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A review on green synthesis of silver nanoparticles (SNPs) using plant extracts: a multifaceted approach in photocatalysis, environmental remediation, and biomedicine

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A sustainable and viable alternative for conventional chemical and physical approaches is the green production of silver nanoparticles (SNPs) using plant extracts. This review centers on the diverse applications of plant-mediated SNPs in biomedicine, environmental remediation, and photocatalysis. *Ocimum sanctum* (tulsi), *Curcuma longa* (turmeric), and *Azadirachta indica* (neem) and many others are plant extracts that have been used as stabilizing and reducing agents because of their extensive phytochemical profiles. The resulting SNPs have outstanding qualities, such as better photocatalytic degradation of organic dyes like methylene blue, antibacterial efficacy towards multidrug-resistant pathogens, biocompatibility for possible therapeutic applications, and regulated magnitude (10–50 nm), enhanced rigidity, and tunable surface plasmon resonance. Significant effects of plant extract type, amount, and synthesis parameters on the physical and functional characteristics of SNPs are revealed by key findings. Along with highlighting important issues and potential paths forward, this review also

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underlines the necessity of scalable production, thorough toxicity evaluations, and investigating the incorporation of SNPs into commercial applications. This work highlights how plant-based SNPs can be used to address global environmental and biological concerns by straddling the division between sustainable chemistry and nanotechnology.

1. Introduction

Due to their incredibly small size (measured in nanometers) and elevated surface to volume ratio, which result in both physical and chemical changes in their properties when compared to most materials with the same chemical makeup, NPs are of great interest.¹ Inorganic NPs include semiconductor NPs (ZnS, CdS, ZnO), metallic NPs (Ag, Au, Al, Cu), and

magnetic NPs (Co, Ni, Fe), while organic NPs contain carbon NPs (fullerenes).² Due to their ecological compatibility, which is attributed to the value of materials produced from the environment. Over the past few decades, green metallic NP-centered goods have become increasingly accepted and popular in research. Given the wealth of resources found in the biosphere that fit into this category, a wide range of goods would always be available to fulfil the need for green NT.³ Plant components like leaves, pods, stem bark, roots, fruits, and others have long been used in the environment friendly synthesis of metallic NPs, including titanium dioxide, gold, copper, zinc, platinum, and silver.^{4,5} Plants have found use in the manufacture of metal NPs, specifically in the field of nanoparticle synthesis involving living organisms.⁶ Compared to other biological methods that are safe for the environment, using plants to synthesize NPs could be advantageous because it reduces the complex procedure of preserving cell cultures. It would be more beneficial for biosynthetic processes to make NPs extracellularly from plants or their extracts in a regulated way that considers their magnitude, dispersity, and form.⁷

One form of nanomaterial with several uses in food packaging, industrial operations, medicine, and water treatment is SNPs.⁸ Their remarkable electrical, thermal, optical, and biological characteristics which also bear similarities to those of noble metals like copper and gold—set them apart from other



Qurat ul ain

to further expand her expertise in the field.

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The goal of this study is to present a thorough background of the green synthesis, characteristics, characterization methods, and uses of SNPs in biological, industrial, environmental, biosensing, and photocatalytic fields. It also emphasizes new developments and viewpoints in this highly competitive field. The sources included in this review were chosen for their topical relevance, recent publications (mostly from the last ten years), and keywords related to the characterization, antibacterial, industrial, biological, environmental, and biosensor uses of SNPs as well as green synthesis.

2.1.1.1 Stabilizer's and capping agent role in green synthesis of SNPs.

SNPs may now be produced sustainably and environmentally by green synthesis, which replaces traditional chemical and physical processes. This method does not use harmful reducing chemicals or stabilizers because it uses biological

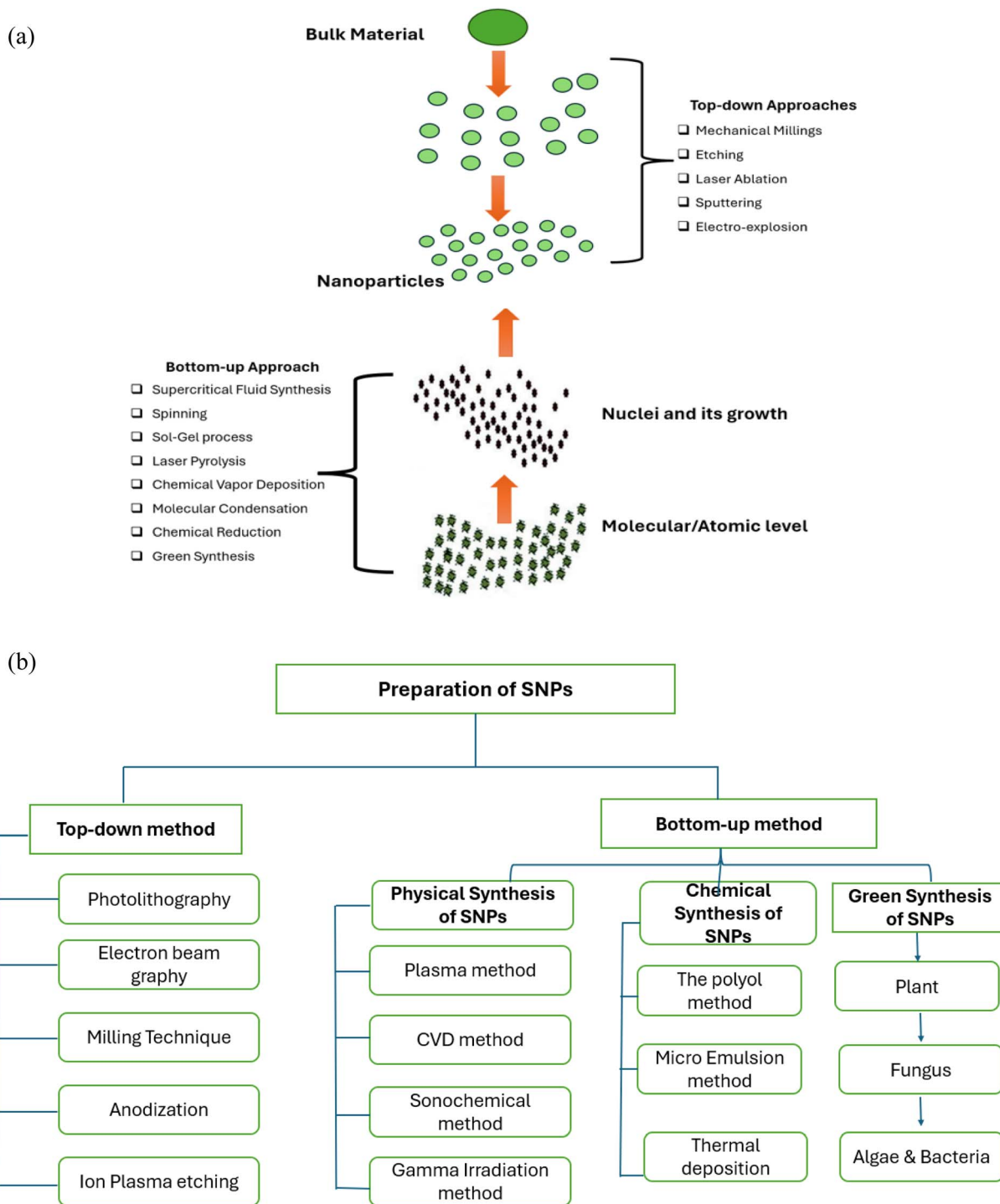


Fig. 1 (a) Methods for producing NPs.²⁹ (b) Enlisting the conventional and green synthesis methods of SNPs (reconstructed and modified from ref. 30).

organisms including fungi, algae plants, and bacteria to convert Ag ions into NPs. The rich source of secondary metabolites that are particularly favored are plant extracts, which serve as both capping and lowering agents.¹³ For example, it has been observed that the utilization of *Azadirachta indica* and *Eucalyptus globulus* plant extract results in SNPs with enhanced antibacterial capabilities as well as controlled size and form.¹⁴

Furthermore, *Syzygium jambos*,³² *Coriandrum sativum*,³³ *Prunus yedoensis*,³⁴ *Bunium persicum*,³⁵ *Vigna radiata*,³⁶ *Adenium obesum*,³⁷ and *Microsorium pteropus*³⁸ *Lantana camara*,³⁹ have all shown encouraging outcomes. In the same way, *Aspergillus niger* and other fungi have been employed to synthesize SNPs that indicate the function of fungal proteins in the maintenance route.^{37,40} Additionally, the algal-mediated production shows



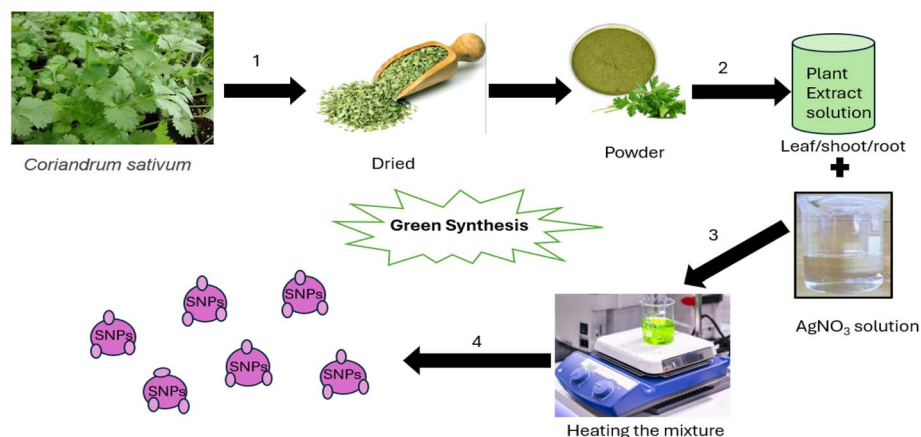


Fig. 2 Preparation method of synthesizing SNPs using *Coriandrum sativum* extract.

promise; in mild conditions, *Chlorella vulgaris* (algae like) can aid in the production of SNPs.^{32,33}

These characteristics make green synthesis a desirable choice for environmental and medical applications. The preparation of SNPs using green procedures is dependent on a number of aspects, including the amount of Ag ions, pH, the type of biological material, temperature, and reaction time. For example, the type of plant extract utilized can have a significant impact on the size and structure of the created NPs as described in Table 3. According to research by Singh *et al.* and Dutta *et al.* the aqueous extract of Parsley leaves generated sphere-shaped SNPs with a standard range of 20–30 nm.^{32,41}

Temperature and pH are examples of reaction parameters that might be quite significant. It has been discovered that in neutral pH conditions, increasing the reaction's temperature encourages the formation of smaller NPs.⁴² The reduction and stabilization processes are further aided by the presence of particular phytochemicals in the plant extracts, such as alkaloids, flavonoids and terpenoids. For example, employing extract from *Camellia sinensis* (green tea),⁴³ flavonoids have been found to be important reducing agents in the production of SNPs.⁴⁴ The green synthesis approach improves the biological activity of the NPs while simultaneously lessening its negative effects on the environment.

2.1.2 Reducing agents. Research has demonstrated that SNPs produced with environment friendly methods have strong antimicrobial, antifungal, and anticancer properties, which makes them appropriate for a variety of medicinal uses.⁴⁴ Fig. 2 shows the vivid representation of the synthesis manner, emphasizing important stages like the withdrawal of bioactive complexes from coriandrum and their contact with Ag ions, which alleviate the reduced Ag ions to form silver NPs, prevent accumulation, and yet bring about the formation of standardized particle dimension. Fig. 3 explained that the method involves multiple steps: (1) gathering fresh leaves, washing them well, and allowing them to dry at room *T* to obtain the plant, algae, or fungal extract; (2) making a fine powder out of the dried leaves and mixing it with distilled water to create an aqueous extract; and (3) heating the blend while continuously

moving it to assurance the withdrawal of bioactive constituents. Strain the extract to eliminate any solids and leave behind a pure solution when it has been heated, generating an AgNO₃ solution at a specific proportions. Next, stir the plant extract and water together in a 1 : 1 ratio while the liquid is still at room temperature. The reaction lasted for a few hours to ensure complete Ag ion reduction. (4) To obtain the final product, centrifuge the synthesized SNPs, rinse them in deionized water to remove any remaining Ag ions or nonreactive plant extract, and then dry them.⁴⁴ Factors that affect the green synthesis methods are discussed in Table 1. From the latest literature review, SNPs can be produced from different plant extracts (as shown in Fig. 3) and their diameter and shape from each plant extract obtained are discussed in Table 3.

3. Properties of SNPs

Having a thorough understanding of SNPs' characteristics is essential to maximizing their possible applications. For the purpose of determining how SNPs affect the environment, the benefits and drawbacks of employing them must be precisely measured. Research and exploration into the potential advantages of SNPs in various applications have been conducted extensively. Adverse effects of SNPs have also been studied by numerous studies. SNPs are discussed in this section along with their morphologies, sizes, crystalline structures, toxicity, and optical, electrical, and catalytic capabilities.

3.1 Structure and size of SNPs

SNP sizes and forms are highly dependent on the solution's concentration. For example, their size and distribution change in proportion to the quantity of precursor metal salts and polysaccharides. The investigation discovered that raising the silver nitrate amount from 2.5 to 15 mM produced bigger particles and Ag clusters. With a higher polysaccharide concentration, larger spherical SNPs were produced.⁹⁷ Raza *et al.* produced SNPs in a variety of sizes and morphologies by employing a variety of reducing and capping agents. According





Fig. 3 Synthesis of Ag NPs using plant extracts: (i) *Azadirachta indica* (neem)^{14,44,45} (ii) *Zingiber officinale* (ginger)^{46,47} (iii) cauliflower (*Brassica oleracea*)⁴⁸ (iv) *Coriandrum sativum* (parsley)^{49,50} (v) *Camellia sinensis* (green tea)^{43,51,52} (vi) *Beta vulgaris* (radish)^{53,54} (vii) *Solanum tuberosum* (potato)⁵⁵ (viii) *Allium cepa* (white onion)⁵⁶ (ix) *Ananas comosus* (pineapple)⁵⁷ (x) *Capsicum annuum* (red pepper)⁵⁸ (xi) *Citrus sinensis*⁵⁹ (xii) *Pandanus atropurpureus*⁶⁰ (xiii) *Eucalyptus globulus*¹⁴ (xiv) *Cannabis sativa*⁶¹ (xv) *Monstera deliciosa*⁶² (xvi) *Piper chaba*⁶³ (xvii) *Salacca zalacca* (snake fruit)⁶⁴ (xviii) *Pandanus tectorius*⁶⁵ (xix) *Adinandra poilanei*⁶⁶ (xx) *Tridax procumbens*⁶⁷ (a) *Musa acuminata* (banana peel)⁶⁸ (b) *Salvia officinalis*⁶⁹ (c) *Vernonia amygdalina*⁷⁰ (d) *Rangoon creeper*⁷¹ (e) *Conocarpus lancifolius*⁷² (f) *Mikania cordata*⁷³ (g) *Persicaria senegalensis*⁷⁴ (h) *Areca catechu*⁶⁶ (i) *Curcuma longa*⁷⁵ (j) *Alhagi graecorum*⁷⁶ (k) *Nervalia zeylanica*⁷⁷ (l) *Reynoutria bohemica*⁷⁸ (m) *Rhus chinensis miller*⁷⁹ (n) *Rhazya stricta*⁸⁰ (o) *Buchanania lanzan spreng*⁸¹ (p) *Morus rubra* (mulberry)⁸² (q) *Bombax ceiba*⁸³ (r) *Champia parvula*⁸⁴ (s) *Allium ampeloprasum*⁸⁵ (t) *Alpinia galanga*⁸⁶ (u) *Ocimum sanctum* (tulsi)^{87–89} (v) *Aloe barbadensis miller* (*Aloe vera*).^{90,91}



Table 1 Factors that affect the green synthesis methods^{30,92,93}

Factors	Description	Impact on NPs synthesis	Ref.
pH	How acidic or alkaline the reaction media is	pH has an impact on the nucleation and growing processes of NPs by changing the charge on their surfaces. Smaller particles are often produced by higher pH, but aggregation can occur at lower pH	94
Temperature	The temperature during the process of synthesis	Greater heat can cause aggregation; lower temperatures promote nucleation and reduction rates, resulting in lesser and more homogeneous NPs	95
Concentration	The quantity of reducing agent and metal precursor	Reducing agent amount impacts stability and reduction rate; higher precursor amounts enhance nucleation sites, producing reduced atoms but can also promote accumulation	49
Time	Time periods of reaction process	Affects the development and maturation of NPs Larger, more definite shapes might result from longer durations, but too much time can also lead to aggregation and polydispersity	30
Light intensity	Crucial factor that significantly impacts the synthesis of SNPs	Since UV light gives off energy that accelerates the reduction of silver ions, its function is very noteworthy	96

to their research, spherical SNPs with diameters of 15 and 43 nm can be created by 1 weight percent decrease of an aqueous starch solution of silver nitrate consuming NaOH and dextrose glucose at of 70 °C for 30 minutes.⁹⁸

