their glycosides) as stabilizing agents of *Scutellaria multicaulis*-based SNPs (Gharari et al. 2023). The effective concentration in the antioxidant assay is a strong parameter defined as the concentration of compounds that scavenge 50% of the free radicals. Compared with the standard ascorbic acid (3.27 µg ml-1) DPPH scavenging assay, the rosemary-mediated SNP had a lower EC50 (7.81 µg mL–1) value. Researchers have demonstrated that this may be due to the upregulation of antioxidant enzymes, the neutralization of harmful effects of hydrogen peroxide, and the diminished effects of reactive oxygen species (Elmehalawy et al. 2025). The presence of phytochemical coatings on the nanoparticle surface, which are generally thought to contribute directly to claimed antioxidant activity, is a crucial difference between chemically manufactured and green-synthesised SNPs. Therefore, rather than the metallic component alone, the antioxidant benefits shown in several investigations are more likely to be due to a synergistic interaction between the silver nanoparticle core and its associated bioactive surface elements. When evaluating antioxidant results, phytochemical composition must be taken into consideration due to this mechanistic complexity. However, there is still a great deal of discrepancy between published results due to differences in assay selection, nanoparticle concentration ranges, reaction parameters, and the units employed to represent antioxidant activity, all of which significantly hinder cross-study comparability. The low extrapolation of in vitro antioxidant measures to biological systems raises further and more basic concerns because physiological efficacy in vivo cannot be accurately predicted by activity shown in restricted laboratory conditions. Therefore, it is still necessary to confirm the therapeutic relevance of many reported findings. In order to more thoroughly evaluate biological applicability and therapeutic promise, future research should integrate cellular and in vivo experimental models and focus on the systematic deconvolution of nanoparticle core and phytochemical coating contributions to overall antioxidant activity.

Anticancer activities of Lamiaceae-mediated SNPs:

Other anticancer agents, such as silver NPs, have tremendous effects. SNPs have demonstrated the ability to cause apoptosis-dependent programmed cell death in the absence of the tumor suppressor p53. When cancer cells lack the p53 protein, conventional cancer treatment frequently fails to induce cell death. The tumor suppressor protein p53 is crucial for interrupting the cell cycle and regulating stress signals linked to apoptosis. When Mentha arvensis-assisted SNPs were added to cancerous cell lines, some morphological changes, such as cell membrane destruction, cell shrinkage, chromatin condensation, fragmentation of nuclei, and the formation of apoptotic bodies, were observed. This finding confirmed the function of SNPs, as the absence of such features in the treatment of cell lines without SNPs (Reddy et al. 2021). SNP can suppress cancerous cell proliferation (Hamad et al. 2016). Compared with plant extracts alone and the common medication doxorubicin, silver NPs produced using *Perilla frutescens* flavonoid-rich fruit extract (PFFE-SNP) demonstrated noticeably greater cytotoxic activity against cancer cell types. The anticancer effects of plant-assisted SNPs are linked to several mechanisms, such as the induction of apoptosis through caspase activation, the production of reactive oxygen species (ROS) that cause oxidative stress, the disruption of the cell cycle through cyclin-dependent kinase inhibition, and the suppression of angiogenesis through vascular endothelial growth factor (VEGF) inhibition (Hou et al. 2023). A flow cytometry study employing Annexin-V/PI labeling demonstrated that silver NPs made from *Salvia miltiorrhiza* leaf extract strongly triggered apoptosis in MDA-MB-231 breast cancer cells. Compared with that of untreated control cells, the percentage of cells that underwent early and late apoptosis increased after treatment with SmL-Ag-NPs, suggesting that programmed cell death was successfully induced. The overall number of apoptotic cells significantly increased, indicating a SNP-specific lethal effect on cancer cells. Reactive oxygen species (ROS), which cause oxidative damage to biological components and ultimately result in cell death, are likely linked to apoptotic activity (Gharari et al. 2023). After treatment with SNP, some morphological changes in cancer cells, such as rounded, granulated, shrunken, and migrated, cause monolayer disintegration, with changes in the level of nuclear DNA breakdown, mitochondrial dysfunction, oxidative stress, and caspase activation, leading to programmed cell death (Fig. 6). SNPs also disrupt the cell proliferation signaling system of cancer cells, thus inhibiting tumor formation. It can hamper the immune response in abnormal malignant cells (Elmehalawy et al. 2025). Numerous investigations have shown that SNPs generated from Lamiaceae cause apoptosis via the production of reactive oxygen species, mitochondrial malfunction, DNA fragmentation, caspase activation, and cell cycle arrest. The corresponding role of each pathway, however, is still unclear and may differ. Additionally, by working in concert with silver-induced oxidative stress pathways, phytochemical residues adsorbed on nanoparticle surfaces may improve anticancer efficacy. The majority of research is still restricted to in vitro tests, despite numerous papers reporting encouraging cytotoxic effects against cancer cells. There is currently a dearth of data from clinical research and animal models. Furthermore, it is challenging to make direct comparisons between research due to significant differences in experimental conditions, nanoparticle concentrations, exposure durations, and cancer cell types. The absence of a thorough assessment of long-term toxicity to healthy cells and tissues is another significant drawback.

