NanoNEXT

Review Article

Green Nanoparticle Synthesis using Xerophytic Medicinal Plants: Linking Stress-Adapted Phytochemistry with Nanoparticle Formation and Surface Properties

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Abstract: Green nanoparticle synthesis using plant extracts avoids the toxic reagents and high energy demands of chemical reduction methods, but most published work treats plant identity as interchangeable and rarely identifies which phytochemicals actually drive metal-ion reduction. Xerophytic and semi-arid medicinal flora carry measurably elevated concentrations of redox-active phenolics and flavonoids relative to unstressed vegetation, yet Indian arid and semi-arid species specifically have received little of the same nanoparticle synthesis attention already given to comparable flora in Sudan and southern Africa. This review draws together the phytochemical rationale for using such flora as synthesis precursors, the mechanism connecting specific compounds to metal-ion reduction and surface capping, and a species-level survey of eleven plants across nineteen separately reported nanoparticle systems. Particle size varied by more than an order of magnitude with no consistent relationship to plant genus or precursor metal. Antimicrobial activity was confirmed in seventeen of the nineteen systems, and the phytochemical capping layer itself contributed measurable antimicrobial activity independent of the metal core. Reaction conditions, including temperature, pH, and extract-to-metal ratio, shaped particle outcomes as much as plant chemistry did. Reproducibility, compound-level mechanistic resolution, and long-term safety evidence remain unresolved. Three species originally scoped for this review, Capparis decidua, Balanites aegyptiaca, and Tecomella undulata, lacked adequate species-specific literature. No related species were substituted in their place.

Keywords: Green Synthesis, Metal Nanoparticles, Xerophytic Plants, Phytochemicals, Antimicrobial Activity, Indian Arid and Semi-Arid Flora

1. Introduction

Most reports of plant-mediated nanoparticle synthesis follow a similar pattern. An extract reduces a metal salt, nanoparticles of a given size and shape appear, and the specific compound responsible for the reduction is never identified [1-3]. That gap sits at the centre of an otherwise fast-growing field. Silver, gold, zinc oxide, copper oxide, and several other metal and metal-oxide systems have all been synthesised this way [3-5]. The appeal is straightforward. Phytochemicals already present in leaf, root, or seed extracts replace the chemical reductants and capping agents that conventional synthesis relies on [4, 6]. What the field has not resolved is why a given plant works, or why the same plant behaves differently from one batch to the next.

Although it is inconsistent, it does have real-world implications. Depending on geographic origin, season and extraction process, the chemical composition of plant will change, affecting the NP size, shape and stability [7, 8]. The same problem occurs when moving a laboratory procedure towards more extensive bulk production – apart from longer reaction times, lack of standard infrastructure: [7] Ongoing toxicologic research is even further behind, and the majority of published studies have been confined to assessing the in vitro effects [2, 9, 10].

The use of xerophytic medicinal plants is comparatively under-studied in this field. The medicinal flora of Sudan for instance has secondary metabolites with redox capacity appropriate for biosynthesis of nanoparticles but very little research has focused on it

[11]. A species pool with even more indigenous South African plant species was also identified to have a high potential for synthesizing iron oxide nanoparticles, with some adapted to arid environments; such an area was also considered underexplored [12]. The medicinal flora of arid and semi-arid regions of India is in a similar situation. Traditional use dates back far and individual species studies have been gradually and somewhat irregularly, increasing over the years. That's where the effort of pulling those threads together still is lacking.

There is a basis for assuming that not just the selection of species, but the actual underlying phytochemistry is important. The rate of antioxidant activity from various plant extracts was correlated with the yield and size of nanoparticles of zinc oxide in one comparative study which also discussed about the polydispersity of such nanoparticles [13]. In another isolated study, it has been found that quercetin produced the greatest reduction of $Ag+$ and it was more efficient than the whole Ocimum sanctum extract it was extracted from, meaning that one biomolecule can equally contribute to the majority of the reducing capacity of the extract rather than a mix of compounds [14].

To a significant degree, after the synthesis, a phytochemical layer surrounding the surface of a nanoparticle (the "corona") will determine its bioaction. The "corona" of a nanoparticle after its synthesis has an effect on its bioaction that is as strong as its colloidal stability. Several studies report higher antibacterial and antifungal activity of the Phytochemically capped nanoparticles than the bare metal core, a key argument for even wanting to pursue phytochemical capping when one must keep in mind the problem with antimicrobial resistance that seems to be growing with us every day [5, 7, 9].

This review process through the proof of the medicinal plants of the Indian arid and semi-arid climatic region with particular emphasis upon the Indian arid and semi-arid region as such. Two primary themes about the phytochemicals as a synthesis platform suggest themselves: first, the case of the plants themselves as a platform; second, the mechanism by which their constituents contribute to the formation of nanoparticles. The review comes to an end following a species by species survey to get at the surface properties and the antimicrobial performance. The goal all the way is to distinguish facts from what remains more speculative.

