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REVIEW

From Geothermal Flora to Green Nanotechnology: Phytochemical Insights into Silver Nanoparticle Synthesis

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Abstract

Physical and chemical synthesis of silver nanoparticles (AgNPs) often involves high energy consumption and hazardous reagents. Green synthesis using plant extracts provides a more sustainable alternative, as plant metabolites act as reducing and stabilizing agents. This review examines the potential of plants from geothermal areas in Aceh as bioreductants for AgNP synthesis, focusing on synthesis mechanisms, nanoparticle characteristics, antimicrobial activity, and development challenges. A narrative review of relevant literature indicates that geothermal conditions may influence plant phytochemical profiles, including polyphenols, flavonoids, tannins, and terpenoids, which facilitate the reduction of Ag^{+} to Ag^{0} and stabilize the resulting nanoparticles. Notably, *Lantana camara* from the Ie Seu'um geothermal area has been reported to produce AgNPs with a mean size of 44 nm, smaller than those obtained from the same species in non-geothermal areas. AgNPs synthesized using plants from geothermal habitats also exhibit potential antimicrobial activity against Gram-positive and Gram-negative bacteria and fungi. However, evidence remains limited, and challenges include phytochemical variability, reproducibility, insufficient standardization, ecotoxicity, and risks of overharvesting local flora. Future research should prioritize comparative studies, chemometric authentication, reaction optimization, standardized safety assessment, and nanocomposite development. Aceh's geothermal flora represents a promising but insufficiently validated resource for sustainable AgNP synthesis, warranting systematic investigation to establish its advantages and practical applicability.

Introduction

The application of green synthesis to the production of metal nanoparticles, particularly silver nanoparticles (AgNPs), has been driven by the limitations of conventional methods. Nanoparticle production using conventional physical techniques, such as spark discharge, pyrolysis, and laser ablation, requires very high energy consumption, produces low yields, and often results in nonuniform particle sizes [1]. Conventional chemical methods are more efficient and cost-effective, but they involve toxic chemicals that can reduce nanoparticle biocompatibility and threaten environmental sustainability. Green synthesis has therefore emerged as a critical alternative because it is may show lower cytotoxicity in some in vitro studies, environmentally friendly, inexpensive, and operates under substantially milder reaction conditions [2–4]. This environmentally benign method uses plant secondary metabolites as natural bioreducing and stabilizing (capping) agents, producing biocompatible nanoparticles for diverse biomedical applications, including drug delivery, imaging, and clinical therapy. Conventional physical and chemical synthesis of silver nanoparticles (AgNPs) often faces major limitations. These approaches require high energy inputs, extreme temperatures, organic solvents, and toxic chemical reagents [5–8]. Such processes not only generate hazardous by-

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products that pollute the environment but may also leave toxic chemical residues on nanoparticle surfaces, thereby restricting biomedical applications [9–11]. Green synthesis (biosynthesis) has emerged as a promising alternative because it is environmentally friendly, safe, cost-effective, simple, efficient, and highly productive [12,13]. This approach uses natural reducing and stabilizing agents derived from biological materials to minimize adverse effects on global ecosystems.

Silver nanoparticles (AgNPs) have attracted considerable attention because of their unique physicochemical properties and broad-spectrum antimicrobial activity, supporting their potential applications in biomedical and healthcare fields. However, conventional physical and chemical synthesis methods often involve high energy consumption, hazardous reagents, and potential environmental contamination, highlighting the need for more sustainable alternatives. Plant-mediated green synthesis has been widely investigated as an environmentally friendly approach, with plant secondary metabolites acting as reducing and capping agents that influence nanoparticle formation, size, stability, and biological activity. Previous studies have demonstrated the potential of various plant extracts to produce AgNPs with antimicrobial properties, while research on plants from geothermal habitats has reported promising results, including AgNPs synthesized using *Lantana camara* and *Calotropis gigantea* from the Ie Seu'um geothermal area in Aceh. These findings provide an initial basis for exploring geothermal flora as a source of bioreducing agents. Nevertheless, the current evidence remains limited, and the relationship between geothermal environmental stress, phytochemical composition, and the physicochemical and antimicrobial properties of the resulting AgNPs is not yet sufficiently established. Further research is therefore needed to compare geothermal and non-geothermal plants of the same species, systematically characterize their phytochemical profiles, optimize synthesis conditions, and evaluate nanoparticle stability, antimicrobial efficacy, and potential ecotoxicity. Addressing these knowledge gaps will help determine whether geothermal flora from Aceh offers distinct advantages for developing reproducible, safe, and sustainable AgNP synthesis strategies.