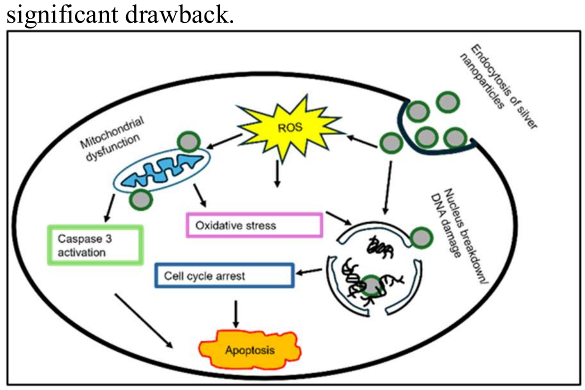

Fig. 6 Possible anticancer activity of Lamiaceae-based SNPs

Study of cytotoxicity:

The human body can be exposed to SNPs in various ways, and SNPs may affect the respiratory, digestive, and reproductive systems, among other systems. The precise mechanisms underlying their toxicity remain unknown, particularly whether the toxicity is attributable to the NPs themselves or to released silver ions. The characteristics and poor biological consequences of NPs can be inhibited by green synthesis methods, which change the particle size toward large particles with coated surfaces (Zhang et al. 2022). *Scutellaria tebesana*-assisted SNP significantly decreased the viability of normal fibroblasts at the highest tested concentration (2 mg/ml). Overall, the plant extract and its produced SNP had negligible cytotoxic effects on normal fibroblasts, suggesting that they may be harmless and selectively harmful to cancer cells (Mehdi et al. 2024). This finding is also supported by other experimental results showing lower IC50 values in cancer cells than in normal cells when treated with *Rosmarinus officinalis*-mediated SNPs. These findings indicate that SNPs are effective against cancer cells and have diminished side effects on normal cells (Elmehalawy et al. 2025). Compared with particles synthesized by physical and chemical methods, plant-based silver NPs are more environmentally friendly and have lower phytoremediation impacts.

Challenges:

The field of green technology-based SNP synthesis is expanding, with a vast array of potential applications. Sustainable production of plant-derived NPs can facilitate the development of effective methods to treat a variety of fatal illnesses. However, there are numerous challenges in the approach to producing SNPs. According to numerous studies, silver NPs may have harmful impacts, which is a serious concern for applications associated with health. Oxidative stress induced by SNPs causes organ and cellular toxicity, and appropriate doses and surface designs are needed for biomedical applications (Xu et al. 2020). The accumulation of SNPs from long-term use has led to phytoremediation, an environmental concern. Although Lamiaceae-based SNPs are eco-friendly, devoid of toxic chemicals at the corona of the particles, the core remains unchanged. Silver ions from the core dissolved and released into the environment may produce complex molecules in nature. This can hamper the soil microbial community and cause other phytotoxic effects. Dose-dependent effects on those parameters need to be properly optimized (Ihtisham et al. 2021). Another technical challenge is to control the physicochemical properties of Lamiaceae plant-assisted SNPs. It can vary with the collecting season, the geographical region of the plant habitat, and the extraction conditions. The changes of the parameters directly affect the size, shape, surface charge, and polydispersity index of the SNPs. Without a laborious experimental framework for standardizing and an exact quantity of profiled phytochemicals, it can lead to batch-to-batch heterogeneity of the SNPs production. The complete identification of phytometabolites responsible for reduction and capping is needed to scale up production (Ahmed et al. 2016). Despite the strong antimicrobial and pharmacological potential of Lamiaceae-mediated SNPs, the main unresolved challenges are biosafety, environmental concerns, unregulated physicochemical properties, and a lack of reproducible and standardized plant-based protocols, which limit their practical application. Proper optimization of all the dependent variables, such as the concentration of plant extracts and silver salt, pH of the reaction media, reaction time, and temperature, is needed to minimize the toxicity of plant-based SNPs (Liaqat et al. 2022). Only changing one variable and keeping others constant, failing to recognize the interaction effects of the reaction parameters. Thus, response surface methodology-related multivariate optimization methodologies can help in the commercialization and deployment of the material.