2. Xerophytic Medicinal Plants and their Phytochemical Characteristics

The morphology, anatomy and physiology of xerophytes is different from that of mesophytic plants and so is their biochemistry [15]. The plants' reaction to drought, salinity and other abiotic stress predominantly involves the phenylpropanoid pathway, which results in the formation of polyphenols that sequester the formation of ROS, help stability of membranes, assist in osmotic adjustment [16]. A number of salt-tolerant and drought adapted species show measurable increases in phenolics and flavonoids between members of the same species when grown in extreme salt levels compared to plants cultivated in less demanding climates [17]. A similar effect to another stress has been shown by species grown at high altitude, where carotenoids, ascorbic acid, tocopherols and polyphenols have been observed to be accumulated to counteract oxidative stress via UVA radiation [18]. Table 1 shows the phytochemical composition of selected xerophytic species.

Table 1. Phytochemical composition of selected xerophytic species

Species	Phytochemical Class(es)	Quantity	Ref.
Aerva javanica	Phenolics, Flavonoids	188.67 mg/g DW, 0.35 mg/g DW	[20]
Xerophyta spekei	Phytosterols, terpenoids, tocopherols, alkaloids	Stigmasterol 12.99 mg/g	[21]
Crithmum maritimum	Terpenoids (γ-terpinene, p-cymene)	Not quantified	[22]
Kei apple	Salicylic, m-hydroxybenzoic, vanillic, gallic acids, catechins	Not quantified	[23]

Note: only species with numeric or compound-level phytochemical data are tabulated. [16–19] support general claims in the prose and are not included.

Xerophytic flora predominated over the arid and semi-arid areas in Rajasthan state and has been reported to be rich in various phytochemicals like alkaloids, flavonoids, terpenoids, glycosides, tannins and phenolic compounds across its different plant species, with the available literature relating to ethnobotanical and industrial applications of this region's flora but not to the synthesis of nanoparticles.

The main non-enzymatic antioxidant defence of these stressed plants is constituted by the phenolic compounds and flavonoids, which usually reach amounts so high to exceed those found in vegetation that does not see the stressful conditions. These accumulations do not occur similarly, but rather include metabolites of different classes, depending on the species. Aerva javanica, a species grown in the deserts of Pakistan, also has a high level of phenolics (188.67 mg/g dry weight), and only a relatively low level of flavonoids in the same tissue (0.35 mg/g) indicating that xerophytic stress does not necessarily equally increase all metabolite classes. This is the case for terpenoid and alkaloid production as well. Flavanoids, phenolics, stained with terpenoids, fatty acids, phytosterols (up to 12.99 mg/g of stigmasterol) and alkaloids, are among the phytochemicals present in Xerophyta spekei. Not even within a species the number and kinds of terpenoids are constant. The increase in salinity increased γ-terpinene and decreased p-cymene concentrations in the halophyte Crithmimum maritimum, and vice versa, biostimulant treatment in the plant's leaves restored the differences [22].

These products such as hydroxy- and carboxyl-rich metabolites, which provide this antioxidant effect are also used to reduce metal ions during the synthesis of nanoparticles. The flavonoids like quercetin bind directly with the metal salts and on combustion they form a metal salt and metal hydroxides which further forms metal oxides on calcination [23]. A similar pathway is taken by phenolic acids. Salicylic acid, m-hydroxybenzoic acid, vanillic acid, gallic acid and catechins are the main antioxidants used for the synthesis of zinc oxide nanoparticles in Kei apple fruit extract [23]. The same functional groups are found in xerophytic tissues and they typically occur at higher concentrations in these than in the mesophytic species; in principle the redox chemistry that has been followed in the mesophytic species should be found in the xerophytic species, although this has rarely been confirmed by direct observation in the latter.

3. Role of Plant Phytochemicals in Nanoparticle Formation

The proposed mechanism of phytochemical-mediated nanoparticle formation is shown in figure 1. The reduction of metal ions by plant phytochemicals begins with direct chelation. Hydroxyl groups on phenolic compounds bind metal ions to form a chelating ring, which then oxidises into a carbonyl-based structure as the metal ion is itself reduced to its zero-valent atomic form [24]. This chelation occurs preferentially at ortho-substituted hydroxyl positions, gallic acid is one example, while flavonoids complex most readily at the hydroxyl group on carbon 3 or 5 alongside the adjacent 4-carbonyl group [24]. The position and number of these hydroxyl groups bear directly on nanoparticle size and shape, since the same sites go on to attach to the growing particle surface [24].