Among the various biological agents available, plant extracts (phytosynthesis) are generally preferred to microorganisms such as bacteria or fungi [14,15]. Plant-mediated synthesis is a simple, reliable, rapid, one-step process that does not require microbial isolation, sterilization, or the complex and costly maintenance of cell cultures. In addition, AgNPs produced through plant-mediated biosynthesis tend to exhibit greater biocompatibility and lower cytotoxicity toward eukaryotic cells. These characteristics make the nanoparticles safer and suitable for clinical applications, including antimicrobial and anticancer therapies and the acceleration of wound healing [16].

The reduction efficiency during AgNP formation depends strongly on the secondary-metabolite content of the plant extract, which serves both as a reducing agent and as a capping agent [5,17]. Active compounds such as polyphenols, flavonoids, tannins, saponins, terpenoids, alkaloids, and proteins can donate electrons or hydrogen atoms to convert silver ions (Ag^{+}) into zero-valent metallic silver (Ag^{0}). This bioreduction can proceed rapidly and efficiently under mild reaction conditions; under certain optimal conditions, approximately 90-92% of the silver ions are reduced within the first 11 min of the reaction [13].

The reduction of silver ions can be visually monitored through a color change in the solution, from pale yellow or light green to dark brown or reddish brown. This color change is a direct consequence of surface plasmon resonance (SPR), caused by excitation of free electrons on AgNP surfaces and characterized spectroscopically by an absorption peak at 400-500 nm [18]. To maximize reduction efficiency and control these optical properties, reaction parameters such as precursor salt ($AgNO_3$) concentration, extract-to-precursor volume ratio, temperature, pH, and contact time must be optimized [19,20]. Statistical optimization approaches, including

Response Surface Methodology (RSM), are frequently used to predict optimal factor interactions and obtain high, uniform AgNP yields.

Particle-size characterization is one of the most critical physicochemical parameters because nanoparticles must have dimensions within the 1-100 nm range. However, different analytical techniques can produce highly variable and even apparently contradictory measurements. Transmission electron microscopy (TEM) or scanning electron microscopy (SEM) measures the metal-core diameter under dry conditions and therefore represents the actual physical size of the particles. By contrast, dynamic light scattering (DLS) measures the hydrodynamic diameter of solvated particles and therefore tends to report considerably larger sizes because it includes the hydration layer and adsorbed organic capping macromolecules surrounding the metal core [5,15,21].

These differences in measurement are clearly evident across plant bioreductants [22]. For example, synthesis using *Centaurea behen* leaf extract produced a mean TEM core diameter of 13.03 nm, whereas the DLS hydrodynamic diameter reached 96.67 nm [5]. A similar pattern was observed for AgNPs synthesized using *Chromolaena odorata* extract, with a mean TEM size of 15.27 nm versus a DLS size of 30.5 nm [22], and for *Rubus discolor* extract, with a mean TEM size of 37 nm versus a DLS value of 151.7 nm [10]. Achieving moderate particles is important because it increases the surface-area-to-volume ratio, promotes more intensive contact with bacterial cell walls, enhances intracellular penetration, and facilitates the release of active silver ions and reactive oxygen species (ROS), thereby producing substantially stronger antimicrobial activity [23].

In addition to mediating reduction, plant-derived organic functional groups act as capping agents that coat particle surfaces and maintain the colloidal stability of AgNPs [6,19,20,23,24]. This bio-organic protective layer prevents direct contact between particles, thereby hindering agglomeration driven by van der Waals attraction [19,20]. The stability of a colloidal dispersion is evaluated electrokinetically using zeta potential (ZP), which measures the surface charge of the particles [9,12,18,25]. According to colloid theory, a suspension is considered to have excellent long-term stability when its ZP is more positive than +30 mV or more negative than -30 mV because strong electrostatic repulsion between particles occurs within these ranges [9,10,14,23].