Reducing agent impact on NP ranges at room *T* was also examined in their investigation. It was discovered that when the reducing agent was applied to the Ag salt in liquid crystalline pluronic P-123 and L-64, spherical Ag particles with a diameter of 8 and 24 nm were produced. In a separate procedure, when the silver nitrate precursor salt was reduced by NaOH in a combination of polyvinyl pyrrolidone (0.053 g) and ethylene glycol (11 g), SNPs were produced in the form of substantial 520 nm self-assembled cubes. Scientists concluded that SNPs may be synthesized into a range of shapes, including as mixed geometries, pure cubes, and stars, by using the capping chemicals PVP and poly(methyl vinyl ether) as shape-modifying agents. Conversely, spherical SNPs were produced by employing NaOH and D(+) glucose as reducing agents in a water-soluble environment.⁹⁹

Commonly the shape of SNPs has a significant impact on their characteristics. The result of intricate combinations of surface, crystalline, and molecular characteristics is morphological transformation. Numerous size- and shape-controlled synthesis techniques for SNPs have been suggested and improved in order to optimize their characteristics. We now have a good understanding of the connections between their morphology—such as size and shape—and certain attributes. For instance, the high surface-to-volume ratio of isotropic geometry—such as that of a spherical form—compared to anisotropic geometry was responsible for the higher antibacterial activity.¹⁰⁰

Smaller particles with a bigger surface area work better as antibacterials than larger ones because SNPs can contact bacterial cells. In terms of plasmonic characteristics, larger particles have a broader UV-vis absorption spectrum than smaller ones. Furthermore, the sizes of their NPs have an impact on their thermodynamic properties. For example, because of its surface free energy, bulk silver has a lower molar

heat capacity than SNPs. Furthermore, it has been demonstrated that NPs have a higher molar entropy than bulk silver. The entropy connected to the initial derivatives of Gibbs free energy is the cause of this. According to a review research, SNPs with common diameters in general applications fall between 1 and 10 nm. SNPs quantum confinement and surface area-to-volume ratio may be impacted by its size. SNP size may potentially have an impact on the presence of bacteria or viruses. SNPs between 1 and 10 nm, for example, have been demonstrated *in vitro* to interact with the HIV-1 virus *via* binding to the host cells. Furthermore, when compared to spherical and rod-shaped NPs, the truncated triangular NPs showed the highest biocidal effect against the Gram-negative bacterium *E. coli*.¹⁰¹

3.2 Toxic behaviour

The exceptional chemical characteristics of SNPs make them useful for a broad extent of purposes. Reports have shown that SNPs are especially efficient antimicrobials against viruses, eukaryotic and bacteria pathogens. SNPs have been linked to certain commercial products, such as feminine hygiene products and contraceptive devices, which may pose a risk to human reproductive health.¹⁰² SNPs have been linked to certain commercial products, such as feminine hygiene products and contraceptive devices, which may pose a risk to human reproductive health. The researchers reviewed the antibacterial activity of SNPs against *E. coli*. SNPs were used in the study at different doses ranging from 10 to 100 µg cm⁻³. Due to the widespread utilization of these materials in several fabrics and cosmetics, the number of dangerous SNPs that are exposed to human skin when using consumer goods may increase. Depending on the aggregate of silver coating, fabric quality, pH, and perspiration formation, SNPs may be released from consumer products. Utilizing fake individual covering, it was found that SNPs were secreted from antibacterial fabric goods into perspiration. In a different findings, SNPs used an *in vitro* method to cause skin cancer and human fibrosarcoma cells to undergo oxidative stress and death.¹⁰³



SNPs can also have a variety of detrimental effects, as numerous studies have shown. These effects include an increase in the oxidative stress and cytotoxicity of human hepatoma HepG2 cells, a decrease in the chemotaxis and proliferation of human mesenchymal stem cells, and more. As discussed before, the toxicity of SNPs depends significantly on their doses and sizes.¹⁰⁴ While there is ongoing discussion over their toxicity mechanisms, other potential pathways have been proposed. For example, structural alterations and eventual damage were brought about by the interaction of SNPs with bacterial membrane constituents, which ultimately resulted in bacterial cell death. On the other hand, SNPs cause cell harm by blocking the respiratory enzyme of bacteria and promoting the production of reactive oxygen. Furthermore, it's also feasible that the chemical changes that the NPs undergo during their intracellular operations is the driving force that causes the toxicity mechanisms. By employing this method, the chemical alteration of SNPs allowed for the successful capture of their 3D dispersion within a single human monocyte. According to the relevant study, elemental silver is converted to Ag⁺ ions and eventually Ag-S species, which are the principal processes indicating particulate silver's harmfulness.¹⁰⁵

3.3 Polycrystalline structures

XRD patterns can be used to reveal the crystalline configuration of SNPs. According to a number of studies, SNPs have a cubic structure, with peaks located at 38.06°, 44.22°, 64.48°, and 77.32°, respectively. These peaks correspond to the dispersing angle 2θ from the (1 1 1), (2 2 0), (2 0 0), and (3 1 1) planes. Furthermore, SNPs exhibit a diffraction pattern at 38.5, 44, and 64.5 (2θ). The fcc silver's (111), (200), and (220) planes can be indexed to these patterns.⁸

3.4 Qualities of optics

Numerous studies have demonstrated that SNPs use a process called the stimulation of localized surface plasmon resonance to grasp EM radiation in the range of 380 to 450 nm in visible

region.¹⁰⁶ It was discovered that the spherical SNPs produced by glucose reduction exhibited Surface Plasma Resonance (SPR) at 400 nm. Furthermore, for the same structure of SNPs formed following NaOH reduction, their analysis found that the NPs absorbed the highest EM radiation at 420 nm. Instead, the scientists illustrated that SNPs synthesized in various proportions using gallic acid utilizing an aqueous chemical reduction method.¹⁰⁷

It was shown that spherical SNPs with a diameter of 7 nm have an SPR at 410 nm, whereas those with a diameter of 29 nm have a resonance at 425 nm. Additionally, a broader band with an extreme at 490 nm was displayed by SNPs with proportions of 89 nm. The width of SPR was found to be correlated with the size distributions of the NPs. SNPs with irregular shapes may exhibit two or more plasmon resonances, contingent upon the proportion of the nanoparticle. The results presented above indicate that sensor devices may be able to make use of SNPs. Their special qualities have recently been exploited to their advantage as sensors for the sensitive colorimetric detection of Cr in vegetable samples, industrialized wastes, and surface waterways.¹⁰⁸ Additionally, the essential micelle concentration of cationic surfactants was found using their superior qualities. Furthermore, it was discovered that their antibacterial activity was dependent on surface plasmon resonances. Furthermore, an SNP-based sensor opens the door to ultrasensitive bio-detection studies using incredibly straightforward, compact, lightweight, durable, and affordable equipment. It has been shown that SNPs increase the signal strength of surface-enhanced Raman scattering (SERS) filter paper. As an alternative, they can be applied to enhance solar cell performance (Table 2).⁹⁷

3.5 Thermal attributes

A material's thermal behaviour is a crucial factor that is carefully considered throughout production or application. Because of the thermodynamic size effect, metal NPs have an amazing low melting temperature. It was frequently used for a variety of

Table 2 Summary of physical properties of some plants^{109,110}

Plant source	Size	Shape	Optical properties	Toxicity
<i>Azadirachta indica</i> (neem)	10–30 nm	Spherical	Sharp SPR peak around 400–420 nm, characteristic of smaller nanoparticles	Low toxicity towards mammalian cells; eco-friendly. Antibacterial activity reduces microbial toxicity
<i>Camellia sinensis</i> (green tea)	10–15 nm	Spherical to slightly oval	Strong SPR peak around 420 nm, indicating small and uniform size	Low toxicity is considered biocompatible. Suitable for biomedical applications
<i>Ocimum sanctum</i> (tulsi)	20–50 nm	Spherical	Moderate SPR peaks around 420–440 nm. Slight red-shift with larger size	Low toxicity, no significant adverse effects on human cells
<i>Zingiber officinale</i> (ginger)	30–50 nm	Spherical to slightly oval	SPR peak around 420–430 nm with good intensity	Low toxicity; non-toxic to humans with potential for biomedical applications
<i>Aloe vera</i>	20–50 nm	Spherical	SPR peak at around 430 nm, moderate intensity	Biocompatible, very low toxicity, suitable for cosmetics and biomedical uses





Table 3 Synthesis of SNPs using variety of plant's extract and their morphology

Plant name	Plant part	Diameter of NPs (nm)	Type of NPs	Shapes of NPs	Ref.
<i>Zingiber officinale</i> (ginger)	Rhizome	28–105	Ag	Spherical	46 and 111
<i>Cauliflower (Brassica oleracea)</i>	White flower	25–100	Ag	Globular	48 and 112
<i>Coriandrum sativum</i> (parsley)	Fresh leaves	8–75	Ag	Spherical	33, 49 and 50
<i>Camellia sinensis</i> (green tea)	Dried leaves	77.4	Ag	Spherical	32, 43, 51, 52 and 113
<i>Beta vulgaris</i> (radish)	Root	15	Ag	Spherical	53 and 54
<i>Solanum tuberosum</i> (potato)	Potato tuber	20	Ag	Spherical	55 and 92
<i>Allium cepa</i> (white onion)	Inner layer	10	Ag	Spherical	47 and 56
<i>Ananas comosus</i> (pineapple)	Leave	40–150	Ag	Hexagonal spherical shape	57 and 114
<i>Capsicum annuum</i> (red pepper)	Fresh leaf	19	Ag	Spherical	58
<i>Citrus sinensis</i>	Fruit peel	25	Ag	Spherical	59
<i>Pandanus atroparpus</i>	Leaves	14	Ag	Spherical	60 and 115
<i>Eucalyptus globulus</i>	Leaves	34.21	Ag	Spherical	14 and 116
<i>Cannabis sativa</i>	Seed	43	Ag	Triangular and quasi-spherical	61 and 117
<i>Monstera deliciosa</i>	Leaf	Spherical NPs = 25–78 Small = 25–40 Large NPs = 40–78	Ag	Spherical	62 and 118
<i>Piper chaba</i>	Stem	19	Ag	Face centered cubic and spherical	63
<i>Salacca zalacca</i> (snake fruit)	Fruit peel	10–50	Ag	Spherical	64
<i>Pandanus tectorius</i>	Aerial roots	10–20	Ag	Spherical	119–121
<i>Adiantum polianei</i>	Leaves and twigs	12–20	Ag	Spherical	66 and 122
<i>Tridax procumbens</i>	Leaves	11.1–45.4	Ag	Spherical	67
<i>Musa acuminata</i> (banana peel)	Banana peel	10–20	Ag	Spherical	123–125
<i>Salvia officinalis</i>	Leaf	41	Ag	Spherical	69, 126 and 127
<i>Rangoon creeper</i>	Leaves	12	Ag	Oval shaped	71 and 128
<i>Conocarpus lancifolius</i>	Leaves	5–30 nm	Ag	Spherical	7, 72 and 129
<i>Mikania cordata</i>	Leaves	26.8–46.0	Ag	Spherical	73 and 130
<i>Persicaria senegalensis</i>	Leaves	23–71	Ag	Diverse shapes including spherical	74 and 131
<i>Areca catechu</i>	Leaves and twigs	12–20	Ag	Spherical	66 and 132–134
<i>Curcuma longa</i>	Leaf	15–40	Ag	Spherical	92 and 135
<i>Alhagi graecorum</i>	Leaves	22–36	Ag	Spherical	76 and 136
<i>Ocimum sanctum</i> (tulsi)	Fresh leaves and stem	17	Ag	Spherical	87–89
<i>Nerolia zeylanica</i>	Leaf	34.2	Ag	Spherical	77
<i>Reynoutria bohemica</i>	Leaf	40–50	Ag	Spherical	78
<i>Rhus chinensis</i> mill	Root and leaf	54.40–30.89	Ag	Spherical	79
<i>Rhazya stricta</i>	Leaves	21–90	Ag	Oval-circular	80
<i>Buchanania lanzan spreng</i>	Green leaves	23–62	Ag	Spherical	81
<i>Morus rubra</i> (mulberry)	Leaves	15–20	Ag	Spherical	82
<i>Bombax ceiba</i>	Stem and flower	19.4–20.6	Ag	Spherical	83 and 137
<i>Champia parvula</i>	Seaweeds	79	Ag	Round	84
<i>Allium ampeloprasum</i>	Aerial part	8–50	Ag	Spherical	85 and 138
<i>Alpinia galanga</i>	Stem	50–90	Ag	Spherical	86
<i>Azadirachta indica</i> (neem)	Leaves	30–50	Ag	Spherical	123
<i>Vernonia amygdalina</i>	Leaves	10–30	Ag	Spherical	70
<i>Aloe vera</i>	Fresh leaves	15	Ag	Spherical	90 and 91

objectives. To investigate the thermal characteristics of SNPs, thermogravimetric analysis or differential scanning calorimeters are frequently used.¹⁰⁷ The Gibbs–Thomson equation is another method for studying the thermal properties of NPs theoretically. More specifically, a material's melting point is important for a number of uses. Because the surface-to-volume proportion in bulk material is low, surface influences on melting point can be disregarded. On the other hand, the melting point of nanomaterials with a high surface-to-volume ratio varies with their size.¹⁰⁶ Thermodynamic theory provides an excellent explanation for this behaviour. There have been numerous experiments carried out to support this notion. The melting temperatures of SNPs with proportions ranging from 4 to 50 nm were examined in these investigations. It was discovered that melting happened at lower temperatures as the size of SNPs shrank. The thermal behaviour of SNPs with sizes ranging from 3 to 6 nm was investigated in a distinct study.¹⁰⁸ It was discovered that SNPs heated to 100 °C did not exhibit any appreciable size changes. Conversely, the samples that were heated to 150 °C had a much higher melting point. Furthermore, at 200 °C, the SNP particle size gradually grew, signifying total melting. Moreover, DSC curves displaying a strong exothermic peak at 150 °C further supported this melting temperature. The average thermal conductivity of bulk silver is 429 W m⁻¹ K⁻¹. According to researchers, SNPs own a 0.37 W m⁻¹ K⁻¹ thermal conductivity. The analysis's minimal result suggested that organic surfactants were present and were stabilizing the NPs in the solution by coating them.¹³⁹

3.6 Electrical characteristics

SNPs can be used in electronic devices because of their special electrical properties. SNPs produced in glass-ceramic medium and ranging in size from 4 to 12 nm were tested for electrical conductivity. 211 SNP films' DC electrical resistance was assessed between 80 and 300 K in temperature. From 120 to 300 K, it was discovered that the surface resistivity rose linear with temperature. The study's other key discovery was that as SNP size increased, so did the effective Debye temperature.¹⁴⁰ As an alternative, SNPs were used in electrically conductive adhesives (ECAs) as conductive fillers. The charge on a particle in the suspension is represented by this parameter. It can also be utilized as a predictor of the colloidal system's possible stability. This characteristic can be described using the widely used technique of dynamic light scattering. All of the particles in suspension have a large negative or positive zeta potential, which suggests that there is no inclination for the particles to flocculate and instead, they tend to reject one another.¹⁴¹ A low worth for this value, on the other hand, indicates that the elements tend to flocculate. Since for this link, Singh *et al.*⁴¹ examined the zeta potential of the hexagonal and spherical SNPs.

It was discovered that the potential of hexagonal and spherical SNPs was -15.3 and -5.11 mV, respectively. These results suggest that compared to spherical SNPs, hexagonal SNPs are more stable. In comparison to isotropic NPs, anisotropic NPs contain more edges and a larger surface area.

Consequently, the anisotropic NPs exhibit an increased amount of negative charge.¹⁴²

3.7 Catalytic features

SNPs have been used as efficient catalytic agents to reduce a variety of dyes, including methyl orange, eosin, yellow-12, methylene blue and Rose Bengal.¹⁴¹ It was discovered that SNPs produced by the peach kernel shell approach might act as a catalyst to convert 4-nitrophenol into 4-aminophenol. Without the catalyst, the reduction process might take 200 min. On the other hand, with the catalyst present, the reduction took 105 s to complete, using the ideal settings of 10.0 mg SNPs and 250 mM NaBH₄.¹⁴³ In contrast, 4-nitrophenol can also be reduced by using resin-Au NPs, gum acacia-Pt NPs, Nipolyvinylamine/SBA-15 composite, SNP-seashell, and Ag/TiO₂ nanocomposite; the last two methods require 8 hours 20 min, 85 min, 4.5 m, and 2 min to completely reduce the compound.¹⁴⁴ Among the previously mentioned suggested catalysts, SNPs-peach kernel shell is the most effective in terms of time. Moreover, their NPs were seen to reduce methyl orange more quickly than those of SNP-seashell, Cu NP, mesoporous silica SBA-15, and Ag/TiO₂ nanocomposite.¹⁴⁵ Similar outcomes were seen when the NPs were utilized to reduce methylene blue more successfully than SNP-seashell, porous Cu microspheres, and Ag/TiO₂ nanocomposite.¹⁴⁶ In the presence of NaBH₄, the reduction mechanisms of a number of dyes utilizing SNPs have been demonstrated to adhere to the Langmuir–Hinshelwood model. NaBH₄ modifies the pH of the entire solution by acting as an e⁻ and H donor.^{147,148} Subsequently, the SNP undergoes a positive surface charge change prior to BH₄⁻, and the dye is simultaneously adsorbed on the SNP surface. Following their receipt from tetrahydridoborate ion, the SNPs transfer the electrons to the dye molecules. Furthermore, the hydrogenation of azo dyes is facilitated by a significant amount of hydrogen provided by NaBH₄ when SNPs are present.¹⁴⁹ Additionally, the end product may desorb to a colorless state due to SNPs' enormous surface area.¹⁵⁰

4. Mechanistic pathway of SNPs synthesis *via* plant extracts

Since past few decades, SNPs have emerged as one of the most widely studied subjects. Their benefit in many applications is their capacity to build SNPs using various synthetic methods based on the desired properties and applications. The most favorable synthesis method nowadays is green synthesis of SNPs. To develop new techniques for creating NPs, researchers are focusing on the green synthesizing process because it is both economical and eco-friendly. The synthesis of large-scale NPs, which could only be accomplished at the laboratory scale, was done using the green method.¹⁰² SNPs have found extensive use in food packaging, medical equipment, and other products due to their potent antibacterial action. Gaining a deeper comprehension of SNPs toxicity and probable toxicity mechanisms is becoming essential due to the growing usage of SNPs.¹⁵¹ SNPs synthesized by using plants are the easiest to



prepare.^{152–157} SNPs need Ag^+ ion solution and reducing unit. The main challenge is the reduction followed by the stabilization of the Ag^+ ions. It can only be completed by combining Ag^+ with other biomolecules like vitamins, amino acids, alkaloids, terpenes and proteins, these are the simplest and cheapest way to synthesize NPs. It is possible to use any plant to prepare SNPs. Plant-based green NPs are also less expected to have serious adverse effects on human beings in comparison to the chemical and physical methods, but these also have widespread applications.