Isolating single compounds from whole extracts confirms that this chelation-reduction sequence, and not the extract's full chemical complexity, drives most of the observed activity. Quercetin on its own reduces silver ions faster than the Ocimum sanctum leaf extract it was drawn from [14], and the same flavonoid binds metal salts directly before its own hydroxyl groups react further to form a metal hydroxide that yields an oxide nanoparticle on calcination [23]. The resolution doesn't pertain to flavonoids only. Ultra performance liquid chromatography and high resolution mass spectrometry of Hypericum perforatum extract indicated that the phenolic acids and flavonoids were the main reductants, while phloroglucinols and naphthodianthrones were more of a reducing property (capping agents) [25]. Proteins do so in a related, but different manner. Extracts with high concentrations of amino acids contain functionalised amino groups and can directly reduce gold ions to gold metal without the use of phenolic chemistry which is common for the reduction of silver [26]. Not only species, but parts of the plant are of importance. The leaf and root extracts of Ricinus communis when tested alongside each other, resulted in silver nanoparticles of different average sizes: 38 nm obtained with leaf extract and 29 nm with root extract, and two sets of phytoconstituents were identified to induce the reduction and capping, with indole-3-acetic acid, L-valine, triethyl citrate and quercetin-3-O-β-D-glucopyranoside which were identified in leaf extracts and indole-3-acetic acid, L-valine, triethyl citrate, which were identified in root extracts [27].

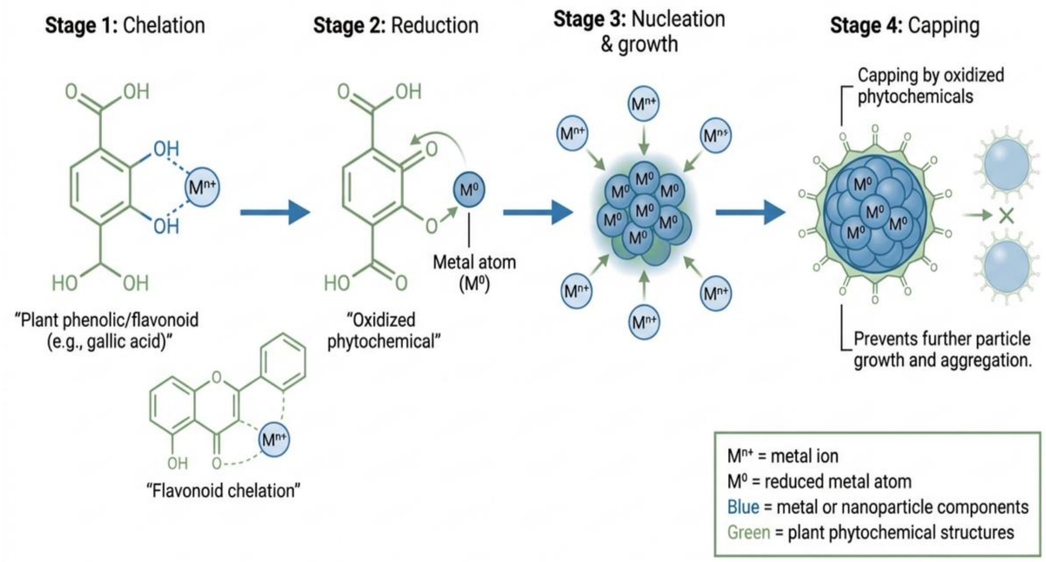

Figure 1. Proposed mechanism of phytochemical-mediated nanoparticle formation: hydroxyl-mediated chelation of metal ions, reduction to the zero-valent metal, nucleation and particle growth, and surface capping by the same oxidized phytochemicals.

The metal nanoparticles tend to remain stable without the addition of a stabiliser. The antioxidants, such as flavonoids, alkaloids, terpenoids, phenolics and enzymes that conducted the reduction will invariably be on the surface of the resulting particle and will stop it from clumping over again [28]. Differentiating plant-mediated synthesis from chemical synthesis involve routes where a pair of the functional groups serving both purposes. Generally, such routes require separate capping agents to be added after the reduction, unlike plant mediated synthesis. This is further influenced by reaction parameters which turn out to have significant individual effects.

The absorbance of the resultant silver nanoparticle solution increased almost fourfold from 20°C to 60°C and when the pH was changed to extremes, such as pH 2 or pH 10, the absorbance of silver nanoparticle increased but the resultant nanoparticles were relatively unstable when compared to the relatively stable nanoparticles at near neutral pH [29]. As well as size, plant extract: metal salt ratio is a key factor in shape. A higher extract-to-metal ratio in the preparation of gold nanoparticles resulted in a change of the particle shape from a triangular to spherical (SN nr. 30) [30]. Their more precise control is further concentrated by isolating a single reducing compound. Physcion extracted from Senna alata resulted zinc oxide (ZnO) nanoparticles of smaller size and with uniform growth, as compared to a larger size of crystallite size obtained from the crude extract, with higher specific surface area [31]. Another optimisation study with extract of Mentha arvensis revealed that in order to get more robust nanoparticles, the effect of the 1:9 ratio of plant extract to metal salt, the metal salt used (e.g., silver and gold nitrate), the reaction temperature (60°C), and the reaction pH (acidic pH) were not independent on one another [32]. Not only concentration, but the morphology is determined by the identity of the reducing compound. As the individual purified antioxidants reacted with the silver nitrate, they yielded different shapes depending on the antioxidants; spherical for ascorbic and gallic acids, triangular for β-carotene and polyhedron for catechin; these shape differences were found to be created by the specific antioxidants itself not by the amount of antioxidant alone used in the reaction [33].