Many plant bioreductants have been shown to produce AgNP suspensions with strongly negative zeta potential values because of the adsorption of charged compounds such as phenols or deprotonated flavonoids [5,9]. For example, AgNPs synthesized using olive oil waste (olive pomace) exhibited a ZP of -32.7 mV [9], *Rubus discolor* leaf extract yielded a ZP of -44.2 mV [10], and *Centaurea behen* extract produced a ZP of -26.6 mV [5]. This substantial negative surface charge generates electrostatic repulsion that maintains AgNP colloidal dispersion, prevents coagulation, and preserves particle quality for more than 6 months of storage without additional synthetic stabilizers [5,10,20,21].

Despite the extensive research on AgNP biosynthesis, a specific scientific gap remains: plants from extreme geothermal environments have received limited investigation. Plants growing in geothermal manifestation zones, such as Ie Seu'um, where fluid temperatures reach 82 °C and soils are rich in chlorine and sulfur minerals, must adapt to extreme conditions. These physiological adaptations alter plant biosynthetic pathways, potentially producing secondary-metabolite profiles that are more distinctive and abundant and that possess stronger reducing and capping capacities than those of the same species grown in ordinary soils. Evidence for this potential advantage includes the use of *Lantana camara*, a weed from a geothermal area, to synthesize moderate AgNPs with a mean size of only 44 nm, and geothermal *Calotropis gigantea*, which produced stable particles with controlled sizes of up to 87.85 nm.

This extreme geothermal stress produces distinctive phytochemical profiles that can be highly effective in nanoparticle reduction. For example, the robust phytoreductant *Calotropis gigantea*, which thrives in the Ie Seu'um geothermal manifestation area, has a high total phenolic content of 14.48 ± 0.98 mg GAE/g. Phytochemical and gas chromatography-mass spectrometry (GC-MS) analyses identified dominant bioactive compounds such as phytol and n-hexadecanoic acid, containing key functional groups including O-H, C=C, and C-H. The hydroxyl and amino groups of these geothermal phytochemicals act as electron donors, reducing silver ions (Ag^{+} to Ag^{0}) while coating the silver-particle surfaces to prevent agglomeration and maintain nanoparticle structural stability.

The synergy between the distinctive phytochemical characteristics of plants from geothermal habitats and the small size of the resulting AgNPs produces strong broad-spectrum antimicrobial activity. Silver nanoparticles synthesized from both leaf and flower extracts of geothermal *C. gigantea* produced significant zones of inhibition against Gram-positive bacteria (*Staphylococcus aureus*), Gram-negative bacteria (*Escherichia coli*), and the pathogenic fungus *Candida albicans*. Against the increasingly urgent global threat of antimicrobial resistance (AMR) [26], this underexplored extreme-geothermal biodiversity offers a promising new source of highly bioactive raw materials for developing stable, environmentally friendly, and biocompatible functional nanomaterials [1,26].

Although the potential of green synthesis has been widely explored globally, studies using vegetation from extreme geothermal environments remain underreported. This research gap is especially compelling because the mineral-rich geochemistry of geothermal soils, including chlorides, sulfates, sulfur, and heavy metals, and exposure to high temperatures impose extreme abiotic stress on surrounding flora. To survive, plants from geothermal habitats undergo localized metabolic adaptations that trigger oxidative stress and stimulate defensive biosynthesis, significantly increasing the concentration, diversity, and yield of secondary metabolites compared with conspecific plants growing under normal environmental conditions. These distinctive quantitative and qualitative phytochemical features represent a specific, insufficiently explored opportunity to optimize the efficiency of metal-reduction reactions.

In response to these knowledge gaps, this review aims to critically examine the potential of geothermal flora from Aceh as a source of plant-based bioreducing and stabilizing agents for AgNP synthesis. Specifically, it explores the influence of geothermal environmental conditions on plant phytochemical profiles, elucidates the roles of secondary metabolites in silver-ion reduction and nanoparticle stabilization, and evaluates the reported physicochemical characteristics and antimicrobial activities of the resulting AgNPs. This review also identifies key challenges related to phytochemical variability, synthesis reproducibility, process standardization, and environmental safety. By integrating current evidence, the review seeks to establish a scientific basis for future comparative studies and optimized synthesis strategies, while identifying research priorities for the sustainable development of AgNPs using geothermal plant resources from Aceh.