4.1 Role of phytochemicals in the Ag ion reduction

Development of metal NPs by a variety of phytochemicals like cellulose, protein, flavonoids, alkaloids, polysaccharides, along with some other secondary metabolites,¹⁵⁸ the modest and cost-effective approach to synthesize NPs. The amount of the reducing agent utilized in the extraction process determines the size of the NPs. Metal ions can be depleted into the metal NPs by the involvement of the hydroxyl group.¹⁵⁹ Extracts obtained from different plants can serve as stabilizers and reductants in the production of metal NPs. NPs are created when different extracts of plants are combined with the solutions of metal and salt. A color shift brought on by the reaction will indicate the formation of NPs. There is a strong demonstration of the fact that wide range of phytochemicals, including proteins, polysaccharides, phenolic compounds, alkaloids, and flavonoids, can produce metal NPs. SNPs are synthesized *via* biochemical, physical, and organic (biological) processes in nanotechnology.¹⁶⁰

For metallic NPs, there are two synthetic methods: bottom-up method and top-down method.¹⁶¹ Several methods are used in the former one to reduce the magnitude of a suitable bulk material into smaller particles. In the later approach, atoms will self-assay themselves into new nuclei, which subsequently expand and form many nanoscale particles, to generate NPs through chemical and biological means. So, one can produce atomic or molecular nanostructures and controlled synthetic forms of certain nanomaterials by looking at the structures of the reactants and target products. One popular technique is chemical reduction, which converts Ag into SNPs but requires a reductant.¹⁶² Common reductants such as citrate,¹⁶³ sodium borohydride¹⁶⁴ and block copolymers¹⁶⁵ play a significant part in ensuring the stability of the SNPs.¹⁶⁶ Production of the SNPs is done by first reducing the Ag^+ ions into the Ag^0 and then by performing the capping of the reduced Ag^0 . This phenomenon is presented in Fig. 4 given below.



Fig. 4 Reduction and capping of SNPs¹⁶⁷

The process of formation of SNPs starts with the generation of Ag atom that will be used as a precursor for the formation of Ag^+ ions. More and more atoms assemble together and form a cluster that regulates the magnitude and form of SNPs. With its extended applications, the advantages of the chemical reduction process seem to be more obvious. The biggest benefit in this method is that extensive quantity of NPs can be produced without difficulty.^{2,168} However, some drawbacks of using this chemical reduction method for synthesis of SNPs are also there. Reductant, metal precursor, and agents responsible for stabilization or capping, like polyvinylpyrrolidone, are needed to confirm stable chemically synthesized colloids. These kind of chemical waste and substrates are damaging for human beings.¹⁶⁹ Naturally occurring phytochemical compounds like terpenes, ketones, flavonoids, aldehydes, as well as carboxylic acids are efficient free radical scavengers. They function as stabilizers and potent reductants in the generation of NPs generation.¹⁷⁰ More studies have revealed that characteristics of the synthesized NPs fluctuate significantly because they are dependent on the part of the plant obtained in the form of extract and then utilized for the synthesis of the SNPs. Saratale *et al.*¹⁷¹ used green leaves of *Punica granatum* to make SNPs. Most ideal SNPs are sphere-shaped, with size ranging from 20 nm to 45 nm. Abbasi *et al.*¹⁷² successfully synthesized SNPs, using bio extract of purple basil.

4.2 Mechanistic pathways of SNPs formation

There is not any well-explained mechanistic pathway for the synthesis of SNPs. The supposed mechanistic pathway for the production of NPs is an enzyme catalyzed reaction in which complex of enzymes that causes reduction are derived from plant extracts which reduce $\text{Ag}(\text{NO}_3)_2$ into Ag^+ and NO_3^{2-} ions as shown in flowsheet diagram Fig. 5a and b. Composite network of metabolites acting as anti-oxidants along with enzymes of the selected plant work together to inhibit oxidative loss occurring in cellular components. Extract derived from plants encompasses biomolecules containing ketones, alkaloids, β -phenylethylamines ascorbic acid, triterpenes, sterols, polysaccharides, and fructose along with enzymes which can be successfully used as reducing agent to react with Ag^+ ions, consequently utilized as frameworks to direct the production of SNPs in the solution. Theoretically, biosynthesized cofactors play a crucial part in reducing the corresponding salts to NPs. Though, it looks possible that NPs are synthesized using glucose and ascorbate to reduce AgNO_3 and HAuCl_4 .^{173–176} Terpenoids act as surface active molecules when neem broth is taken as substrate, which help in stabilization the NPs and reaction is probably facilitated by proteins and reducing sugars containing amino groups, also played dynamic part in the reducing SNPs produced through *Capsicum annum* extract. There is a change in the secondary structure of proteins that was also formed after reacting with Ag ions.^{178,179}

Leaves of *Ficus benghalensis* leaf comprise of large number of antioxidants and polyphenols like flavonoids and quercetin can be used for scavenging molecular species of active oxygen. Hydrogen atoms can donate electrons or hydrogen atoms which



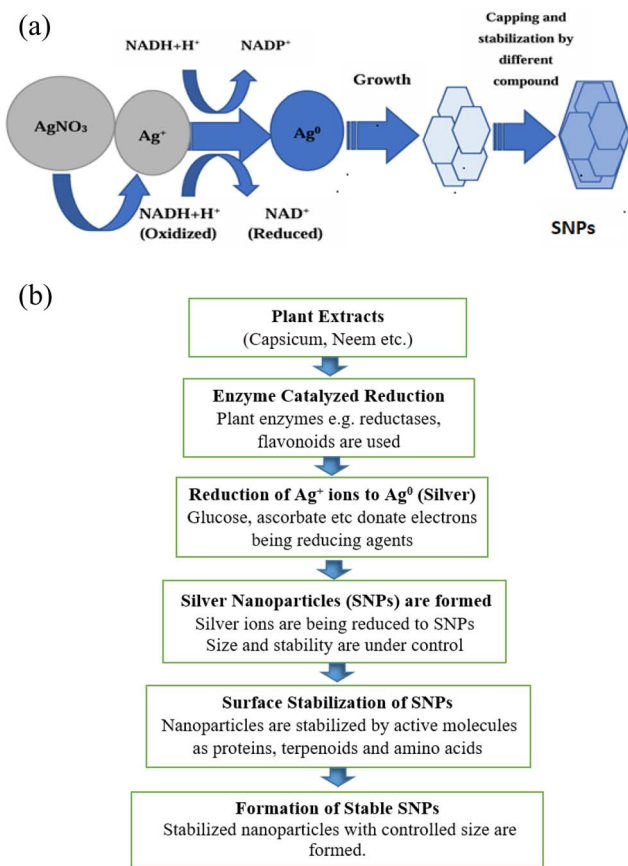


Fig. 5 (a) The supposed biosynthesis mechanism of SNPs.¹⁷⁷ (b) Flowsheet diagram showing mechanistic pathway of SNPs.

help them in their antioxidant action, which will then act as a precursor for changing keto form to enol group. Proteins, phenolic compounds, and other chemicals present in the extract obtained from the leaf of different plants reduce Ag salts and also provide tremendous persistence against accumulation, which can be used to apprehend the mechanistic pathway of development by biological systems.^{176,180}

4.3 Influence of plant components on the synthesis of SNPs (plant metabolites)

The utilization of bio-mediated routes for SNPs synthesis is appealing due to its ability to produce nontoxic and cost-effective NPs in a single step. Additionally, the production of SNPs can be regulated in size and shape, depending upon the extent of interaction among SNPs and the phytochemical capping agents used in the respected process. The precise interaction between the Ag salts and phytochemicals in the solution that react to form SNPs must be identified and understood. The precise interactions between all phytochemicals have not yet been determined, despite the fact that a widespread phytochemicals, such as amides, flavonoids, and peptides, have been identified as being involved in SNPs biosynthesis.¹⁸¹ Alkaloids can operate as reducing agents while terpenoids along with flavonoids mostly act as capping and

stabilizing agents, while protein and carbohydrates play its part as reducing as well as stabilization agents throughout the transformation of metallic salts to metallic NPs.

4.3.1 Flavonoids. Plants include well-known secondary metabolites called flavonoids. Plants produce secondary metabolites due to biotic and abiotic stress; flavonoids are also one of them. The synthesis pathways and structural variations of flavonoid are subjected to variation. As a result, leaves, flowers, fruit skin, *etc.* contain them. Among the flavonoids are anthocyanidins, flavanols, flavanones, flavan-3-ols, flavones, and iso-flavones.¹⁸² Studies have shown that electrons as well as hydrogen-donating ability of the flavonoids make them attractive agent for the synthesis of NPs.

4.3.2 Terpenoids. These are naturally occurring substances that plants release in reaction to biotic and abiotic stressors. The terpene synthase gene is activated by stimulation, which leads to the production of terpenes. Naturally occurring organic molecules, terpenes assemble differently and are generated from five-carbon isoprene units. These types of organisms have the capacity to create both mono-terpenoid and sesquiterpenoid. Terpenes in their oxygenated form are called terpenoids. Terpenoids are a class of chemical molecules that are a constituent of the essential oils that plants contain. Out of roughly 3000 recognized essential oils, only 300 are significant from a business standpoint. A basic hydrocarbon molecule called an isoprenoid is frequently present in terpenoids and all other secondary metabolites.¹⁸³ Terpenoids with a lot of potential for depleting Ag^+ ions into metal oxide NPs include eugenol and methyl chavicol (estragole).¹⁸⁴

4.3.3 Alkaloids. These find applications in a variety of pharmacological settings. Alkaloids have also been utilized as drugs to treat serious illnesses. One alkaloid that is employed as an insecticide is atropine. Treatment for ovarian cancer involves the use of paclitaxel and its derivative.¹⁸⁵ Quinine is another kind of alkaloid, it was used in the treatment of the malaria. It can be found in cinchona tree bark.¹⁸⁶ The production of amino acids such as proline, ornithine, *etc.* is the first step in the synthesis of alkaloids. Afterwards, these amino acids become alkaloids.¹⁸⁷

4.4 Factors affecting synthesis

Certain physiochemical characteristics, including temperature, time, pH, optical, substrate concentration, and enzyme sources, influence the creation of NPs. The information in Table 1 provides the explanation of different factors that affect the synthesis of SNPs.

4.4.1 Effect of temperature. The primary physical factor influencing NP production is temperature. According to reports, $\text{Ag}(\text{NO}_3)_2$ and starch solution can be autoclaved at 121 °C and 15 psi to create SNPs.^{188,189} Ag and iron NPs were synthesized at standard room temperature utilizing plant's extracts, like aqueous extracts of sorghum bran, according to Njagi *et al.* (2011).¹⁸⁹ The temperature also affects the additional stability of the NPs; the SNPs produced are kept between 18 and 25 °C for two to three months.¹⁹⁰



4.4.2 Effect of concentration of the substrate and the reducing agents. SNPs synthesis can be influenced by amount of plant extract and salt concentrations.¹⁹¹ Ag nitrate (AgNO_3) is often employed as a precursor for the production of NPs by using Ag ions. The size and rate of the NPs is greatly influenced by the quantity of salt present in the solution. Larger NPs sizes are frequently the outcome of higher salt concentrations since there are additional Ag ions available for carrying out the reduction. Conversely, low concentration of the salt can produce smaller NPs.¹⁹² Plant extracts have a wealth of bioactive chemicals, which makes them useful as stabilizing and reducing agents when making NPs.¹⁹³ Increasing the quantity of plant extract can result in larger NPs and a quicker elimination of Ag ions. But excessive concentrations can also lead to inadequate reduction or aggregation, which degrades the NP's quality. The preparation of NPs using chemical methods, such as Tollens' reagent (ammonical Ag nitrate), that causes the reduction of carboxyl group of substrates of sugar like $\text{C}_6\text{H}_{12}\text{O}_6$ and ribose, can provide a better understanding of the effect of pH. The size of the NPs is dependent on the ammonium concentration, and this reaction causes the development of a stable complex ion due to ammonia's strong attraction for Ag^+ . Therefore, it is thought that concentration of ammonia and type of reductant used both have a significant influence on the formation of SNPs.¹⁹⁴

4.4.3 Effect of pH. Another physical element which influences the morphology (size and shape) is pH.¹⁹⁵ Particle size is influenced by the structural differences between disaccharides and monosaccharides. At pH 11.5, disaccharides in this reaction often yield smaller particles than monosaccharides. Furthermore, compared to particles formed at pH 12.5, those obtained at pH 11.5 were smaller. One way to reduce polydispersity is to lower the reaction medium's pH.

5. Types of plants used for synthesis

5.1 Examples and case studies

Although the mechanism behind the process of reducing metal ions using green extracts was initially recognized in the early 1900s, it was not fully understood. Subsequently, a variety of metals have been effectively decreased by the use of numerous parts and materials of plants. While throughout the previous 35 years, there has been great attention of scientists towards the biosynthesis of SNPs utilizing extracts from different parts of plants or even the entire plant.¹⁹⁶ Temperature, reaction pH, contact time, and the relative quantities of plant extract and metal salt are some of main variables affecting kind, yield, quality, and characteristics of SNPs produced.¹⁹⁷ SNPs were synthesized utilizing *Z. officinale* and *O. gratissimum*, and UV-vis spectra was examined to verify their identity in detail.¹⁹⁸ SNPs were bio-synthesized utilizing waste extract from cauliflower and their prospective uses in the light – mediated catalytic degradation of methylene blue dye Hg^{2+} bio sensing were further tested.¹⁹⁹ The thrombolytic action of *Coriandrum sativum* extracts and *Murraya koenigii* leaf extract carried out manufacturing of SNPs. The aim of the study was to create the SNPs made from *Murraya koenigii* and *Coriandrum sativum*

which will have the capacity to lyse clots. GC-MS analysis was performed on the methanolic extract that was extracted from both leaves. After the produced NPs from leaf extracts were analyzed, the standard pattern and peaks were obtained by using XRD technique.²⁰⁰ A wide range of plant extracts, including those from lucerne, pine, persimmon, magnolia, platanus, apple, pineapple, and ginkgo, were used extensively in the biosynthesis of SNPs. Similarly, it was discovered that the extract of *Phyllanthus amarus* (stone breaker) leaves was useful in the synthesis of SNPs because of its antibacterial and catalytic qualities. Furthermore, *Beta vulgaris* L.'s aqueous extract showed promise for SNPs biogenesis since it contains pigments, vitamins, manganese, folate, and magnesium in addition to other nutrients that help in the reducing the metal ions to NPs. SNPs biosynthesis is dependent on several important parameters, including as pH, Ag nitrate concentrations, and incubation time.²⁰¹ The aqueous extract of pineapple peel was used to create, describe, and assess SNPs. Colloidal solutions of SNPs exhibited highest absorption at approximately 460 nm following the optimization of SNPs production.²⁰² *Capsicum annuum*, a chili pepper that is grown all over the world and is highly acknowledged for accumulating large amounts of active chemicals, is a viable option for SNPs biosynthesis. The aggregation of $4.38 \text{ mg g}_{\text{DW}}^{-1}$ of total capsaicinoids, $14.56 \text{ mg}_{\text{GAE}}^{-1} \text{ g}_{\text{DW}}^{-1}$ of total phenol containing compounds, $1.67 \text{ mg}_{\text{QE}}^{-1} \text{ g}_{\text{DW}}^{-1}$ of total flavonoids, and $1.03 \text{ mg}_{\text{CAE}}^{-1} \text{ g}_{\text{DW}}^{-1}$ of total phenolic acids was revealed by phytochemical screening of the aqueous extract of *C. annuum* pericarps. Every identified aromatic compound has a variety of active functional groups that contribute to SNPs production and have a strong potential for antioxidants. As a result, the current study concentrated on the simple, rapid, and efficient process for the bio-synthesis of SNPs, which were then examined for their morphology, including size and form (shape), using scanning UV and FTIR along with some other techniques.²⁰³ The fabrication of metal NPs using green extracts especially plant extracts has garnered more interest because of its numerous applications, low cost, and less toxic consequences. SNPs were created using an extract from *Eucalyptus globulus*. SNPs formation was verified by observing the color shift from light brown to reddish brown. It was further confirmed by observing the peak of UV-vis spectral lines at 423 nm.²⁰⁴ In Indonesia, people eat the pulp of the snake fruit, but discard its peel. In this case, the aqueous extract of snake fruit's phytochemical composition not only aided in reduction process carried out for the creation of SNPs. The phytochemical screening revealed that SNPs were synthesized using snake fruit peel, which contains tannins, alkaloids, saponins, flavonoids and polyphenols.⁶⁴ *Salvia officinalis* extract obtained from its leaves was effectively used in the biosynthesis of SNPs. SNPs are created by causing the reduction of metal salts from Ag^+ to Ag^0 , which releases the abundant phyto-constituents found in extracts of plants, like flavonoids, alkaloids, and terpenoids. It was further verified by FTIR and EDX signals obtained by the observation of their spectra. This method of creating NPs was widely accepted because it is economical, non-toxic, sustainable, and environment friendly.²⁰⁵