Research gap and prospects:

There are still several unanswered questions regarding the environmentally friendly synthesis of silver NPs utilizing Lamiaceae family plants. Firstly, optimization of phytochemical content in the plant extract by fixing the plant collection season, region, extraction process, and use of the best solvents is a dearth of studies. Yet the majority of the green synthesis of nanoparticles did not focus on those variables, reporting only the nanoparticle synthesis process and characterization of the particles without metabolite profiling of the plant. This can resolve the replication problem related to phytochemicals-dependent physicochemical properties of SNPs and aid in large-scale production. The specific mechanisms of reduction, stabilization, and the synergistic role of phytochemicals in plant-based silver NPs are still unclear. Moreover, the Lamiaceae plant family contains thousands of species, but a small number of species have been explored for green technology. By finding correlations between particular metabolite classes and nanoparticle characteristics across phylogenetically related species, broadening the taxonomic scope of study could provide mechanistic insights in addition to diversifying the structural and functional array of the resulting SNPs. Biological activity of Lamiaceae-based SNPs is descriptive, and screening-based prediction is insufficient for therapeutic application. Although the majority of research has focused on antibacterial action, with little attention given to thorough toxicity evaluations, environmental effects, and large-scale production methods. However, the mechanism of these bioactivities is not clearly understood. These gaps must be resolved to utilize Lamiaceae-mediated SNPs sustainably and effectively. Furthermore, recent research indicates that phytochemicals affect the biological activity of nanoparticles as well as their production. Surface-bound phytochemicals synergistically help to improve antibacterial, antioxidant, and anticancer properties. However, a lot of previous work ignores the role of residual phytochemical coatings and instead approved biological effects only to silver nanoparticles. Future studies should concentrate on pinpointing the precise role of metabolites in nanoparticle formation and elucidating their synergistic participation in bioactivities.

Conclusion:

The present review systematically endorses experimental knowledge on Lamiaceae-mediated synthesis of SNPs, highlighting the promising potential of the plant species as environmentally friendly resource for biosynthesis of nanoparticles. The plants of this family are rich in phytochemicals like terpenoids, polyphenolic compounds, and flavonoids, which serve as reducing, capping, and stabilizing agents during nanoparticle fabrication. So, it can be helpful in nanotechnology to replace toxic chemicals as well as energy-consuming physical processes. Different reaction attributes control the physicochemical features of nanoparticles. Such as concentration of silver nitrate, plant extract, pH of the reaction media, temperature, and reaction time govern significant participation in determination of nanoparticle size, shape, and colloidal stability. Characterization of the green synthesized SNPs was performed using UV-visible spectroscopy, FTIR, XRD, SEM, TEM, EDX, and DLS, which demonstrated that most of the synthesized nanoparticles were spherical in shape, size range within 1nm to 100nm, with Surface plasmon resonance band in between 400-450nm. Instrumentation techniques also explored the involvement of plant matrix during the nano-synthesis process. The antimicrobial efficacy of the synthesized SNPs is the most abundantly studied bioactivity. The antimicrobial efficacy was revealed by the agar well diffusion assay, minimum inhibitory concentration, and antibiofilm assay, performed against broad-spectrum pathogenic Gram-negative, Gram-positive bacteria, and fungi. Some studies reported lower MICs than conventional antibiotics. The diversified mechanism of action of the SNPs has been discussed, such as cell wall disruption, ROS generation, and DNA damage. This Lamiaceae mediated SNPs showed promising potential to fight against antimicrobial resistant, a global concern. Antioxidant assessment utilizing ABTS, DPPH, and other techniques has revealed that Lamiaceae-based SNPs displayed significant free radicle scavenging ability of silver and synergistic contribution of phytochemicals. Furthermore, anticancer potential of SNPs was evaluated by in vitro cytotoxicity assay against various cell lines compared to normal cell line, demonstrating apoptosis-related mechanisms observed in carcinoma cells. Despite these findings, many challenges remain to be addressed before clinical application. These include optimized reproducible synthesis protocol, in vivo toxicological studies, precise elucidation of mechanism of action, and mass production methods. Furthermore, clarification of the role of phytochemicals during SNPs production can help to gain control over size and shape of the particles. The phytochemical-rich family Lamiaceae-mediated silver nanoparticles can drive the development of the next generation of the pharmaceutical industry, making meaningful contributions to green nanomedicine.

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Authors' contribution:
Conceptualization of the study [Sutapa Maiti & Nilanjana Banerjee], Literature search, data analysis, writing the original draft, and critical analysis [Sutapa Maiti], Supervision, reviewing, and editing the manuscript [Nilanjana Banerjee]. All authors read and approved the final draft.

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