Silver Nanoparticles (AgNPs)

Nanoparticles are generally defined as materials with very small external dimensions or diameters ranging from 1 to 100 nanometers (nm) [27]. When a material is reduced to this scale, its physical and chemical properties change dramatically from those of the corresponding bulk material as a consequence of the quantum size effect. In metallic silver, this transformation produces distinctive physicochemical properties, including very high thermal and electrical conductivity, superior catalytic activity, and a marked decrease in melting point as particle size declines. The electrokinetic stability of nanoparticle colloidal suspensions is determined by their surface charge, evaluated using zeta potential (ZP); a ZP magnitude above approximately 30 mV is generally required for electrostatic repulsion to prevent particle agglomeration.

Nanoparticle morphology is also highly variable and can be systematically controlled by manipulating chemical reaction parameters and the type of capping agent used. Silver nanoparticles, for example, can be synthesized in numerous forms, including spherical or quasi-spherical, irregular, cylindrical, cubic (nanocubes), triangular (triangular nanoprisms), rod-shaped (nanorods), truncated octahedral, and flower-like structures. Reducing particle size to the nanoscale produces a much larger surface-area-to-volume ratio than in the bulk material, increasing the proportion of atoms located on the outer particle surface. This increase directly enhances chemical reactivity, surface energy, adsorption capacity, and surface-reaction efficiency.

In addition to these structural properties, noble-metal nanoparticles, particularly copper, silver, and gold, exhibit distinctive optical properties governed by localized surface plasmon resonance (LSPR) within the visible spectrum. This phenomenon occurs when the free conduction-electron cloud at the metal surface undergoes coherent, collective oscillation in resonance with the incident electromagnetic field of visible light. LSPR in spherical AgNPs generally produces a strong absorption band at 400-500 nm, visually indicated by a change in solution color from pale yellow to dark brown or reddish brown. The wavelength and width of this absorption band are highly sensitive to particle geometry, size, degree of agglomeration, and the refractive index of the dielectric medium surrounding the particle surface. In addition to LSPR, moderate nanoparticles (below 10 nm) or clusters of a few atoms (nanoclusters) can exhibit strong fluorescence or photoluminescence [12] .

Among their functional properties, silver nanoparticles (AgNPs) are well known for effective, broad-spectrum antimicrobial activity against Gram-positive bacteria, Gram-negative bacteria, and fungi. This activity occurs through several simultaneous toxicity mechanisms, including direct attachment of nanoparticles to microbial cell walls, release of toxic silver ions (Ag^{+}) that damage structural proteins and cellular DNA, and induction of reactive oxygen species (ROS), which cause intracellular oxidative stress. Antimicrobial efficacy is inversely related to particle size: smaller particles exert stronger bacterial inhibition because they provide a larger biologically active contact surface. Particle shape also affects bactericidal efficacy; triangular particles show the strongest antimicrobial activity among the various morphologies because their sharp vertices can damage bacterial cell-wall structures and they exhibit greater exposure of active crystal facets [20].

Concept of Green Synthesis of AgNPs

The green biosynthesis (green synthesis) approach is grounded in the twelve principles of green chemistry, which guide the development of synthesis protocols that are environmentally friendly and energy efficient and minimize or eliminate the use and generation of toxic chemicals that threaten human health and the environment[30] . This method offers significant physical, economic, and ecological advantages over conventional approaches. Physical methods generally require high energy consumption, extreme temperature or pressure conditions, and expensive instrumentation, whereas chemical methods often employ toxic organic solvents and hazardous reducing agents that leave contaminating residues on particle surfaces and thereby limit their safety for biomedical applications. By contrast, green synthesis relies entirely on safe, inexpensive, and abundant biological materials and proceeds under mild reaction conditions without extreme energy inputs [14].

In this one-step bioreduction process, secondary metabolites, such as flavonoids, polyphenols, tannins, and proteins, act as reducing agents by donating electrons or hydrogen atoms to reduce metal ions (Ag^{+}) to neutral metal atoms (Ag^{0}), which subsequently undergo nucleation and crystal growth. After the particle nuclei form, the same active metabolite molecules, for example, ketone groups generated by flavonoid deprotonation and oxidation, play dual roles as capping and stabilizing agents. These molecules bind strongly to and coat the external nanoparticle surface, forming a protective bio-organic layer [5].