5.2 Phytochemical profile of different plants

The selection of the extract of various species of the plants may also be important because selected plants may have such kind of molecules which can take part in reduction and stabilization of NPs. Different plants, their family name and details about the size and shape of the NPs have been discussed in the table given below (Table 4). A detailed reference to the phytochemicals accountable for the reduction of the Ag salt along with the applications is also debated. The majority of the SNP particles made using plant components produced spherical SNPs, typically measuring between 5 and 85 nm in size.²¹⁶ However, employing *Eclipta prostrata* leaf extract, non-spherical SNPs, in the form of triangles, pentagons and hexagons were also recorded. The reaction took place at room temperature, and the particle size was observed to be varied in between 30-60 nm.²¹⁷ Similarly, the seeds of *Artocarpus heterophyllus* and *Trachyspermum ammi* were used to create both cubic and irregular SNPs.²¹⁸ Reaction times for biosynthesis varied from 10 to 300 minutes at room temperature. One explanation for the Ag precursor's bio-reduction was the high concentration of biomolecules found in the various plant components, including the leaves, seeds, fruits, bark, flowers, and roots. These biomolecules could include a wide variety of biomolecules, including alcohols, alcoholic compounds, alkaloids, alkynes, amino acids, amide, amino acid residues, ascorbic acid, anthraquinones, benzoates, carotenes, carbohydrates, flavonoids, glycosides, leucocyanidin, saponins, proteins, phenolic compounds, steroids, sugars, traces of reducing sugars, tri-terpenes, and vitamin C.²¹⁹

The bacterial cell death brought about by SNPs piercing the cell wall and triggering the bacterial degradation in cytotoxic assays employing cell lines of humans further confirmed the efficacy of SNPs manufactured utilizing floral extracts as anti-bacterial agents. Additionally, it was demonstrated that SNPs demonstrated effective catalytic activity by producing active free radicals ($\cdot\text{O}_2^-$, $\cdot\text{OH}$, and $\text{HO}_2\cdot$) that could reduce cationic dyes like methylene blue when NaBH_4 was present.²²⁰ Additionally, fruit extract (*Lycium barbarum*) mediated SNPs are generated and effectively employed as sensors.²²¹ While in 2019 Ameen *et al.*²²² described the successful synthesis of SNPs using flower extracts of *Mangifera indica*, there was no indication of phytochemical accountable for reduction. Some other scientists mainly Hamedi and Shojaosadati²²³ however, involve a broad screening and characterization of the phytochemicals in case of the synthesis of SNPs.

5.3 Bio synthesis using some other parts of plant

Fast biosynthesis of SNPs using plant extracts has been stated by some other plant parts like pericarp extracts of *Sapindus emarginatus*,²²⁴ *Musa* sp. (banana) peel extract *Allium stipitatum* (shallot),²²⁵ and apricot tree gum,²²⁶ latex extract of, ²²⁷ inflorescence of *Cocos nucifera*,²¹⁵ and banana peel extract.²²⁸ The majority of the biosynthesized SNPs were spherical and had particle sizes ranging from 4 to 60 nm, similar to the majority of other plant extract-derived NPs. Alcohol, amines, amide II, aldehydes, carbohydrates, carboxylic acid, alkanes, amino

Table 4 Some plants used in the synthesis of SNPs¹⁸¹

Sr. no.	Plant	Family	Size of SNPs (nm)	Shape	Phytochemicals required for Ag salt reduction	Applications	Ref.
1	<i>Alpinia officinarum</i> (rhizome)	Zingiberaceae	20 to 80	Hexagonal	Amides, polypeptide, carbonyl groups	Photocatalytic degradation of methylene blue	206
2	<i>Centella asiatica</i>	Apiaceae	30 to 50	Spherical	Proteins, polyphenols, terpenoid, flavonoids	Catalytic degradation of methyl red, methyl orange	207
3	<i>Aegle marmelos</i>	Rutaceae	22.5	Hexagonal, roughly circular, spherical	Phytosterols, flavonoids, and amino acids	Antibacterial activity	208
4	<i>Bergenia ciliata</i>	Saxifragaceae	25 to 73	Spherical	Flavonoids, amino acids, and pigments	Antibacterial activity	209
5	<i>Gracilaria birdiae</i>	Gracilariaceae	20.2 to 94.9	Spherical	Polysaccharide	Antibacterial activity	210
6	<i>Dunaliella salina</i>	Dunaliellaceae	15.26	Spherical	Peptide, polyphenolic	Anticancer potential	211
7	<i>Waltheria americana</i>	Malvaceae	7 to 24	Rectangular flakes	Alkaloids, anthraquinones, glycosides, phenols, terpenoids	Antibiotic and antimicrobial activity	212
8	<i>Areca catechu</i>	Arecaceae	18.2	Spherical	Polyphenols	Catalytic antioxidant activity	213
9	<i>Delphinium denudatum</i>	Ranunculaceae	<85	Spherical	Proteins, terpenoids, amine, alcohol, ketone, aldehyde and carboxylic acid	Antibacterial and mosquito larvicidal activities	214
10	<i>Punica granatum</i> (peel)	Lythraceae	30	Spherical	Hydrolysable tannins, chebulic, ellagittannins, esters, gallic acid, and chebulic acid	Catalytic activity on reduction of methylene blue	215



acids, carbonyl compounds, cellulose, ester, hemicelluloses, hydroxyl group, lycopene, pectin, proteins, vitamins (K, C, E), and β -carotene were among the biomolecules found to be involved in bio reduction.⁴⁴

5.4 Comparative analysis of different plants in SNPs synthesis

Although the synthesis of SNPs *via* chemical and physical means has been thoroughly investigated, one crucial area of nanotechnology is the development of dependable NPs production technologies.²²⁹ Synthesis of the NPs by chemical and physical means may have substantial ecological defect, and are usually expensive.¹¹⁵ The biological methods, using enzymes and microorganisms, have been suggested as possible eco-friendly substitutes.¹⁷³ Green synthesis of the NPs, which is carried out by using plants or plants extract which aids in reduction of synthesis process, are more advantageous over other biological processes.²³⁰

Additionally, plant-mediated synthesis of NPs is favored because it is an inexpensive, environment friendly, single-step process, safe for use in human therapy, and can be easily considered for large-scale synthesis. They do away with the complex process of culturing and maintaining the cell. This green synthesis approach appears to be a non-toxic, economical, ecofriendly alternative to the conventional microbiological, chemical and physical methods. It would be suitable for developing an organic process for large-scale production. These SNPs might be applied to lower the microbial burden throughout the waste treatment process.²²⁸

5.5 Gaps and future research in synthetic mechanism

5.5.1 Specific mechanisms of reduction. The precise mechanisms by which phytochemicals reduce silver ions remain unclear. Further research is required for elucidating the molecular interactions between numerous phytochemicals and silver ions. Additionally, the role of specific functional groups in plant metabolites necessitates further investigation.¹⁹⁹

5.5.2 Size and shape control. Controlling the size, shape, and morphology of silver nanoparticles is vital, yet the underlying mechanisms are not fully implicit. While certain conditions, such as pH, temperature, and concentration, manipulate these characteristics, a more nuanced understanding of their relationship at the molecular level is prerequisite.

5.5.3 Toxicity and biocompatibility. The potential toxicity of silver nanoparticles produced employing plant extracts is an arduous concern. The potential toxicity of silver nanoparticles produced employing plant extracts is an arduous concern. Further investigation is essential to evaluate the environmental and health bearings of these biosynthesized nanoparticles.

5.5.4 Interaction with plant components. The interactions between plant components, such as secondary metabolites, and silver ions are complex and multifaceted. Further exploration is desirable to elucidate how these interactions manipulate the synthesis mechanism, morphology, and stability of nanoparticles.

5.5.5 Scalability. While laboratory-scale synthesis has been considerably investigated, scaling up the green synthesis process for industrial applications establishes significant challenges. Developing standardized protocols and understanding the challenges of large-scale production are indispensable for practical applications which further requires extensive research.

6. Characterization of SNPs

Measurement of size, behavior as well as nanostructure of the NPs was made possible with the use of different characterization techniques. There are diverse techniques designed for the analyzation of the NPs. These take into account UV-vis spectroscopy,²³¹ SEM, FT-IR, TEM, XRD, and SAED, as some important characterization techniques. Moreover, there are techniques like EIS and Photocurrent measurements that are considered for measuring the performance of Ag@m-TiO₂.

6.1 UV-visible spectroscopy

The modest and potent technique for the determination of characterization of synthesized NPs is the use of UV-vis spectroscopy. SNPs are able to interlink with particular wavelength of light due to their photosensitive characteristics.²³² A UV-vis spectrophotometer is capable of characterizing variety of NPs morphologies. It is a quick, practical, and careful method for characterizing NPs.²³³ Due to closeness of valence and convection bands, electron mobility is permitted. These free electrons oscillate when exhibited to light waves, which is the reason for the development of SPR. The environment of chemicals and particle size affects the absorption of light by NPs.^{234,235} A detailed spectra of the SNPs prepared by using pure plant extract and mixtures of the plant extracts of capsicum, garlic and ginger has been discussed in Fig. 6 given below. Fig. 6a shows the pure plant extract while Fig. 6b shows the mixture of plant extracts.

UV-vis spectroscopy has shown that SPR peaks at the same wavelength, supporting the constancy of SNPs produced *via* biological processes for over a year. To provide comprehensive information regarding SNPs, UV-vis spectroscopy by itself would be inadequate. Within the reaction media, the UV-vis spectra of SNPs were monitored at 15, 30, 45, and 60 minutes, respectively. The results of the performed research indicated that the SNPs from garlic, ginger, and cayenne pepper caused absorbance peaks extending between 375 nm and 480 nm. A strong resonance was seen at 375 nm, 400 nm, and 480 nm for the first, fifteen, and sixty minutes, respectively.

The SNPs steadily developed throughout the course of the following 24 hours, as indicated by the UV-vis spectra, in less than 60 minutes. The results of the 15 minutes experiment revealed that after a considerable degree of decreasing capacity, the strongest plasmon bands were found at 480 nm in cayenne pepper and the strongest bands between 400 nm and 435 nm in ginger. At 375 nm in spectrum obtained by using UV-vis technique, garlic's SNPs were absorbed. We used absorption spectroscopy to study the optical properties of SNPs. The UV-vis spectra showed a characteristic peak at 440 nm, which verifies the synthesis of SNPs (Fig. 6).²³⁶



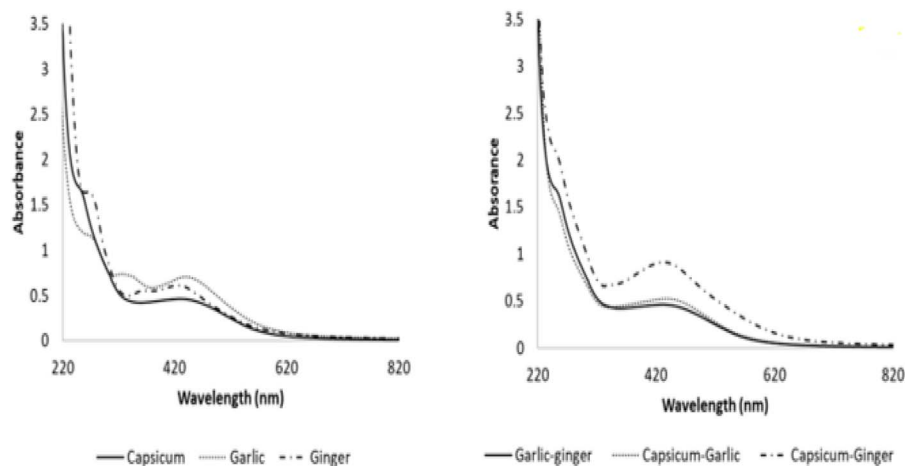


Fig. 6 UV-vis spectra of SNPs (left) extracts of pure plants, (right) extracts obtained from mixtures of plant extracts²³⁶

6.2 Scanning electron microscopy

This electronic microscopy is the unique process that managed to capture molecules' surface structure. It aids in analyzing the dimensions and dissemination of NPs.^{237,238} When used in combination with SEM, EDX, it provides insight into the sample's constitution.²³⁹ Using SEM, only the external surface of the sample can be analyzed, excluding internal details, while the degree of purity and the presence of aggregates can be assessed.²⁴⁰

The composition, shape, and size distribution of SNPs are among those variables that may significantly impact their antibacterial activity. Thus, SEM was used to characterize the form and size of SNPs. The images of SNPs obtained from SEM are displayed in Fig. 7. The measurements of the capsicum (Fig. 7a), garlic (Fig. 7b) and ginger (Fig. 7c) has been determined. According to SEM data, the produced SNPs' size was less than 100 nm.²³⁶

6.3 Transmission electron microscopy

It is a prominent, widely used, and crucial method to calculate the arithmetical values of particle distribution, magnitude, and form. By removing the objective lens from the sample and

its image plane, one can calculate the magnification of the TEM.²⁴¹ The method works well for analyzing the volume fraction and the NPs' shape. In addition to offering finer structural resolution, it can be used for additional analytical measurements.²³¹ TEM makes use of beam of electron that intermingles with the sample to generate an image on the photographic plate. Individual NPs' chemical and electrical structures can be ascertained using this technique.²⁴² Consequently, TEM provides improved resolution and sample information presentation.²⁴³

It is cleared from Fig. 8 given above that Garlic (Fig. 8a), ginger (Fig. 8b), and cayenne pepper (Fig. 8c) all had average diameters of 5.28, 12.97, and 10.86 nm, respectively. Moreover, spherical morphologies with homogeneous particle size distribution have been observed by using TEM imaging of SNPs generated from the spice extracts.

6.4 Fourier transform infrared spectroscopy

Physiochemical properties of particles are analyzed using this method to find out the role played by biomolecules in the creation of metallic NPs.²⁴⁵ In addition, since the functionally active molecules will be imbedded onto the metal during the

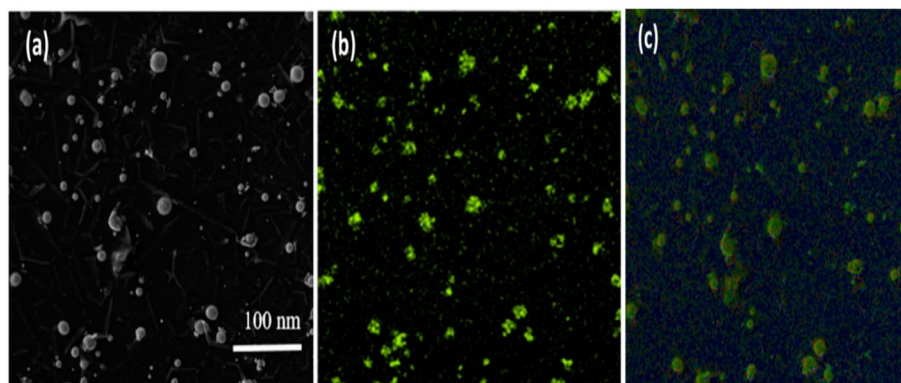


Fig. 7 SEM measurements of (a) SNPs with capsicum (b) SNPs with garlic (c) SNPs with ginger.²³⁶

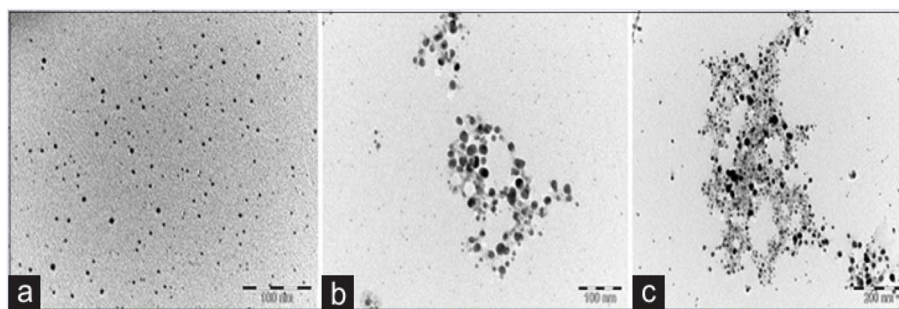


Fig. 8 Micrographs of SNPs taken through TEM (a) garlic, (b) ginger, and (c) cayenne pepper.²⁴⁴

catalytic process, FTIR can disclose the information exchange between the substrate and the enzyme.^{183,246} In this technique, an IR beam of radiation enters the taken sample and infiltrates or is absorbed by the remaining portion. The radiation that the sample has absorbed and transmitted can be inferred from the changing spectrum. Less sample heating and quicker data gathering are made possible by FTIR. In light of this, it is thought to be a useful, non-invasive, and practical method for characterizing NPs.