In spite of the control of this parameter the chemical processes are not completely understood. Despite extensive work in the field, the real biomolecules and mechanisms behind plant biomass reduction has remained only partially known; as plant compositions are highly variable [34]. The shape and size of nanoparticles formed and optical properties of the extract tested against the same metal target vary according to the phytochemicals found predominant in the extract [35]. The other is that same variability, as it's the real-world significance that makes formation-condition studies as important as they are. Tuning temperature, pH, and extract ratio is, in effect, a way of compensating for chemistry that cannot yet be specified compound by compound in every plant source.

4. Xerophytic Medicinal Plants as Sources for Green Nanoparticle Synthesis

4.1 Calotropis Procera

Leaf extract of Calotropis procera yields copper oxide nanoparticles 20 to 80 nm in diameter, spherical in shape, with confirmed antifungal activity against Rhizopus oryzae and antibacterial activity against Escherichia coli [36]. Latex from the same plant yields a different result. Iron oxide nanoparticles just 3 to 5 nm across were applied as a catalyst for biodiesel production from the plant's own seed oil, with no antimicrobial testing reported for this system [37].

4.2 Calotropis gigantea

Leaf extract of Calotropis gigantea, rich in tannins, alkaloids, flavonoids, and polyphenols, reduces silver ions into nanoparticles with a spherical-to-cubic morphology, 10 to 25 nm by scanning electron microscopy and 20 to 50 nm by transmission electron microscopy. Confirmed antioxidant and antibacterial activity followed [38].

4.3 Withania Somnifera

Zinc oxide nanoparticles synthesised from Withania somnifera leaf and root extracts, across four different solvents, produced spherical particles 70 to 90 nm across, confirmed crystalline by X-ray diffraction. Total flavonoid, phenolic, and alkaloid content measured higher in the crude extracts than in the resulting nanoparticles. Root extracts in n-hexane and ethyl acetate produced the strongest free-radical scavenging activity, and the nanoparticles showed antibacterial activity against Escherichia coli, Staphylococcus aureus, and Bacillus subtilis [39]. Its wider phytochemical profile has been discussed in detail separately, in which along with a detailed overview of its withanolide scaffold, structure-activity relationship, structural modifications, Withania's pharmacological targets have been elaborated [40]. Figure 2 outlines the distribution of the eleven surveyed species across India.