This natural capping layer generates strong electrostatic and/or steric repulsion between particles, as indicated by the negative surface charge observed in zeta-potential analysis. This repulsion effectively counteracts van der Waals attraction that could otherwise induce agglomeration, coagulation, or sedimentation, thereby maintaining the stability of the colloidal suspension during long-term storage [15].

Characteristics of Geothermal Environments and Their Effects on Plant Physiology

Aceh Province contains several active geothermal manifestation areas with extreme abiotic conditions, including the Seulawah Agam geothermal system and Jaboi Crater on Weh Island, Sabang [26,33,34]. At Seulawah Agam, manifestations such as Ie Seu'um, Ie Jue, and Van Heutsz Crater are characterized by high reservoir temperatures and highly distinctive water geochemistry. The Ie Seu'um reservoir is estimated to reach 120-242 °C and contain chloride-type water (Na-K-Cl), whereas the Ie Jue and Van Heutsz Crater reservoirs are estimated at 150-316 °C and contain sulfate-type water (Ca-SO_4) [34,35]. Jaboi Crater exhibits hot springs, fumaroles, and sulfur deposits; the mean temperatures at sites JK2 and JK4 reach 79.17 ± 0.02 °C (pH 2.29 ± 0.01) and 96.07 ± 0.02 °C (pH 2.66 ± 0.01), respectively [26]. The dry, nutrient-poor soils enriched with sulfur and other extreme mineral constituents in both areas create severe abiotic pressures that greatly restrict the vegetation capable of surviving nearby [2,4,36].

The soil-temperature gradient surrounding geothermal manifestations directly affects the zonation, species composition, and structure of the overlying vegetation. A study at Seulawah Agam, for example, divided the vegetation into three zones based on soil temperature: Zone I (≥28 °C), Zone II (26 to <28 °C), and Zone III (<26 °C) [33]. In Zone I, the seedling stratum was dominated by *Cynodon dactylon*, the sapling and pole strata by *Meyna spinosa*, and the tree stratum by *Vitex pinnata*. In Zone II, the seedling and tree strata were dominated by *Desmodium triflorum* and *Ficus racemosa*, respectively, whereas in Zone III, the seedling, sapling, and tree strata were dominated by *Cynodon dactylon*, *Erioglossum rubiginosum*, and *Melia azedarach*, respectively. Differences in thermal habitat conditions among zones produced very low vegetation-similarity indices (averaging below 50%), indicating specific spatial adaptation of each plant community to soil heat levels [33,37].

Beyond the physical stresses of extreme temperatures and mineral-rich soils, plants surviving in geothermal environments show substantial physiological adaptation through increased biosynthesis of secondary metabolites. Tannins, for example, were identified as the most ubiquitous secondary metabolites across various plant species in the Seulawah Agam geothermal areas (Ie Brôuk, Ie Jue, and Ie Seu'um), indicating their crucial role in plant defense against environmental stress [2,38]. Thermal and chemical stresses characteristic of geothermal environments also promote the accumulation of antioxidants and phenolic compounds at levels found in the same species from non-geothermal environments. Species such as *Streblus asper*, and *Antidesma montanum* exhibited very strong DPPH radical-scavenging activity, with IC50 values of 34.80 and 35.21 ppm for the first two species, respectively [36,38].

The contrasting effect of geothermal stress on plant chemical profiles is further supported by comparative studies of conspecific plants from non-geothermal areas [39]. In laban (*Vitex pinnata* L.), for example, geothermal conditions at Ie Seu'um stimulate the synthesis of defensive phenolic and alkaloid compounds, as reflected in the substantially greater extract mass and yield obtained from geothermal leaves; the difference in yield of the polar methanolic extract reached 11.59% relative to the non-geothermal sample [40]. Infrared chemometric analysis (FTIR/NIR) of seurapoh (*Chromolaena odorata* Linn.) leaves also revealed differences in phytochemical spectral profiles and cytotoxicity levels (BSLA assay) significantly associated with geothermal versus non-geothermal growing habitats [36,39]. Remarkably, this distinctive

environmental stress may alter plant metabolic pathways so profoundly that *Lantana camara* growing at Ie Seu'um lacks the alkaloids and terpenoids that are typically abundant in conspecific plants from normal environments [1].