Fig. 9 given above gives detailed information about the FTIR spectra of the SNPs of garlic, ginger and cayenne pepper.

6.5 Selected area electron diffraction (SAED)

There are two main reasons why TEM is better than SEM: it can perform more thorough research and has a higher resolution. The high vacuum requirement, small sample size, and labor-intensive sample preparation procedure of TEM are major downsides. One of the convenient technique for visualizing and analyzing the crystalline structure of NPs is SAED (Selected Area Electron Diffraction). Electron scatter-back diffraction studies are commonly carried out in TEMs by means of

electrostatic attraction, which accelerates the electrons to the proper frequency and velocity prior to their interaction with the material under examination. After becoming polydisperse, SNPs were mostly spherical, having an average diameter of about 14 nm.⁽¹⁰⁶⁾

6.6 X-ray diffraction

This widely used method for analyzing NPs determine the crystalline formations, statistical complex magnification, various chemical types, the degree of crystallinity, and physical characteristics.^{247,248} Interference between the scattering X-rays was observed by applying Bragg's equation to the polycrystalline material's property.²⁴⁸ Thus, a broad variety of substances, such as biomolecules, polymers, super conductors, and so on, that can be investigated using XRD research. The only way to analyze the components stated above is to look for diffraction peaks. The physical and chemical characteristics of crystal molecules can be investigated using this method.²⁴⁹ It can be used to examine crystalline materials that are inorganic or inorganic in their nature (Fig. 10).

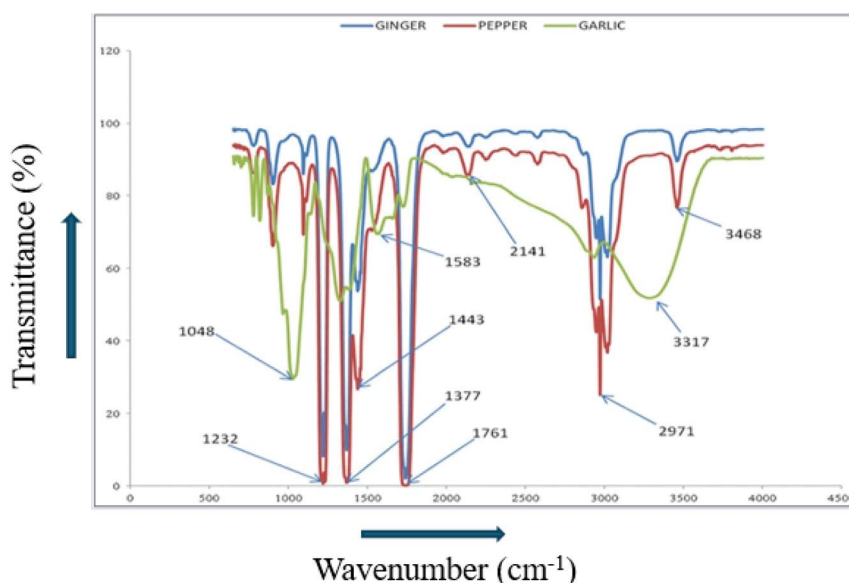


Fig. 9 FTIR spectra of SNPs from garlic, ginger, and cayenne pepper²⁴⁴



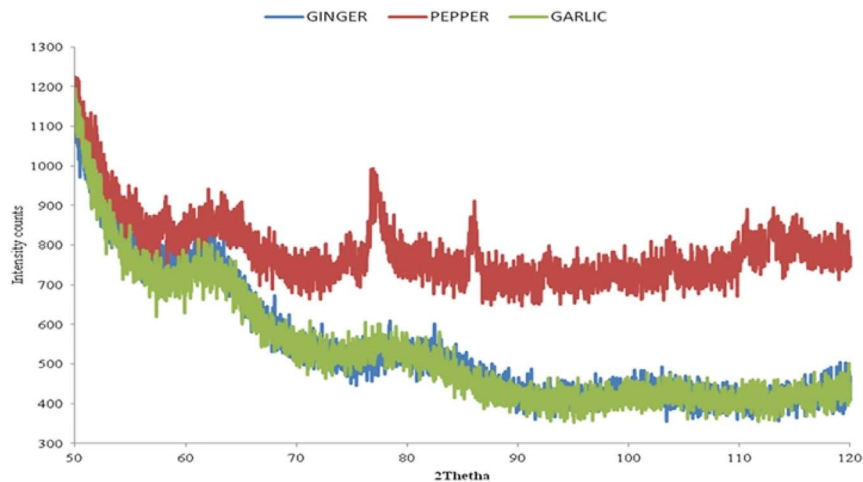


Fig. 10 XRD of SNPs obtained by using garlic, ginger, and cayenne pepper²⁴⁴

6.7 EIS (electrochemical impedance spectroscopy) measurements

In order to manufacture SNPs, several contemporary methods additionally use titanium oxide nanotubes (TNT) as a base. To recognize the effect of SNPs and flaws in *m*-TiO₂, measurements of the Ag@*m*-TiO₂ nanocomposite, EIS and LSV measurements were taken by exposing it to visible light is used in addition to other techniques. It helps in understanding their photo-electrochemical behavior. EIS is a potent method for measuring the separation efficiency of the photo-generated the charge transfer resistance and electron-holes and over the surface of photo-electrodes.²⁵⁰ Smaller radius of arc in the EIS plot generally shows lower electron transfer resistance, which usually leads to quick charge shift and more successful segregation.⁹² The Ag@*m*-TiO₂ photo-electrode had the lowest semi-circular arc when compared to the other photo-electrode containing *p*-TiO₂ and *m*-TiO₂. This implies faster interfacial charge transfer and better partition of the photo-generated electron-hole pairs under the irradiation of visible light. This implies that the synergistic effects of defects and SPR lead to the highly productive of photo-initiated electrons into holes. This improves the photoelectrochemical performance by facilitating quicker charge transfer between the surfaces of the photo-electrodes. These results are also consistent with photocatalysis activity.²⁵¹

6.8 Measurement of photocurrent

For the exploration of the synergistic outcomes of the SPR phenomena of SNPs and flaws in *m*-TiO₂ on the visible light outcome of Ag@*m*-TiO₂, LSV was implemented for the Ag@*p*-TiO₂ and Ag@*m*-TiO₂ nanocomposites under light and in dark along with *p*-TiO₂ *m*-TiO₂ (107) In comparison to the *m*-TiO₂ NPs, the photoelectrode containing *p*-TiO₂ NPs showed a reduced photocurrent response; due to wider band gap. Conversely, attaching SNPs to the *p*-TiO₂ NPs significantly amplified the photocurrent responsiveness. The Ag@*p*-TiO₂ NPs showed elevated photocurrent than the *p*-TiO₂ and *m*-TiO₂ NPs because

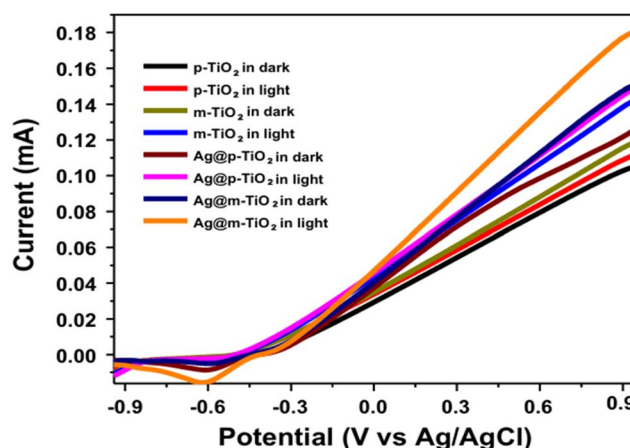


Fig. 11 Linear scan voltammograms of the *p*-TiO₂ and *m*-TiO₂ NPs as well as Ag@*p*-TiO₂ and Ag@*m*-TiO₂ nanocomposites photoelectrodes in the dark and under visible light irradiation.²⁵³

SNPs exhibit SPR. After the SNPs were anchored at outer area of the *m*-TiO₂ NPs, the photocurrent reflux significantly enhanced due to the synergistic outcomes of the defects in the NPs and the SPR phenomena of the SNPs. The Ag@*m*-TiO₂ photocurrent enhancement revealed improvements in both the photo-generated electron-hole pair separation and the photoinduced carrier transport rate. A different theory is that a Schottky junction forms at the metal-metal oxide border, which could help in isolating the holes and photoelectron as well as in increase in the photocurrent.²⁵² Observing these results, it was reported that the *m*-TiO₂ NPs' surface flaws and the SPR phenomena detected on the SNPs work together to enhance their visible light harvesting capabilities (Fig. 11).

7. Applications

In recent years, significant progress has been made in the plants-based synthesis of SNPs. Hence being used in tremendous fields including antimicrobial activity, biomedical,



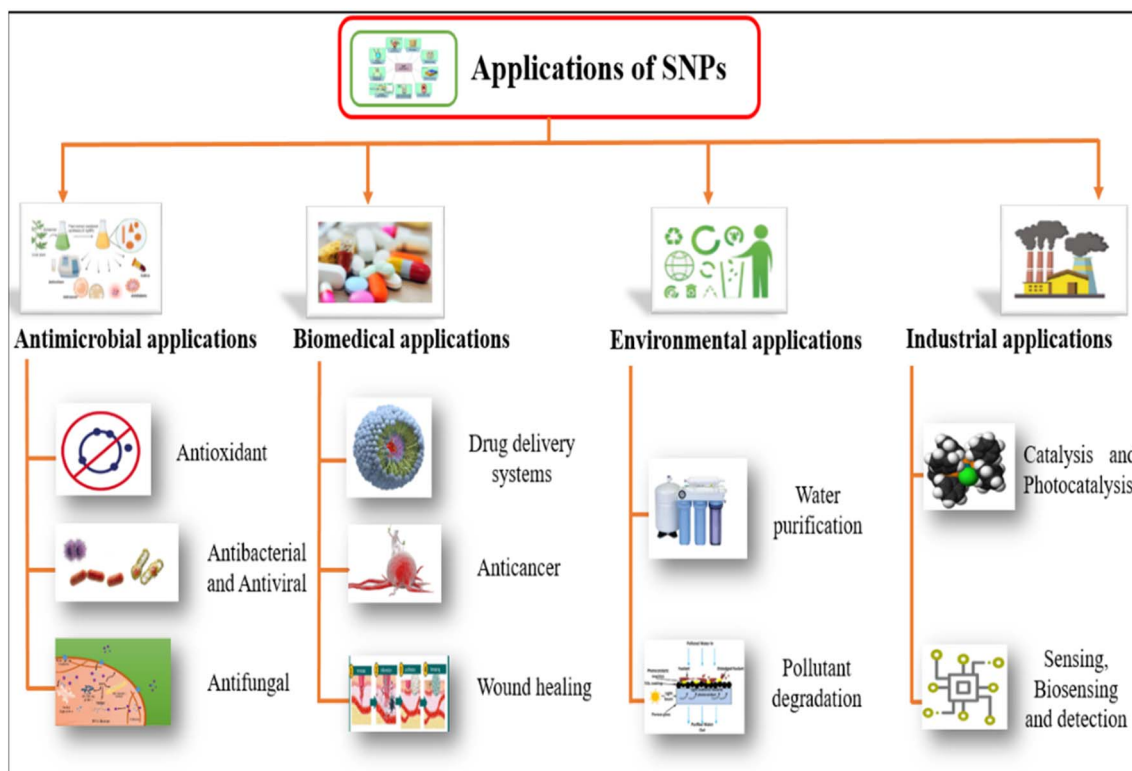


Fig. 12 Applications of plants-based SNPs in various sectors.²⁵⁴

environmental and industrial applications. Weather utilized in medicines, cancer treatment, wound healing, drug delivery systems, water purification, pollutant degradation, catalysis or sensing and detection. SNPs have shown strong applications prospects. Applications of SNPs in various sectors have been shown in Fig. 12.

7.1 Antimicrobial activity

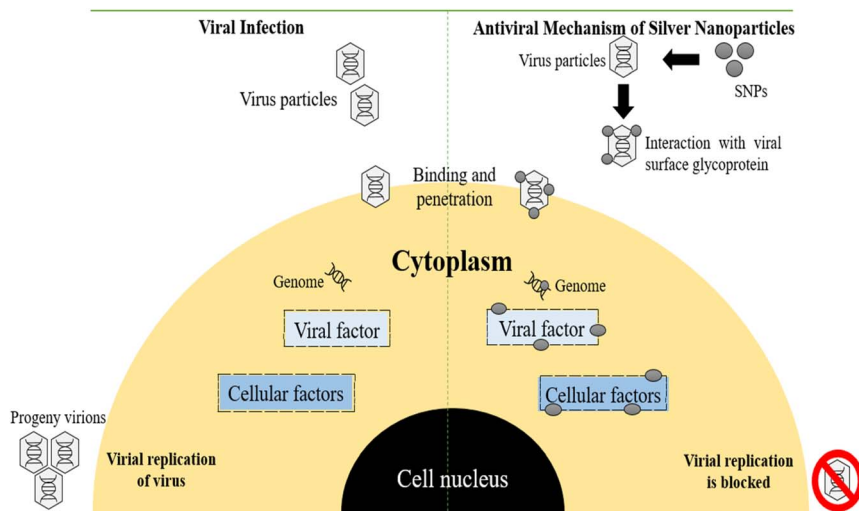
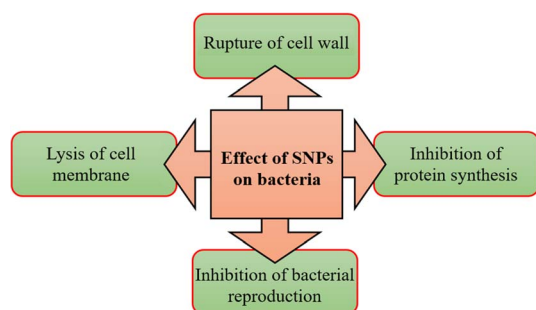
Silver is a widely known antibacterial ingredient that can effectively combat more than 650 pathogenic organisms, including various types of bacteria (both Gram –ve and Gram +ve), fungi and viruses. SNPs are currently being utilized as a form of metal. Silver has been noted as an agent of healing for numerous ailments in the ancient Indian medical system known as Ayurveda. Starting in 1884, it became widely accepted to apply drops of aq. AgNO₃ to the eyes of newborns following childbirth in order to stop the spread of *N. gonorrhoea* from affected mothers. Among all the metals with antimicrobial capabilities, silver was discovered to exhibit the most potent antibacterial activity while being the least detrimental to animal cells. Silver gained widespread usage in pharmaceuticals, particularly in the care of injured soldiers during World War I, as a source to inhibit the growth of microorganisms.²⁵⁵ The medicinal benefits of silver have been recognized for over two thousand years.²⁵⁶ Plant extracts from various sources have been utilized to synthesize SNPs, which were then tested for their antibacterial properties against a range of microorganisms.

7.1.1 Mechanism of action against viruses. Despite there are some studies on the impact of SNPs on viruses, there is a lack of specific information on the nature of these interactions and mechanism supported universally. However, this may be attributed to the intricate nature of virus structure, which hinders our understanding of the process by which SNPs act on viruses. Salleh *et al.* proposed two mechanisms by which SNPs interact with harmful viruses: (1) SNPs bind to the outer covering of the virus, preventing its binding to cell receptors, and (2) SNPs attach to the RNA or DNA of the virus, inhibiting its reproduction or transmission.²⁵⁷ Fig. 13 shows the mechanism of action against viruses.

7.1.2 Mechanism of action against bacteria. SNPs have a significant function as antibacterial agents. Silver nano formulations have demonstrated a strong capacity to hinder the proliferation of bacteria and other microbes. SNPs effect bacteria in following ways; rupturing of cell wall, lysis of cell membrane, inhibition of protein synthesis, and bacterial reproduction as shown in Fig. 14.²⁵⁸

According to research, SNPs have potent antibacterial properties against both Gram –ve and Gram +ve bacteria. In contrast to Gram +ve bacteria, which possess a thick peptidoglycan layer with a periplasmic membrane, Gram –ve bacteria are characterized by a thin peptidoglycan layer and an extra outer membrane. Research findings indicate that Gram-positive bacteria have a higher degree of resistance to SNPs.²⁵⁹ Moreover, literature has indicated that the presence of SNPs has been found to enhance the antibacterial efficacy of certain

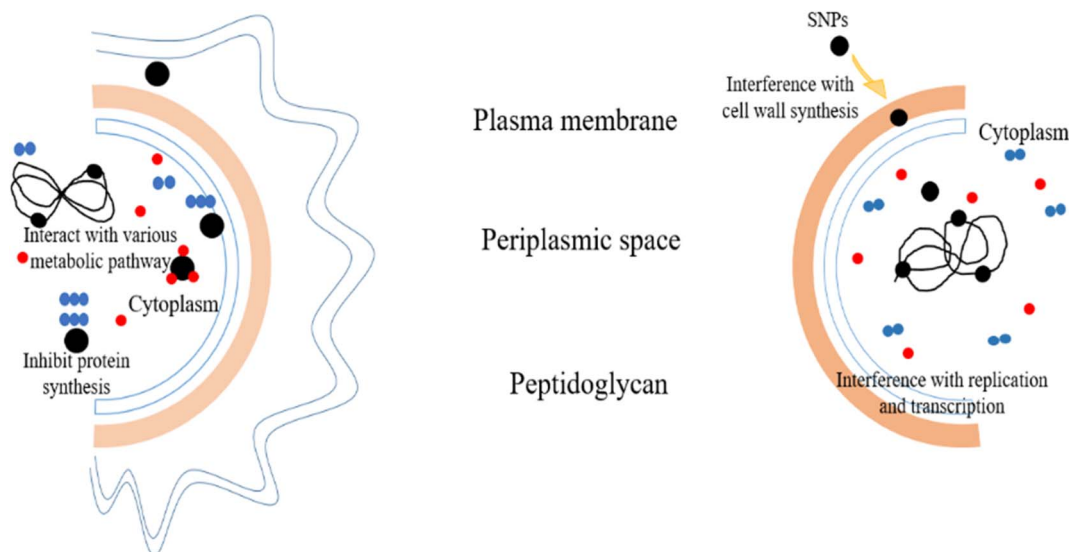
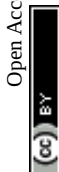


Fig. 13 Viral infection and antiviral mechanism of SNPs.²⁵⁷Fig. 14 Effect of SNPs on bacteria.⁸⁷

medicines. Numerous studies have demonstrated the interaction between SNPs and the bacterial membrane, resulting in cell penetration and subsequent disruption of cellular function,

generating reactive oxygen species, structural integrity, inhibition of protein synthesis, interaction with various metabolic pathways, interference with replication and transcription and eventual cell death.²⁶⁰ Fig. 15 shows mechanism of action against bacterial strains.