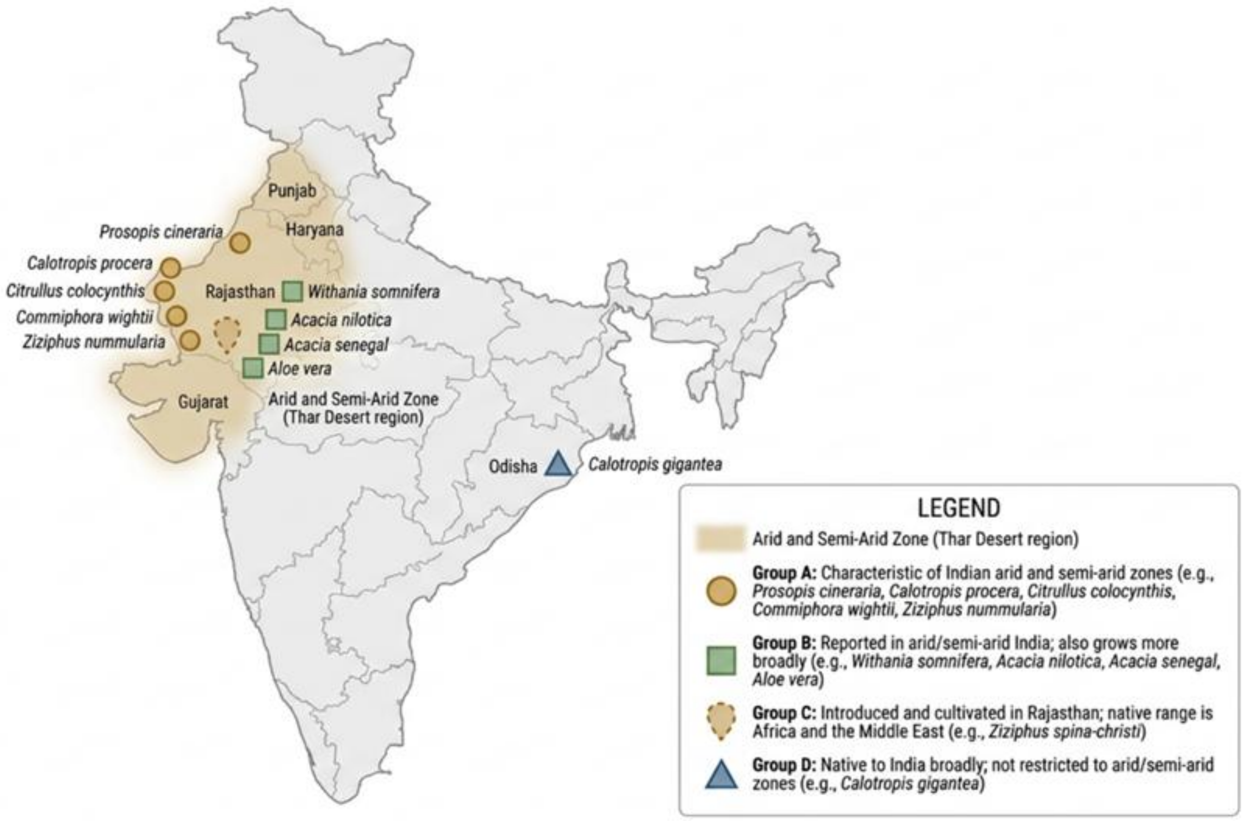

Figure 2. Distribution of the eleven surveyed species across India's arid and semi-arid zones, distinguishing zone-characteristic species, species present but not zone-restricted, an introduced and cultivated species (Ziziphus spina-christi), and a native Indian species not restricted to arid zones (Calotropis gigantea).

4.4 Prosopis Cineraria

Microwave irradiated extract of Prosopis cineraria in single protocol produced both silver nanoparticles and copper nanoparticles of size 20 to 44.49 nm and 18.9 to 32.09 nm, respectively, and hexagonal to spherical shape with antibacterial activity against multidrug-resistant pathogens and reasonable cytotoxicity towards the MCF-7 breast cancer cells [41]. The same species is also used to obtain titanium and zinc oxide as nanoparticles which have shown antibacterial activity on both live and dead cells using confocal microscopy [42] and an antioxidant effect on spatial memory and antioxidant enzyme activity in a drug-induced amnesia mouse model [43], respectively.

4.5 Ziziphus spina-christi

In a single step, a trimetallic copper oxide, silver and zinc oxide nanocomposite was synthesised by using the leaf extract of Ziziphus spina-christi, which forms spherical particle-shaped nanocomposite having an average size of 7.11 nm, which is less than any other system reported in this survey except that of Calotropis procera where spherical iron oxide nanoparticles with an average size of 5.7 nm were formed. The Zeta potential was 21.5 mV, which is on the less stable side of the range generally considered to be locations that would impart colloidal stability. Elemental mapping revealed that the surface was really a nanocomposite and the antimicrobial activity of the nanocomposite was realised against multiple drug resistant (MDR) human pathogens with concentrations ranging from 150 to 200 μg/mL [44].

4.6 Citrullus Colocynthis

Citrullus colocynthis produced three separate systems and Prosopis cineraria produced four, the most for any species in this survey. Microwave-assisted combustion of zinc nitrate with fruit, seed, and pulp extracts used as biofuels produced hexagonal wurtzite zinc oxide nanoparticles ranging from 27 to 85 nm. Zeta potential, hydrodynamic size, and antioxidant activity all varied depending on which biofuel extract was used, and the nanoparticles showed antibacterial activity against Bacillus subtilis, MRSA, Pseudomonas aeruginosa, and Escherichia coli, with no toxicity to 3T3 cells below 0.26 mg/mL [45]. A separate study synthesised zinc oxide nanoparticles from fruit and leaf extracts prepared in four different solvents, n-hexane, methanol, ethyl acetate, and water, using zinc acetate as precursor. These particles measured 64 to 82 nm and appeared spherical by SEM, with flavonoid, phenolic, and alkaloid concentrations measured higher in the crude extracts than in the resulting nanoparticles. Bioactivity depended strongly on which plant part and solvent fraction was used. Fruit aqueous-extract nanoparticles showed stronger antioxidant activity than the crude extract itself, leaf n-hexane nanoparticles showed strong antifungal activity, and fruit n-hexane and aqueous nanoparticles reached 93.42% and 82.54% antidiabetic activity respectively [46]. A third study used leaf extract with copper sulfate to produce spherical, face-centered cubic copper nanoparticles measuring 17 ± 4.2 nm, which degraded 65% of methylene blue dye within 160 minutes and showed antibacterial activity against Pasteurella multocida, Bacillus subtilis, Staphylococcus aureus, and Escherichia coli [47].

4.7 Commiphora Wightii

Aqueous extract of Commiphora wightii, with synthesis optimised by precursor ratio, pH, and temperature, produced polydispersed gold nanoparticles averaging 20.2 ± 6.6 nm, with FTIR confirming biomolecule involvement in both reduction and stabilisation. The nanoparticles were tested for antioxidant and anti-inflammatory activity across seven separate assays, but specific IC50 values were not reported in the available data [48].

4.8 Zizith's Nummularia

Leaf extract of Ziziphus nummularia produced zinc oxide nanoparticles averaging 17.33 nm with spherical to irregular morphology. These nanoparticles showed antifungal activity against multidrug-resistant clinical Candida isolates that exceeded four standard azole antifungal drugs tested for comparison and potent cytotoxicity against HeLa cervical cancer cells [49].