7.1.3 Mechanism of action against fungi. Advancements in recent research pertaining to the composition, framework, and role of fungal cell walls in drug tolerance have facilitated the identification of emerging targets against diseases caused by fungi. Additionally, these advancements have contributed to a deeper comprehension of the mechanisms behind the development of antifungal resistance. SNPs may have a significant influence on the degradation of resistance. These induce surface protein impairment, nucleic acid damage and cellular wall disintegration, through the generation and generation of reactive oxygen species (ROS) and free radicals, as well as the

Fig. 15 Mechanism of actions (ROS activation) of SNPs against Gram –ve and Gram +ve bacteria.²⁶¹

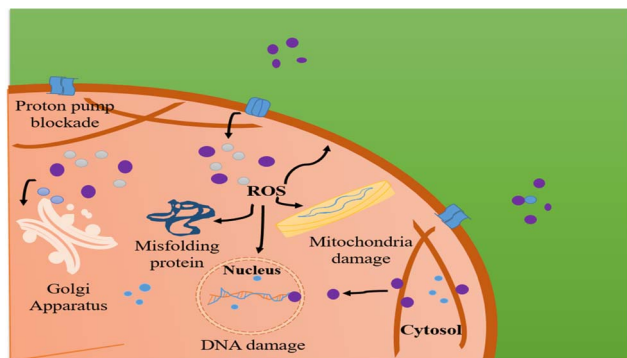


Fig. 16 Mechanism of action of SNPs against fungi.²⁶⁵

inhibition of proton pumps, interaction with fungal DNA, protein denaturation. One hypothesis is that the presence of SNPs results in the buildup of silver ions, therefore impeding respiration through the outflow of intracellular ions and subsequently causing damage to the electron transport system.²⁶² The observed antifungal activity can be related to the smaller size and large surface ratio of NPs. Smaller-sized SNPs have enhanced permeability across cellular membranes. The toxicity of SNPs might be partially ascribed to the generation of ROS, which subsequently induces apoptosis. The hypothesis

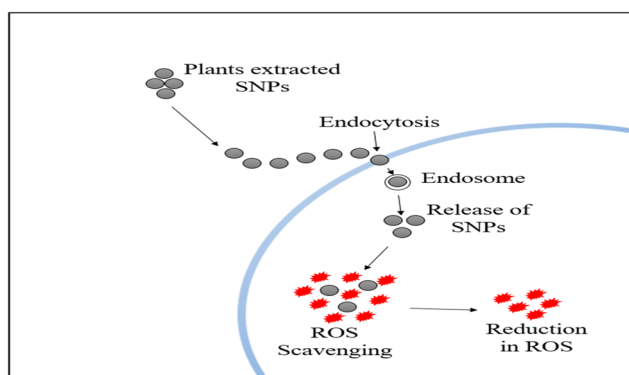


Fig. 17 Radical oxygen scavenging mechanism.²⁶⁶

postulated that the observed toxicity of SNPs *in vitro* can be attributed to either the combined influence of silver ions and SNPs, or their individual effects. Further evaluation is required to elucidate the exact modes of action of SNPs.^{263,264} Fig. 16 shows mechanism of action against fungi.

7.1.4 Mechanism of action of antioxidant. Antioxidants obtained from eco-friendly sources have demonstrated extraordinary efficacy in neutralizing free radicals, namely the DPPH radical, also known as DPPH. NPs derived from natural sources have the ability to capture free radicals by several processes, such as chelation of metal ions, enzyme inhibition and direct scavenging of ROS. It is worth mentioning that in certain cases, the natural extract may have a higher antioxidant power than the artificially created NPs, while in other situations, the reverse may be true. The effectiveness of these environment friendly NPs in preventing oxidation depends on the amounts of phenolic compounds and flavonoids found in the extract.²⁵⁴ Radical oxygen scavenging mechanism follows endocytosis process for the reduction of ROS. Fig. 17 shows radical oxygen scavenging activity mechanism.

7.1.5 Examples of antibacterial and antifungal studies and results. SNPs have emerged as very promising agents in the ongoing struggle against diseases during the worldwide search for innovative bio medicines. The vast majority of studies supports the notion that SNPs have the power to hinder the growth and trigger the death of harmful bacteria responsible for many human illnesses globally. Currently, plant extracts serve as an invaluable source for the manufacturing of SNPs. The capacity of SNPs to adhere to many biomolecules in microbes enables them to exert a persistent antibacterial influence.²⁶⁷ Table 5 shows different antifungal and antibacterial activities of SNPs extracted from different plant sources.

7.1.6 Examples of antiviral studies and results. The emergence of contagious diseases outbreaks caused by recently identified virulent viruses and those who have developed immunity to existing antiviral medications has driven the search for new antiviral agents.²⁸¹ In the course of the evolution of humanity, viruses have consistently been recognized as extremely fatal human infections. Viruses exhibit pathogenicity by attaching to and invading into the host cell. Avoiding cell

Table 5 Antifungal and Antibacterial activities of SNPs extracted from different sources

Plant sources	Bacteria	Fungi	Ref.
<i>Euphorbia hirta</i>	—	<i>C. albicans</i> , <i>C. kefyr</i>	268
<i>Usnea longissima</i>	<i>S. aureus</i> , <i>S. Pyrogenes</i> , <i>S. Viridans</i> , <i>C. xerosis</i>	—	269
<i>Adathoda vasica</i>	<i>V. parahaemolyticus</i>	—	270
<i>Svensonia hyderabadensis</i>	<i>Proteus mirabilis</i>	<i>Fusarium</i> , <i>Rhizopus</i> , <i>A. flavus</i> , <i>A. niger</i>	271
Green tea	<i>Klebsiella pneumonia</i> , <i>Pseudomonas aeruginosa</i>	—	272
Green tea	<i>B. subtilis</i> , <i>E. coli</i> , <i>S. aureus</i> and <i>S. pyogenes</i>	—	273
<i>Solanum torvum</i>	<i>P. aeruginosa</i> , <i>S. aureus</i>	<i>A. flavus</i> and <i>A. niger</i>	274
<i>Cucumis sativus</i> plant extract	<i>M. tuberculosis</i>	—	275
<i>Vigna radiata</i>	<i>S. aureus</i> , <i>Escherichia coli</i>	—	276
<i>Citrus limon</i>	—	<i>F. oxysporum</i> , <i>A. brassicicola</i>	277
<i>Pu-erh</i> tea leaves	<i>E. coli</i> , <i>K. pneumoniae</i> , <i>S. typhimurium</i> , <i>S. enteritidis</i>	—	278
<i>Boerhavia diffusa</i>	<i>A. hydrophila</i> , <i>P. fluorescens</i> and <i>F. branchiophilum</i>	—	279
<i>Argemone mexicana</i>	<i>E. coli</i> ; <i>P. aeruginosa</i>	<i>Aspergillus flavus</i>	280



Table 6 Antiviral activities of SNPs extracted from various plants

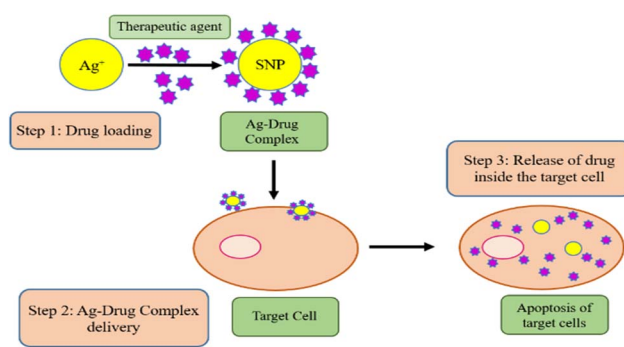
SNPs extracted from plants sources	Virus	Application	Ref.
<i>Cinnamomum cassia</i>	H7N3	Inhibits contaminating the vero cells	282
<i>Andrographis paniculata</i>	Chikungunya	Prevents affecting vero cells in a dosage dependent manner	283
<i>Phyllanthus niruri</i>	Chikungunya	Prevents affecting vero cells in a dosage dependent manner	283
<i>Tinospora cordifolia</i>	Chikungunya	Prevents infecting vero cells in a dosage dependent manner	283
<i>L. coccineus</i> hexane	HSV-1, HAV-10, and coxsackie B4	Prevented infection of vero cells	284
<i>L. coccineus</i> aqueous SNPs	HSV-1	Prevented infection of vero cells and showed weaker antiviral activity against this virus	284
<i>M. lutea</i>	HAV-10 and CoxB4	Prevents infection of vero cells	284

infection is best achieved by preventing such penetration and binging.²⁶⁷ Table 6 shows several plants used to extract SNPs and their antiviral activity.

7.1.7 Examples of antioxidant studies and results. Several scholars conducted a study on the antioxidant properties of plant extract-mediated produced SNPs at different times. The antioxidant activity of NPs generated using plant extracts is improved, possibly due to the efficient absorption of antioxidants from the plant extracts onto the surface of the NPs. The disease-fighting abilities of a silver phyto-nanosystem are enhanced by their antioxidant qualities. Therefore, it was shown that silver phyto-NPs obtained from plant extracts possess significant antioxidant activity.²⁸⁵ According to Salari *et al.* the SNPs produced using an aqueous extract from the fruit of *Prosopis farcta* have shown exceptional efficacy in removing free radicals.²⁸⁶ The same impact was demonstrated in a laboratory setting for a water-based extract of apple,²⁸⁷ *Indigofera hirsuta*,²⁸⁸ and leaf extracts of *Elephantopus scaber*.²⁸⁹ Thus, elevated levels of antioxidant phyto-nanoparticle activity may be linked with particular encapsulation of antimicrobial SNPs, particularly for medicinal plants, which contains various bioactive compounds such as polyphenols and flavonoids.²⁷⁶

7.2 Biomedical applications

7.2.1 Drug delivery system. Drug delivery by SNPs has shown to be a highly efficacious approach in the management of several medical conditions. The efficacy of drug delivery systems is contingent upon two primary strategies: the gradual and continuous release of drugs, as well as the precise targeting of drug delivery to specified targets. These criteria can be satisfied by employing either active or passive delivery techniques.²⁹⁰ SNPs earned significant interest in the realm of designing and advancing innovative drug-delivery systems.⁹ In a more precise manner, the use of green synthesized SNPs has the potential to address the drawbacks commonly connected with current treatments by mitigating their adverse effects and augmenting their effectiveness. The surface properties of SNPs can be modified to improve the targeting capabilities. For instance, positively charged NPs have shown enhanced interaction with negatively charged cell membranes, facilitating targeted drug delivery to specific tissues and cells.²⁹¹ Fig. 18 shows the drug delivery system in the target cell.

Fig. 18 Drug delivery system in the target cell.²⁹²

The integration of green SNPs with anti-cancer medications presents a novel strategy for enhancing disease therapy. By leveraging the SNPs capacity to traverse diverse biological barriers, the direct delivery of pharmaceuticals to tumor tissues may be achieved.²⁹³ The intercellular drug absorption and distribution are influenced by the size of the NPs by the process of endocytosis. SNPs derived from the extract of *Aerva javanica*, when combined with the anti-cancer medication gefitinib, exhibited greater apoptotic efficacy compared to gefitinib alone when tested on MCF-7 cells.²⁹⁴ In addition to its application in cancer, SNPs have been employed in conjunction with anti-seizure medications targeting brain eating amoebae (*Naegleria fowleri*) for the treatment of central nervous system infections. Pharmacological compounds with anti-seizure properties, including diazepam, phenobarbitone, and phenytoin, were incorporated onto the outer surface of SNPs as stabilizing agents. These medications exhibited broad-spectrum anti-amoebic effects against both trophozoite and cyst stages. The conjugation of SNPs with medicines have shown a significant enhancement in fungicidal efficacy against both trophozoite and cyst amoebic phases, in comparison to the individual medications.²⁹⁵ Drug delivery involves the transportation of natural or pharmaceutical chemicals to achieve intended therapeutic outcomes. Several preparations utilizing NPs have been documented to have a significant impact on targeting drugs for specific disorders.⁸⁷ Benyettou *et al.* developed a drug-delivery system using SNPs to transport medications like doxorubicin and alendronate directly into cells at the same time. This drug-



delivery method has demonstrated the ability to enhance the therapeutic effectiveness of both medications in treating cancer.²⁹⁶ A separate study has shown that combining Fe_3O_4 and SNPs can serve as effective magnetic hyperthermia mediators with exceptional performance.²⁹⁷

7.2.2 Wound healing. Wounds arise due to the transection, cutting, tearing, or burning of epidermal tissues in reaction to external stimuli or traumatic events. The classification of wounds encompasses two distinct categories: acute and chronic, delineated by the duration of healing and potential problems. SNPs show considerable anti-inflammatory aspects that can be effective in handling chronic inflammation-related diseases, such as rheumatoid arthritis. Chronic inflammation is often linked to protein denaturation, which NSAIDs aim to inhibit. SNPs have been shown to reduce levels of Vascular Endothelial Growth Factor (VEGF),²⁹⁸ a key player in inflammation, by inhibiting the phosphorylation of Src kinase at Y419, thereby decreasing vascular permeability induced by inflammatory mediators like VEGF and IL-1. This action not only reduces mucin hypersecretion but also mitigates the secretion of pro-inflammatory cytokines like TNF- α and IL-12. SNPs suppress the expression of Hypoxia-Inducible Factor (HIF)-1, which regulates genes associated with inflammation and promotes angiogenesis. By inhibiting HIF-1 activity, SNPs prevent the transcription of pro-inflammatory genes and reduce the inflammatory response in tissues. Experimental studies have demonstrated that SNPs can effectively decrease mucin production in lung tissues and alleviate perivascular inflammation in models of allergic responses, highlighting their potential as a safer alternative to traditional anti-inflammatory medications by minimizing side effects while enhancing therapeutic efficacy.²⁹⁹ Fig. 19 shows anti-inflammatory mechanism for wound healing process.