4.9 Acacia Nilotica

Bark extract of Acacia nilotica with silver nitrate, optimised at 0.1 M precursor concentration and 3 mM reaction conditions, produced variably shaped silver nanoparticles measuring 20 to 50 nm. These particles showed anticancer activity against HepG2 cells, antidiabetic activity through α-glucosidase inhibition, and antioxidant activity, though exact IC50 values were not given [50]. A separate study used aqueous Acacia nilotica extract as a bioreductant for silver-doped titanium dioxide nanoparticles. These spherical particles showed antibacterial and anticandidal activity in the order Escherichia coli, Candida albicans, MRSA, Pseudomonas aeruginosa, and reduced MCF-7 breast cancer cell viability while increasing reactive oxygen species and lipid peroxidation [51].

4.10 Acacia Senegal

Acacia senegal plant material produced silver oxide and silver iodide-related nanocrystallites averaging 14.31 nm by atomic force microscopy, with a maximum of 34.50 nm, described as semi-spherical and homogeneously dispersible in a cubic spinel configuration. Antibacterial testing found the greatest efficacy against Staphylococcus epidermidis, with lower efficacy against Staphylococcus aureus, Escherichia coli, and Klebsiella species [52].

4.11 Aloe Vera

Two independent 2025 studies synthesised silver nanoparticles from Aloe vera, with different results. Using aqueous extract, one study achieved conversion within about 15 minutes at room temperature without hazardous chemicals, confirmed by XRD, HRTEM, zeta potential, Raman spectroscopy, and cyclic voltammetry; the nanoparticles inhibited both Escherichia coli and Bacillus subtilis, though the available excerpt does not report a specific particle size [53]. Using leaf extract and a central composite design to optimise reaction conditions, a second study found that 2.2185 mM silver nitrate, pH 11.91, and 2.91 hours of incubation produced the most consistent nanoparticles, spherical, averaging 68.79 nm, with a polydispersity index of 0.374 and a highly crystalline silver phase making up 70.8% of the sample. These nanoparticles inhibited Salmonella typhae, Escherichia coli, Staphylococcus aureus, and Aspergillus niger [54].

4.12 Comparison of Synthesis Approaches and Nanoparticle Characteristics

Across the eleven species and nineteen nanoparticle systems surveyed here, particle size spans more than an order of magnitude, from 3 nm (Calotropis procera, iron oxide, latex) to 90 nm (Withania somnifera, zinc oxide), with no consistent relationship to plant genus, metal precursor, or synthesis method. Species from the same genus did not converge on similar outcomes: Calotropis procera's two systems differ by more than twenty-fold in size, and Acacia nilotica's two systems used entirely different metals, silver versus silver-doped titanium dioxide, not simply different sizes of the same one.

Multiple nanoparticle systems were reported for five of the eleven species, Calotropis procera, Prosopis cineraria, Citrullus colocynthis, Acacia nilotica, and Aloe vera, and within every one, plant part, solvent, or precursor changed the outcome measurably. Citrullus colocynthis and Prosopis cineraria each yielded three distinct systems, tied for the most of any species here.

Antimicrobial activity was confirmed for seventeen of the nineteen systems surveyed. The two exceptions, Calotropis procera's latex-derived iron oxide nanoparticles and Commiphora wightii's gold nanoparticles, were developed and tested for other purposes, biodiesel catalysis and antioxidant/anti-inflammatory activity respectively, not because antimicrobial testing was attempted and failed. Quantitative reporting is also uneven. Several studies give exact inhibition zones, IC50 values, or percentage activity; others describe an effect as present without the underlying number. That's where this review has broken it down: this breaking and naming is not done into a single collapsing, but rather at each species where it has been seen. Table 2 compares the species-level nanoparticle synthesis survey with bioactivity.

5. Phytochemical Composition, Surface Properties and Antimicrobial Performance

5.1 Particle Size and Morphology

Fractionating Elaeagnus umbellata extract by solvent produced silver nanoparticles that differed in shape, size, and bactericidal activity across fractions, evidence that a single plant can yield several distinct synthesis systems depending on which chemical subset of its extract is used [55]. Fagonia indica illustrates the same point without changing species at all. Cell cultures treated with the phytohormones melatonin or thidiazuron zuron produced silver nanoparticles averaging 15 nm and 19 nm respectively, both smaller than the 22 nm particles from extract of the naturally grown plant. The plant treated with the phytohormone had a different metabolite profile than the control resulting in a different particle size [56]. The same takes place at species' level in a three-way comparison with one synthesis protocol.

Table 2. Species-level nanoparticle synthesis survey (Section 4)

Species	Part	NP	Size / Morphology	Key Bioactivity	Ref.
Calotropis procera	Leaf	CuO	20–80 nm, spherical	Antifungal, antibacterial	[36]
Calotropis procera	Latex	Fe_2O_3	3–5 nm	Biodiesel catalyst only	[37]
Calotropis gigantea	Leaf	Ag	10–25 / 20–50 nm, spherical-cubic	Antioxidant, antibacterial	[38]
Withania somnifera	Leaf & root	ZnO	70–90 nm, spherical	Antibacterial	[39]
Prosopis cineraria	Leaf	Ag	20–44.49 nm	Antibacterial, anticancer (MCF-7)	[41]
Prosopis cineraria	Leaf	Cu	18.9–32.09 nm	Antibacterial, anticancer (MCF-7)	[41]
Prosopis cineraria	Leaf	TiO_2	Not reported	Bactericidal	[42]
Prosopis cineraria	Leaf	ZnO	Not reported	Cognition, antioxidant enzyme activity	[43]
Ziziphus spina-christi	Leaf	CuO/Ag/ZnO	7.11 nm, spherical	Antimicrobial, MDR pathogens	[44]
Citrullus colocynthis	Fruit/seed/pulp	ZnO	27–85 nm, wurtzite	Antibacterial	[45]
Citrullus colocynthis	Fruit & leaf	ZnO	64–82 nm, spherical	Antioxidant, antifungal, antidiabetic	[46]
Citrullus colocynthis	Leaf	Cu	17 ± 4.2 nm, spherical	Antibacterial, dye degradation	[47]
Commiphora wightii	Aqueous	Au	20.2 ± 6.6 nm	Antioxidant, anti-inflammatory	[48]
Ziziphus nummularia	Leaf	ZnO	17.33 nm	Antifungal, cytotoxic (HeLa)	[49]
Acacia nilotica	Bark	Ag	20–50 nm	Anticancer, antidiabetic	[50]
Acacia nilotica	Aqueous	Ag/TiO_2	Not reported	Antibacterial, anticancer (MCF-7)	[51]
Acacia senegal	Plant material	Ag_2O/AgO/AgI	14.31 nm avg	Antibacterial (S. epidermidis)	[52]
Aloe vera	Aqueous	Ag	Not reported	Antibacterial	[53]
Aloe vera	Leaf	Ag	68.79 nm, spherical	Antimicrobial (multi-organism)	[54]

The particle size for the various plant extracts were found to be 28.5 nm for Ocimum gratissimum, 20.2 nm for Apium graveolens and 15.07 nm for Aloe arborescens in the same manner as described above, clearly demonstrating that even though all the other synthesis variables were kept identical, the particle size can vary for different plant extracts [57].

5.2 Surface Functional Groups and Phytochemical Capping

It is possible to measure the capping layer directly. The electron microscopy (EM) test of the capped particle diameter relative to the bare metal core mean diameter has formed a 10.7 nm average layer of organic material around each silver nanoparticle core after the treatment with green coffee bean extract [58]. This organic layer has its own antimicrobial properties without the presence of the metal which it is wrapped around. When tested individually, capped Musa sapientum (MSNAPs) nanoparticles exhibited strong antibacterial activity against all tested bacteria at 62.5 to 1000 μg/mL against the raw plant extract and uncapped and capped nanoparticles for all tested bacteria and plant parts [59].

5.3 Surface Charge and Colloidal Stability

The surface charge will take on how the biomolecules are dominating in the capping monolayer. The zeta potential in case of silver nanoparticles coated with orange peel extract was found to be −19.0 mV [60]. When the semiconductor material is doped with another element, there's another added dimension. The same trend was observed in case of the iron doped zinc oxide nanoparticles, where the extent of the shift in the value of the zeta potential could not be determined separately in this review [61].

5.4 Phytochemical Corona and Nanoparticle-Biological Interactions

This surface charge is a property that can be determined by identifying the biomolecule. Tandem mass spectrometry on orange peel-capped silver nanoparticles identified three specific proteins responsible for most of the capping, confirming the corona is a defined, identifiable set of biomolecules [60]. That corona changes after formation, too. Pre-existing capping agents can pick up additional biomolecules from the surrounding medium after synthesis, so the corona identified in a fresh preparation may not match what is present once the particle enters a biological system [60].

5.5 Antimicrobial Activity as a Function of Surface Properties and Phytochemical Capping

Smaller, more uniformly spherical particles produced stronger antimicrobial results in direct comparison. Among the three plant-extract systems compared above, the smallest particles reached a minimum inhibitory concentration as low as 1.016 μg/mL against E. coli and S. aureus [57]. Biogenic copper oxide nanoparticles from Solanum nigrum leaves produced inhibition zones of 11 mm against Bacillus subtilis and 12 mm against Escherichia coli, compared with only 2 mm and 3 mm, respectively, for chemically synthesised copper oxide nanoparticles tested under the same conditions [62]. The above-mentioned capping-agent activity corroborates this pattern in other ways. As well as the metal core, the organic surface is a critical component to the antimicrobial effect since it contributes measurably to the effect [59].