Scientific evidence has shown that the manufacture of SNP by *Fusarium oxysporum* is precise when conducted *in vivo*. The

generated SNPs possess a diameter ranging from 20 to 40 nm. Subsequently, they are combined with Enox for a duration of 28 days in model of *in vivo* burn wound.³⁰¹ In a study conducted by Garg *et al.*, the therapeutic efficacy of biogenic SNPs derived from hydrogel containing *A. nobilis* extract from its root was established. An investigation was conducted to examine the healing efficacy of SNPs with a diameter ranging from 40 to 70 nm and spherical morphology, utilizing an excision wound model. The hydrogel preparation exhibited a substantial enhancement in wound contraction and closure within the initial and subsequent weeks. Over a period of 14 days, the albino rats exhibited a wound healing rate that was 9.34% faster compared to the control group. Conversely, after 21 days, the control group had a wound healing rate that was 1.78% faster than that of the albino group.³⁰² SNPs, either alone or in conjunction with anti-bacterial drugs, are frequently employed to facilitate wound healing while preventing infection. In both laboratory settings using fibroblast cell cultures and clinical trials involving patients with partial thickness burns, dressings containing SNPs have been applied. A study has demonstrated that these dressings do not impact the growth of fibroblasts and keratinocytes, which are responsible for the regeneration of healthy skin.³⁰³

A subsequent investigation conducted a comparison of the effectiveness of two antibacterial substances, specifically nanocrystalline silver and cadexomer iodine. This study conducted a randomized controlled trial on community nursing clients who had leg ulcers that were affected by a high number of germs. Their injuries were cured using either Ag or I dressings. The outcomes substantiated that the utilization of Ag compounds expedited the therapeutic process, resulting in a rapid rate of recovery.⁸⁷ In addition, the combined use of SNPs and antibiotics, namely tetracycline, demonstrates greater efficacy compared to using either SNPs or tetracycline alone in combating bacterial infection. Furthermore, this combined

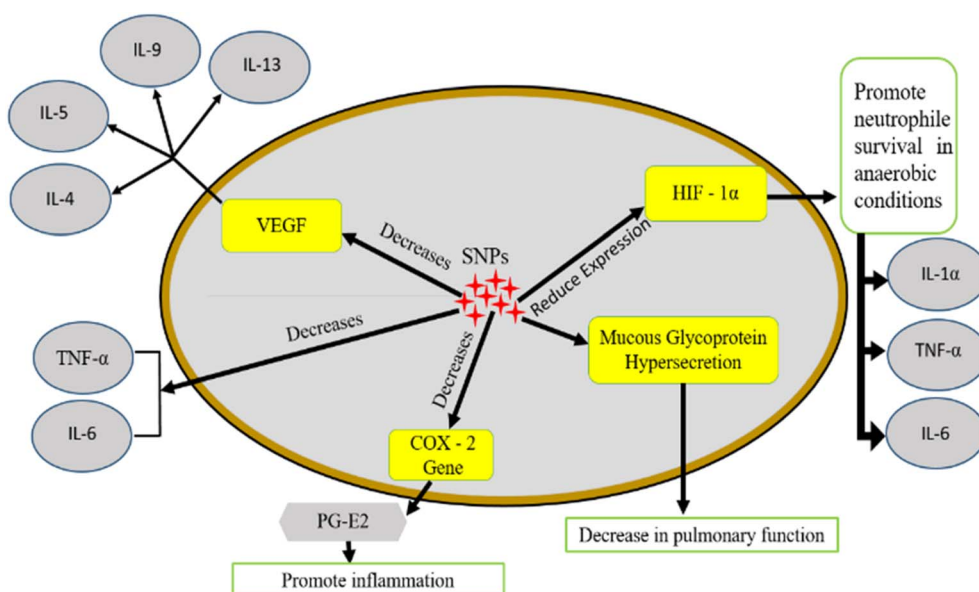


Fig. 19 Anti-inflammatory mechanism of plant extracted SNPs for wound healing process.³⁰⁰



treatment also leads to an increase in wound contraction at a macroscopic level. Moreover, these findings indicate the potential application of a blend of SNPs and anti-bacterial medications in the treatment of infected skin injuries.³⁰⁴

7.2.3 Anti-cancer properties. Medicinal plants provide natural products or active substances that have been scientifically demonstrated to play a function in preventing cancer by effectively destroying cancer cells. SNPs have a significant function in inhibiting cancer cells and thus, preventing the formation and progression of the illness. Researchers discovered that SNPs could inhibit the growth of malignant cells by leading to DNA degradation, disruption of mitochondrial membrane potential, ROS generation and oxidation, inhibitory enzymes, controlling signaling pathways, and inhibiting the cell cycle. Furthermore, SNPs can inhibit malignant cells spread by reducing angiogenesis within the lesion or inducing malignant cell apoptosis by deactivating proteins and controlling signaling pathways.^{305,306} Fig. 20 shows Anticancer mechanism of plant extracted SNPs.

Research was conducted using lymphoma cell lines to examine the efficacy of SNPs as an antitumor agent in both laboratory settings and living organisms. The work validated the dosage-dependent toxicity of SNPs against lymphoma cells in a controlled laboratory setting, and also suggested their involvement in triggering programmed cell death. Furthermore, there were reports indicating that NPs had a substantial impact on prolonging the survival duration in the mouse model with tumors. Additionally, NPs were shown to play a function in reducing the volume of ascitic fluid in mice that had tumors.⁸⁷

The study investigated the cell damaging and reactive properties of SNPs derived from *P. ginseng* leaves on human cancer cell lines. The results showed that the nanoformulation

has antineoplastic efficacy.³⁰⁷ Khateef and his colleagues investigated the harmful effects of SNPs at different concentrations. The observation was made that the suppression of cell proliferation was intensified as the quantities of SNPs increased. Furthermore, the rise in the concentration of SNPs resulted in a reduction in cell viability.³⁰⁸ In addition, the use of wortmannin, a substance that inhibits autophagy, greatly increased the effectiveness of SNPs in treating melanoma cells.³⁰⁹ Numerous investigations have shown the potential of SNPs, including those derived from different plant extracts, to have anti-cancer properties.³¹⁰ Further, studies showed below in Table 7 some other anticancer results of various plants synthesized SNP.

7.3 Environmental applications

7.3.1 Water purification. The purification of drinking water is an imperative in contemporary times, given that water derived from various sources has the potential to include pathogenic microbes, heavy metals, and organic compounds at hazardous quantities.³²⁹ SNPs that possess enhanced stability, cost-effectiveness, and the ability to be controlled in their release rate have demonstrated successful utilization in the elimination of inorganic anions,³³⁰ heavy metals,³³¹ organic pollutants,³³² and bacteria³³³ from water. These findings indicate a promising outlook for the application of SNPs in the field of water and wastewater treatment. Nevertheless, the direct use of SNPs may result in their aggregation within aqueous environments, so slowly diminishing their effectiveness over an pre-longed duration.³³⁴ In the present context, the use of SNPs affixed to filter materials presents a potentially superior option for mitigating the issue of aggregation, while also offering cost-effectiveness and demonstrating good antibacterial properties,

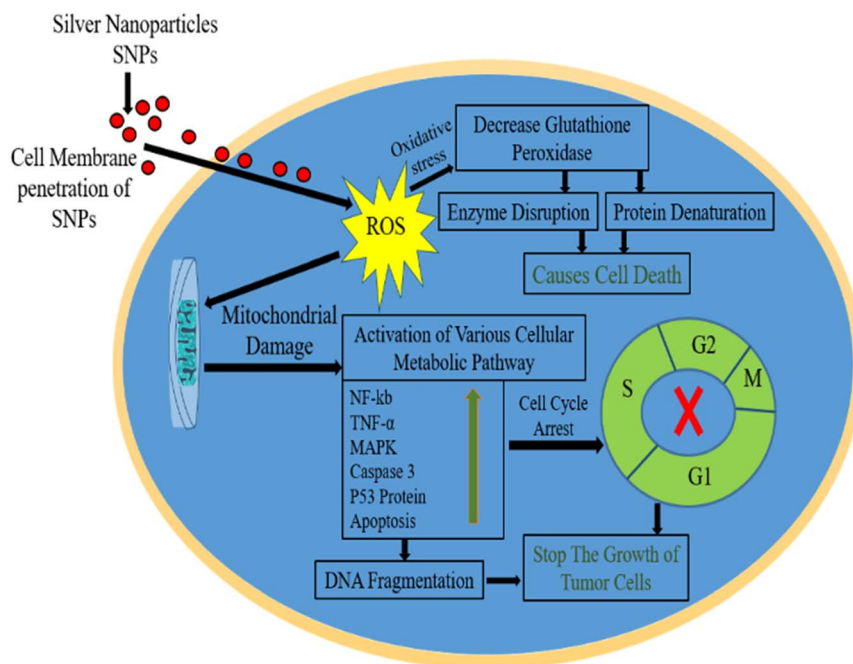


Fig. 20 Anticancer mechanism of plant extracted SNPs.³⁰⁰



Table 7 Anticancer studies of various plants synthesized SNPs

SNPs extracted from plants	Cancer cell line	IC ₅₀ value ($\mu\text{g mL}^{-1}$)	Ref.
<i>Curcuma longa</i> and <i>Zingiber officinale</i> mixture	HT-29	150	311
<i>Solanum trilobatum</i>	MCF-7	30	312
<i>Dimocarpus longan</i>	PC3	10	313
<i>Punica granatum</i>	A5449	5	314
<i>Detarium microcarpum</i>	HeLa	31.5	315
	PANC-1	84	
<i>Achillea biebersteinii</i>	MCF-7	20	316
<i>Melia dubia</i>	MCF-7	31.2	317
<i>Ulva lactuca</i>	MCF-7	37	318
<i>Cucumis prophetarum</i>	HepG-2	94.2	319
<i>Rosa damascene</i>	A549	80	320
<i>Gossypium hirsutum</i>	A549	40	321
<i>Syzygium aromaticum</i>	A549	70	322
<i>Podophyllum hexandrum</i>	HeLa	20	323
<i>Heliotropium indicum</i>	Siha	20	324
<i>Gum arabic</i>	HT-29	1.55	325
	Caco-2	1.26	
<i>Alternanthera sessilis</i>	PC-3	6.85	326
<i>Gracilaria edulis</i>	PC-3	53.99	327
<i>Dimocarpus longan</i>	VCaP	87.33	328

as evidenced by many research.³³⁵ The deposition of SNPs on cellulose fibres has demonstrated notable antibacterial efficacy against *Escherichia coli* infections. Furthermore, the loss of Ag^+ from these sheets does not surpass the established target level of 0.1 ppm for drinking water, as determined by the environmental protection agency and the World Health Organization.³³⁶ Furthermore, there has been a notable rise in the use of SNPs that are integrated into ceramic materials and membranes for the purpose of disinfecting and treating water intended for domestic consumption at the point of consumption over the past twenty years.³³⁷ An additional use of SNPs in the field of water treatment is the prevention of fouling in membrane filters employed inside water treatment systems.³³⁸ The SNPs may be readily detached from the beads and effectively suppress the proliferation of microorganisms in an actual water sample. Utilizing paper impregnated with SNPs to facilitate the passage of bacterially tainted water might serve as a very efficient method for emergency water treatment.³³⁹ The polyacrylonitrile (PAN) sorbent, employed in the process of water treatment, effectively retains harmful bacteria on its surface. Nevertheless, the application of SNPs prevented the occurrence of biofilm growth on the surface.³⁴⁰ The water purification membrane, which was created by incorporating 1 mg L^{-1} of biosynthesized SNPs onto nitrocellulose membrane filters, effectively eliminated the microbial population of *E. coli*, *E. faecalis*, *P. aeruginosa*, and *S. aureus* suspensions. Furthermore, it achieved a significant reduction in the presence of *E. coli* and *S. aureus*, with reductions of up to 6 and 5.2 orders of magnitude, respectively.³⁴¹

7.3.2 Pollutant degradation. The catalytic activity of SNPs is triggered by the transfer of electrons from silver ions to a reducing substance (e^- donor) and a dye (e^- acceptor).³⁴² That depend on its dimensions, form, and surface characteristics, as well on their overall and surface composition. Catalysts

composed of tubular nanocomposites with tiny SNPs exhibited superior catalytic performance compared to those with larger NPs.³⁴³ The SNPs produced by biosynthesis showed a potent chemo catalytic effect, leading to the complete breakdown of 4-nitrophenol into 4-aminophenol,³⁴⁴ methyl orange, and methylene blue using sodium borohydride.³⁴⁵ The rate constantly exhibited a positive correlation with the quantity of SNPs employed as a catalyst. In addition, SNPs have been used as nano catalysts to break down dyes in wastewater and effluents. They also possess distinctive features that are essential for the process of carbon dioxide electrolysis, which plays a major role in turning CO_2 into CO .³⁴⁶ SNPs function as a catalyst with different properties in the process of eliminating halogenated organic contaminants using BH_4 .³⁴⁷ The involvement of SNPs in the process of photocatalytic degradation of pollutants such as crystal violet, methylene blue, and malachite green has been investigated.³⁴⁸ SNPs enhance the photocatalytic activity of metal oxide by altering the absorption of the visible region.³⁴⁹

7.4 Industrial applications

7.4.1 Catalysis. The use of NPs for water filtration may be categorized into three main kinds of contaminants: halogenated organics (such as pesticides), heavy metals, and microorganisms.³³⁸ The characteristic catalytic degradation mechanism often entails the adsorption of pollutant molecules onto the surface of the nanoparticle, which is then followed by electron transfer activities. SNPs possess notable characteristics such as a substantial surface area, reactivity, and tunable features, rendering them very efficient catalysts for the degradation of dyes.³⁵⁰ Various parameters can exert an impact on the catalytic activity, including the size and shape of SNPs, the presence of capping agents, the concentration of SNPs, as well as the pH and temperature conditions. Particles of smaller size



that possess a greater surface area have enhanced catalytic activity.³⁵¹

In the presence of sodium borohydride, SNPs derived from extracts of *Hyptis capitata* leaves, fruits, and stems exhibited catalytic reduction of methyl orange colour. The reaction reached completion within a time frame of 3 hours, suggesting that the SNPs effectively facilitated the reduction of the azo-dye.³⁵⁰ The synthesis of SNPs utilizing an extract derived from the *Sphagneticola procumbens* plant shown the ability to photocatalytically degrade the harmful Orange G and Direct Blue-15 azo dyes when exposed to UV radiation.³⁵¹ Printing and dye wastewater provide a significant challenge due to their intricate composition among the several forms of wastewater.³⁵² The substantial quantities of non-biodegradable oil and hazardous 4-nitrophenol that are dissolved in wastewater present an immediate and pressing concern.³⁵³ SNPs play a crucial role in the catalytic degradation of 4-nitrophenol³⁵⁴ because of their large specific surface area, numerous showed low-coordination sites, and affordable price. Nevertheless, as a result of the surface's elevated energy, there is a propensity for diminished catalytic activity over time. Furthermore, the retrieval of the granules from the water is exceedingly challenging, hence resulting in potential secondary pollution. Consequently, the act of immobilizing SNPs within porous oil absorbent materials has been found as a highly successful method for enhancing the capacity to reuse SNPs.³⁵⁵ Melinte *et al.* synthesized several photo catalysts using silver, gold, or silver-gold NPs supported on photo cross-linked natural materials. These hybrid structures facilitated the photo-catalytic breakdown of polymers, namely 4-nitroaniline.³⁵⁶ Roy *et al.* investigated the process of breaking down methylene blue dye using biogenic SNPs that were created using (yeast) *S. cerevisiae* extract. In conclusion, various well-documented publications have demonstrated the catalytic degrading effectiveness of SNPs, indicating their potential utility in water treatment systems. When constructing a water treatment system using SNPs, it is important to take into account the potential discharge of these NPs and the possibility for secondary water pollution.³⁵⁷ A separate investigation resulted in the effective production of multifunctional 3D filter cotton by immobilizing PDA and SNP on the surface. The treated 3D filter cotton has exceptional catalytic degradation

capabilities, making it suitable for the decomposition of water-soluble 4-nitrophenol. Additionally, it demonstrates remarkable effectiveness in separating oil and water, as well as the capacity to be reused.³⁵⁸ A research has described the use of green synthesis to produce very stable SNPs, which have demonstrated effectiveness as catalysts, photocatalysts, and antibacterial agents in treating wastewater.³⁵⁹

7.4.2 Photocatalytic activity. Photocatalytic activity is the speedup of a photoreaction with the help of a catalyst, which in this case is often SNPs. These NPs have received a lot of interest because of their unusual features and ability to degrade organic contaminants, notably synthetic colors, when exposed to light. The use of plant extracts to synthesize SNPs not only provides an environmentally preferable alternative, but it also improves their photocatalytic capabilities. SNPs have been deeply studied for their capacity to breakdown dyes that are frequently found in industrial effluent. The photocatalytic activity of these NPs is increased by their large surface area and the formation of ROS when exposed to light. Photocatalytic activity by using various plant sources can be used to degrade dyes, organic pollutants and waste water treatment.¹⁸¹ Photocatalytic activity of SNPs extracted using several plants sources are given in the following Table 8.

7.4.3 Sensing and detection. Mobile and wearable medical gadgets might be an excellent option for observing patients. SNPs, because of their highly conductive nature, find uses in stretchy sensors.³⁷⁰ Notably, colorimetric, optical, and electrochemical sensors have demonstrated their efficacy in the analysis of environmental materials.^{371,372} An essential use of nanotechnology in the field of electro analysis is the modification of sensors using NPs to achieve cost-effective, highly sensitive, and selectively responsive devices.³⁷³ These sensors are created by distributing or covering SNPs on the surface of carbon-based nanomaterials' surface such fragmented graphene sponges, multiwalled carbon nanotubes onto polydimethylsiloxane, reduced graphene oxide, and carbon black.³⁷⁴ The prepared sensors have been used for producing electrocardiograms.³⁷⁵ for showing exceptional temperature-sensing aspects, *etc.*³⁷⁰ SNPs may be easily synthesized, and several batches consistently provide SNPs with uniform size, shape and dispersion. Therefore, they are appropriate for SERS sensors. It has been

Table 8 Photocatalytic applications of SNPs extracted from different sources

SNPs extracted from plants	Photocatalytic application	Ref.
<i>Zingiber officinale</i> (ginger)	Degradation of methylene blue and methyl orange	360
<i>Brassica oleracea</i> (cauliflower)	Removal of dyes or organic pollutants	361
<i>Coriandrum sativum</i> (parsley)	Effective degradation of industrial dyes under UV light	362
<i>Camellia sinensis</i> (green tea)	Photocatalytic reduction of organic pollutants and dyes	363
<i>Ananas comosus</i> (pineapple)	Efficient removal of organic dyes in wastewater treatment	364
<i>Capsicum annuum</i> (red pepper)	Photocatalytic treatment of wastewater pollutants	365
<i>Citrus sinensis</i>	Removal of textile dye pollutants in water	366
<i>Pandanus atrocarpus</i>	Degradation of environmental organic pollutants	367
<i>Eucalyptus globulus</i>	Effective degradation of methylene blue dye	368
<i>Piper chaba</i>	Effective photocatalytic degradation of organic dyes	63
<i>Azadirachta indica</i> (neem)	Photocatalytic removal of environmental contaminants and heavy metals	369



Table 9 Biosensing applications of SNPs extracted from various plant sources

SNPs extracted from plant sources	Applications	Ref.
<i>Citrus sinensis</i>	Detection of heavy metals and glucose	382
<i>Piper chaba</i>	Detection of methylene blue dye	63
<i>Psidium guajava</i>	Detection of glucose	305
<i>Piper longum</i>	Detection of bacterial infections	231
<i>Curcuma longa</i> (turmeric)	Biomarker detection	305
<i>Azadirachta indica</i>	Detection of pathogens	383

discovered that the intensity of SERS diminishes as the distances between particles rise.³⁷⁶ SNPs are also employed as a substrate in SERS to detect sialic acid linked with breast cancer, prostate-specific antigen (a biomarker for prostate cancer), and infertility.³⁷⁷ Colorimetric sensors are technological instruments that provide the real-time detection of an analytes in a given sample by providing visual information in the form of colour.³⁷⁸ Karimi and Samimi employed a colorimetric sensor and SNPs derived from the algae *Chaetomorpha* spiral to quantify the presence of mercury ions (Hg^{2+}) in both mineral and tap water across a broad concentration spectrum ranging from 0.01 to 200 mmol L^{-1} .³⁷⁹ SNPs are utilized as colorimetric sensors for the detection of carbohydrate antigen 125 (CA125), that is present on numerous ovarian cancer cells.³⁸⁰

7.4.4 Biosensing. Plant-extracted SNPs are gaining significant popularity for biosensing applications due to their unique features, notably in the detection of environmental contaminants and biomolecules. SNPs have unique qualities, such as strong electrical conductivity and large surface area, making them ideal for developing advanced biosensors. They can function as electron transfer enhancers between biomolecules and electrodes, increasing the sensitivity and selectivity of sensors.³⁸¹ Different plant sources extracted SNPs used in biosensing applications are given below in Table 9.

8. Advantages and challenges of using plants-based synthesis methods

The advantages and challenges of plant-based synthesis of SNPs highlight both the potential and the limitations faced in the innovative field.

8.1 Benefits of using plants-based synthesis of SNPs methods

The benefits of using plants-based synthesis methods are below.

8.1.1 Environmental friendliness. The plant-based production of SNPs follows the principles of green chemistry, which prioritize the use of non-toxic substances and methods that reduce harm to the environment. This approach employs plant extracts as stabilizing and reducing agents, therefore substantially decreasing the requirement for toxic chemicals commonly employed in traditional synthesis procedures. This method not only reduces pollution but also encourages the sustainable utilization of natural resources.³⁸⁴ SNPs synthesized using green

methods can be utilized for environmental remediation purposes, including water treatment and soil cleansing. Their capacity to engage with contaminants and diseases renders them highly helpful in tackling environmental concerns.³⁸⁵

8.1.2 Biocompatibility. SNPs developed from plant extracts are often more biocompatible and less poisonous than those synthesized using chemical procedures. The inherent chemical constituents found in plant extracts enhance the safety and durability of the NPs, rendering them appropriate for many biological uses without causing substantial hazards to human well-being or the ecosystem.²⁵⁴

8.1.3 Sustainability. Utilizing sustainable plant resources for the production of NPs contributes to the advancement of sustainability. Plants include a wide range of bioactive chemicals that help to decrease silver ions, enabling effective production under gentle settings. In contrast to traditional procedures, which can need significant energy inputs and produce hazardous by-products.³⁸⁶

8.1.4 Cost-effectiveness. The utilization of plant-based extraction method for the production of SNPs is frequently more economical compared to conventional approaches. The use of easily accessible natural substances reduces the necessity for costly chemical agents and intricate apparatus, resulting in substantial reductions in manufacturing expenditures. Research suggests that the process of green synthesis can result in cost reductions of up to 40% when compared to traditional approaches.²⁵⁴

8.1.5 Availability of plant-based synthesis methods. The accessibility of the plant-based synthesis method enables convenient scalability, rendering it viable for large-scale manufacturing. Scalability is crucial for satisfying industrial requirements without significant rises in expenses or intricacy.³⁸⁶

8.1.6 Energy storage and economic viability. The use of agro-industrial waste for synthesis promotes economic viability by transforming waste into profitable goods.²⁵⁴ Green synthesis processes often need fewer energy inputs, hence leading to total cost reductions. Studies have demonstrated that employing these approaches can result in a 30% decrease in energy usage when compared to conventional synthesis methods, rendering them more environment friendly and financially feasible.^{254,385} Due to the growing demand for environment friendly products, SNPs produced from plants are expected to gain more market recognition. Their distinct characteristics and reduced ecological footprint provide them a favorable position in competitive marketplaces, hence improving their economic feasibility.³⁸⁶



8.2 Challenges and limitations

The challenges of plants-based synthesis of SNPs primarily revolve around variability in synthesis methods, scalability and reproducibility of results.

8.2.1 Variability. A significant challenge is the lack of consistency in the chemical composition of plant extracts, which can result in differences in size, shape, and stability of the synthesized SNPs. Plants have various concentrations of phytochemicals, including flavonoids and phenolic acids, which function as reducing and stabilizing agents. The diversity in these compounds plays a crucial role in stabilization and reduction of silver ions in SNPs. For example, secondary metabolite like flavonoids, terpenoids, and phenolic compounds plays crucial role in nanoparticle formulation. The variability can impact the efficacy of silver ion reduction and the ultimate characteristics of the NPs. Different environmental conditions such as soil type, climate, and cultivation methods can influence the phytochemicals concentration. This variability could result in batch-to-batch inconsistencies during SNPs synthesis. Batch to batch variability in composition is a challenge that needs to be minimized. For instance, plants grown in nutrient rich soils might produce higher concentrations of polyphenols, which could result in better reduction of silver ions and higher nanoparticle yield. Higher concentrations of silver ions can lead to agglomeration while lower concentration may lead to fewer nanoparticles. A delicate balance must be maintained to achieve an optimal yield of well dispersed SNPs. Due to inconsistency nanoparticles characteristics such as size, shape, and stability can vary. Moreover, composition of plant extracts can vary based on several factors like plant species, growth conditions, seasonality, and geographical location.³⁸⁷

8.2.2 Understanding the mechanism and standardization issues. The exact biochemical pathways and mechanisms by which plant extracts reduce silver ions to SNPs are not fully understood. This makes the work harder to predict and control the synthesis.²¹⁶ There is no universal protocol for plants-based synthesis of SNPs making it difficult to replicate results across different studies. Different plants are used due to which size shape, stability and yield differs and limits the research.⁹⁴

8.2.3 Scalability. The content of plant extracts can exhibit substantial variation depending on factors such as geographical location, seasonal fluctuations, and extraction techniques. The unpredictability maintaining consistent reaction conditions in SNPs synthesis might hinder the capacity to scale up production while ensuring consistent nanoparticle size and characteristics.³⁸⁷ Expanding the synthesis process focuses meticulous optimization of several factors, such as pH, temperature and the concentration of plant extracts and silver ions. The process of optimization can be intricate and time-consuming, as the optimal conditions for small-scale synthesis may not simply correspond to higher sizes.³⁸⁵ The duration of the synthesis process can be prolonged as the scale increases. Increased quantities might result in extended response durations, thereby impacting the effectiveness and financial feasibility of the procedure. Raising output may need

the inclusion of more infrastructure, such as specific reactors and purification systems, which might raise the initial investment expenditures and operating complexities. Different extraction techniques can yield different concentrations and quality of active phytochemicals. Variations in extraction conditions like temperature, time and solvent type can lead to differing yields. Inefficient extraction led to insufficient reducing agents for effective nanoparticle synthesis. Plants based synthesis is more economical than traditional methods, but in large scale operations may incur higher costs due to the need for larger quantities of raw materials, extraction and processing equipment. The availability of specific plant materials can be seasonal or limited by geographical factors. This variability can affect the scalability of SNP production since consistent access to high quality raw materials is crucial for large scale production.³⁸⁴

8.2.4 Seasonal and geographical factors. Different plants or even different parts of the same plants contain various concentrations of phytochemicals, which leads to different size, shape and stability of synthesized SNPs.³²⁸ The concentrations of active compounds may vary depending upon the seasonal and geographical locations where plants are grown affecting the synthesis of process.³⁸⁸

8.2.5 Reproducibility. Obtaining consistent results in terms of nanoparticle size, shape, and stability can be challenging due to the natural diversity in plant extracts. This lack of consistency can hinder the dependability of the synthesized SNPs for usage in manufacturing. Currently, there is no accepted worldwide procedure for creating SNPs utilizing plant extracts. The absence of uniformity in procedures can result in variations in outcomes among various laboratories and research, making it difficult to compare data and identify optimal methods.³⁸⁷ Characterizing SNPs is essential for interpreting their characteristics and possible uses. Nevertheless, the characterization techniques employed might produce varying outcomes based on the synthesis conditions and the particular plant extracts utilized. This heterogeneity might also hinder the capacity to reproduce results.³⁸⁵ Our current knowledge of the methodologies involved in the biosynthesis of SNPs utilizing plant extracts is very restricted. The lack of understanding in this area might result in unexpected impact and challenges while producing effective synthesis techniques. Variability in plant composition such as species differences, environmental factors, extraction method, plant material availability and process controlling conditions highly affects reproducibility of SNPs.³⁸⁹

8.2.6 Potential toxicity. SNPs have wide range of applications in various fields but on other hand it poses certain risks.³⁹⁰ These nanoparticles may potentially be toxic to aquatic organism and their wide spread use as antimicrobial agents and disinfectants could contribute to the development of bacterial resistance.³⁹¹ As the release of nano silver from SNPs may cause level to increase toxic threshold. Studies aimed at determining the toxicity limit of SNPs are insufficient as the toxicity depends on various factors, such as the concentration, size, shape, and surface area of the nanoparticles. Moreover, factors like the source of SNPs, the route of entry into the body, the methods of



toxicological assessment and the units of measurement can significantly influence the results, making it challenging to establish a precise toxicity range for SNPs.³³⁹

8.3 Environmental and economic aspects

The conventional techniques employed for manufacturing NPs are expensive, toxic, and environmentally unfriendly. In order to cover these problems, scientists have identified the precise green routes, which are naturally existing origins and their constituents that may be utilized to produce NPs through synthesis. The origin of sustainable synthesis may be classified into 3 groups: (a) employing microorganisms such as fungus, yeasts, bacteria, and actinomycetes, (b) utilizing plants and its extracts, and (c) employing membranes, viral DNA, and diatoms. This paper primarily examines the process of synthesizing SNPs utilizing plant extract using a method known as green synthesis.³⁸⁶ The use of plants and its extracts in green synthesis has become more popular because of its rapid advancement, simplified procedure, cost-efficient approach, lack of pathogenicity, and environmentally sustainable nature.²¹⁶

The utilization of plants extracts in the green synthesis of SNPs is in accordance with the ideals of sustainable development. This approach decreases the dependence on harmful substances and reduces environmental contamination linked to conventional chemical synthesis, which frequently contains dangerous ingredients. Conventional synthesis processes frequently produce hazardous waste, but plant-based synthesis substantially decreases trash generation. The use of water or ethanol as solvents also enhances the eco-friendliness of this method.^{384,386} Plant-based approaches often provide SNPs that exhibit higher biocompatibility in comparison to chemically synthesized ones. The presence of phytochemicals in plant extracts serves as both stabilizing and reducing agents, hence improving the safety profile of NPs used in biomedical applications.^{385,386} Utilizing renewable plant resources for nanoparticle synthesis encourages the adoption of environmentally sustainable techniques. Plants include several active chemicals that help in reduction of silver ions, enabling the synthesis process to be more efficient with less energy and milder conditions.³⁹²

The eco-friendly production of SNPs is more cost-effective compared to traditional approaches. Plant extracts are easily accessible and affordable, obviating the necessity for expensive chemical reagents and intricate equipment. This facilitates the procedure for large-scale manufacture. The simple nature of the plant-based synthesis method enables convenient expansion to suit industrial requirements without substantial cost escalation. The capacity to scale is essential for commercial applications in many domains such as health, agriculture, and environmental remediation.³⁸⁴ The economic feasibility is further supported by the wide-ranging uses of plant-derived SNPs, which encompass several sectors including agriculture (for pest management), medicine (as antibacterial agents), and environmental remediation (for water purification). Their market worth is enhanced by their wide-ranging application.³⁸⁵

9. Future perspectives

The current progress in the green synthesis of SNPs highlights an important shift towards sustainable and eco-friendly manufacturing methods. Using biological resources, including plant extracts and agricultural waste, offers a new method that reduces adverse environmental effects while increasing the value of byproducts from the food industry. Plant extracts, including those from *Citrus sinensis* and pomegranate,^{393,394} have demonstrated effectiveness in transforming silver ions into NPs that possess significant antibacterial characteristics. In addition, the utilization of agricultural waste such as banana,³⁹⁴ potato³⁹⁵ and onion peels³⁹⁶ not only decreases waste but also acts as a cost-efficient source for the synthesis of SNPs, exhibiting antibacterial and antioxidant properties.³⁹⁰ Generally smaller sized NPs have enhanced antibacterial activity as a result of increased surface area that comes into proximity with the microbial cell. Within the same size range, the antibacterial activity of SNPs follow this order: triangular > pentagonal, hexagonal, cubic, nano-rod > spherical. The triangular shape exhibited the maximum level of activity mostly because of its superior edge fitting, which is attributed to its sharp edges and the dominating stable (1 1 1) facet.^{391,397} Hexagonal, cubic, and nano-rod NPs possess curved edges, which may potentially decrease their effectiveness against bacteria in comparison to triangular-shaped NPs. On the other hand, NPs with a spherical form that have no sharp edges and are mostly composed of (1 0 0) face exhibited the lowest antibacterial effects.³⁹⁸ Discovery and utilization of a broader range of plants could pave way for further emerging trends in plants-based synthesis of SNPs. The enhanced biocompatibility and decreased toxicity of SNPs produced using environment friendly techniques are gaining more recognition, particularly in the field of medical applications such as cancer therapy. These NPs demonstrate increased cytotoxicity against cancer cells while protecting the structural integrity of normal cells.³⁹⁹ The several applications of these NPs encompass antibacterial and antifungal purposes, drug delivery systems, environmental remediation, and catalysis in chemical reactions.⁴⁰⁰

Some other key future directions which should be focused are to establish a standardized protocol that can widely be adopted to minimize the variability in the synthesis of NPs. This may include innovative methods like automated systems for high-throughput screening of plant extracts, enabling the rapid identification of most effective plant species and conditions for SNPs synthesis.³²⁸ In depth mechanistic studies can be done by using advanced techniques like genomics, proteomics, and metabolomics can be utilized to understand the molecular interactions between plant phytochemicals and silver ions, leading to more precise and predictable synthesis processes.^{216,388} The integration of plant-based synthesis of SNPs with other biotechnologies, such as biosensors, biocatalysts or bioimaging could lead to innovative applications in diagnostics, environmental monitoring and industrial processes.⁹⁴ Characterization methods for SNPs have made great progress, offering valuable information about their dimensions,³⁹⁵ morphology,



In the future, SNPs made from steamed plant extracts show great potential for being used in several industries. These NPs have the potential to enhance wound healing, facilitate drug delivery, and optimize cancer therapy in the field of biomedicine.^{384,405} Their capacity as natural preservatives in the food industry has the potential to transform food safety by prolonging shelf life without the use of synthetic chemicals.⁴⁰⁶ Moreover, their efficacy in environmental remediation, including tasks like water purification and soil restoration, establishes them as useful agents in tackling pollution. SNPs may be utilized in cosmetics manufacturing to enhance items due to their antioxidant and antibacterial capabilities. Similarly, in the textile industry, SNPs provide antibacterial effects and contribute to self-cleaning features. Their optical characteristics also render them appropriate for the creation of sensors and their utilization in the fields of electronics and optoelectronics. The collaboration between researchers in materials science, chemistry, biology, medicine, and engineering is essential for fully realizing the capabilities of SNPs and promoting innovation in various fields. Future research will delve deeper into the mechanisms by which plant extracts reduce and stabilize SNPs. Understanding these processes at a molecular level will help in optimizing synthesis protocols and improving the reproducibility and scalability of nanoparticle production.³⁸⁴

The green synthesis of SNPs using plant extracts has been a sustainable, economically effective, and eco-friendly substitute to traditional chemical methods. The characterization of these SNPs using techniques such as FTIR, XRD, SEM, TEM, SAED, EIS, and LSV-UV discovered their high-quality, crystalline morphology and appropriate physical and chemical characteristics. The synthesized SNPs exhibited remarkable performance across a range of efforts, including photocatalysis for environmental cleanup, antimicrobial activity, and boosted resources in biomedical and biosensing technologies. This review emphasizes the potential of green-synthesized SNPs in focusing global confronts related to environmental pollution, healthcare, and industrial processes. The biocompatibility and functional adaptability of these SNPs opens new routes for sustainable nanotechnology, with wide-accomplished implications for future scientific advancements and practical applications. Further research of plant-based materials and accessible production techniques will increase the pertinency of SNPs in real-world scenarios. By addressing unresolved issues, green synthesis can develop into a more robust and scalable knowledge, paving the way for groundbreaking solutions to global

trials in environmental sustainability, healthcare, and resources. This expedition towards harnessing the full potential of green synthesised SNPs underscores the importance of interdisciplinary research in shaping a sustainable opportunity.

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

There are no conflicts to declare.

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