6. Current Status, Limitations, and Research Needs

Section 3 also shows species variations to other phyochemical constituents, regional variations, variations depending on the season, variations stemming from different extraction processes, and variation based on different parts of the plant, all of which are also known to lead to batch-to-batch batch variation [7, 8]. Finding that variable this way is not so common in the literature but has been seen in isolation once before. Interestingly, one SF extract alone was able to yield three NP classes (5.9 nm, 10.5 nm and 16.1 nm) under the same synthesis conditions, and radical differences in plant chemistry were responsible for this variation in particle size even when all the reaction parameters were kept at the same value [63]. Similarly, strict control can be maintained when performing careful optimisation of a single system. The average size of zinc oxide nanoparticles was 12.41 nm with low polydispersity index one of the smallest sizes (less than 25 nm) reported for this type of nanoparticles till date [64].

There is still an unresolved problem with the field, that is, a mechanistic interpretation. The same kind of comments were made above for this section on Section 3 regarding the biomolecules and pathways controlling the reduction are poorly understood: in most crude-extract processes, one does not observe that any particular biomolecules or pathway is controlling, but rather some cooperativeness of biomolecules is controlling the nucleation and growth process [34, 35].

This same variability with respect to reproducibility and scale-up. Through a wide-ranging 2025 review, batch variability and the compositional fluctuations in extracts observed during manufacturing of reproducible high quality are identified as two key challenges to reproducibility and quality control, and suggest three possible avenues for green synthesis to become scalable to an industrial level: bioprocess engineering, real time monitoring, and lifecycle assessment [65].

Evidence indicating safety is even further behind than reproducibility and mechanistic resolution. In 2026, an antimicrobial application evaluation of biogenic nanoparticles confirms that data on long-term toxicology, pharmacokinetics and environmental safety are still significantly lacking throughout the discipline and that these are specific needs that need to be addressed prior to regulatory evaluation or clinical translation [9].

7. Future Prospects

The liquid chromatography-mass spectrometry has identified three particular reducing compounds (riboflavin 5′-phosphate, chlorogenic acid and methoxsalen) in entirely different nanoparticle systems (one selenium, one copper). This is feasible these days, using the same instruments on even more contrasting materials, including Catharanthus roseus and Tordylium trachycarpum [66, 67]. By making this ability possible, a real change from characterising finished particles to profiling the chemistry of an extracts will be achieved in advance.

It is as important as species choice to use the correct extraction method. Water extraction and extraction with hydro-alcoholic solvent resulted in the production of different sparkling nanoparticles originating from the same plant in terms of phenolic content, flavonoid content and antioxidant activity [68]. The level of species requires that only the species name be recorded (but not the method of extraction) so that a variable is missing that is capable of measuring the differences in the result.

For the first time two species were introduced into this world of literature with functional results. For the first time two species were introduced about the functional results in this world. Tordylium trachycarpum was used for copper nanoparticles and Tinospora cordifolia was used for gold nanoparticles, the first time ever being synthesised [67]. Neither is xerophytic. A tiny fraction of Indian arid-zone flora has been subjected to the synthesis first time and so is the case with the 11 species reviewed here; what would the response of Indian flora to similar synthesis for the first time, is outside the scope of this review.

8. Conclusion

The review aimed to clarify if xerophytic and semi-arid medicinal flora can be considered a viable, yet underutilised platform to produce GNPs and the corroborating data gathered supports this conclusion. Xerophytic and halophytic species carry measurably distinctive phytochemistry, redox-active phenolics and flavonoids elevated relative to unstressed vegetation, and the chemistry connecting those metabolites to metal-ion reduction and surface capping is well characterised in the broader literature. Eleven species examined in detail produced nineteen separately reported nanoparticle systems, all of them functional. Seventeen carried confirmed antimicrobial activity, and the remaining two were developed and validated for different purposes, biodiesel catalysis and antioxidant activity, entirely on their own terms.

Two limitations are worth stating plainly. No study identified here tested nanoparticle outcomes from the same species grown under stress against non-stress conditions, so stress adaptation specifically stays a plausible driver, not a demonstrated one. Three species originally scoped for this review, Capparis decidua, Balanites aegyptiaca, and Tecomella undulata, had no species-specific primary literature we could locate. The nearest available data for Capparis decidua turned out to belong to a different species and was excluded, not used as a stand-in. Reproducibility, compound-level mechanistic resolution, and long-term safety data all lag behind the field's demonstrated synthetic capability.

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Author Contribution Statement

H.B. conceived the review, conducted the primary literature analysis, and wrote the manuscript. R.C. and A.V. contributed to literature review. R.K.M. contributed to final drafting of the manuscript. All authors read and approved the final manuscript.

Generative AI Statement

During the preparation of this review, the authors used generative AI tools to assist with the basic drafting and grammar checks. Every citation and data point sourced through this process was independently verified against the original primary literature by the authors before inclusion. The authors reviewed, edited, and take full responsibility for the content of this publication.

Other Ethics Statements

This Article did not involve human participants, animal subjects, or the collection of primary data, and therefore did not require ethical approval.

Does this article screened for similarity?

Yes

Conflict of interest

The Author’s declares that there is no conflict of interest anywhere.

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