Extreme abiotic stress in geothermal areas also drives plants to produce defensive compounds with strong antimicrobial and antibiofilm bioactivities as an adaptive response. Extracts of plants from the Jaboi Crater geothermal area, including *Memecylon edule*, *Aporosa octandra*, *Syzygium myrtifolium*, and *Hydnophytum formicarum*, are rich in phenolic compounds and terpenoids and exhibit significant antiplanktonic and biofilm-inhibitory effects against resistant pathogenic bacteria such as *Staphylococcus aureus* and *Pseudomonas aeruginosa* [26,41]. Similarly, in phytoreductant species such as *Calotropis gigantea*, which thrives in the Ie Seu'um outflow area, the phenolic content (14.48 ± 0.98 mg GAE/g) serves as a natural bioreducing system in the green synthesis of broad-spectrum silver nanoparticles (AgNPs) capable of inhibiting microbial pathogens [1–4].

Collectively, these findings confirm that geothermal manifestation areas in Aceh are not merely extreme environments that constrain biodiversity, but also natural laboratories with considerable potential as sources of novel bioactive compounds. Nevertheless, comprehensive studies integrating vegetation ecology, physiological and chemical adaptation, and the bioactivity potential of Aceh's plants from geothermal habitats remain limited.

Adaptive Phytochemical Profiles of Plants from the Seulawah Agam Geothermal Area

Phytochemical screening of various plant species growing in geothermal areas has shown that tannins are the predominant secondary metabolites accumulated in leaves and are ubiquitous throughout the Seulawah Agam area [36,37]. This accumulation is thought to protect against reactive oxygen species (ROS), thereby minimizing cellular damage caused by extreme thermal and mineral stress. In geothermal laban (*Vitex pinnata* L.), phytochemical analysis of leaf samples detected a broader range of active compounds, including alkaloids, steroids, terpenoids, saponins, flavonoids, phenolics, and tannins; by contrast, non-geothermal laban leaf samples contained neither flavonoids nor tannins [40]. Extreme geothermal stress also appears to induce a shift in the biosynthetic profile of aqueous leaf extracts of *Lantana camara* from the Ie Seu'um geothermal manifestation area, characterized by the loss of alkaloids and terpenoids and the retention of only flavonoids, phenolics, saponins, tannins, and steroids. A similar pattern was observed in ethanolic leaf extracts of seurapoh (*Chromolaena odorata* L.), which consistently accumulated tannins, phenols, flavonoids, saponins, and steroids and displayed FTIR/NIR spectral profiles that differed significantly from those of non-geothermal samples, consistent with exposure to high temperatures and elevated soil chloride concentrations [39].

The extract yields of laban (Vitex pinnata L.) leaves collected from geothermal (Ie Seu'um) and non-geothermal areas using different organic solvents are compared in Figure 1.

In Table 1, more targeted phytochemical screening across different plant organs and solvent fractions also revealed highly selective accumulation profiles. In the phytoreductant *Calotropis gigantea* from the Ie Seu'um area, screening of flower and leaf extracts showed contrasting distributions of active compounds: flavonoids and terpenoids were abundant in flowers, whereas steroids were identified exclusively in leaves [4]. In two species of the family Phyllanthaceae (*Antidesma montanum* and *Baccaurea pyriformis*) from Ie Brôuk, sequential screening of dried leaf samples confirmed that steroids were consistently soluble across all solvent fractions (n-hexane, ethyl acetate, and ethanol), whereas tannins were extracted most efficiently in the polar ethanol fractions of both species and, specifically for A. montanum [38], in the semipolar ethyl acetate fraction. Meanwhile, thin-layer chromatography (TLC) and bioautography of plants from Jaboi Crater showed that antibacterial activity and active

compounds were detected only in leaf extracts; stem-bark extracts from the same species (*Garcinia dioica*, *Aporosa octandra*, and *Syzygium sp.*) showed no activity. Based on these qualitative spot tests, phenolic compounds accumulated in the leaves of *Memecylon edule*, *G. dioica*, and *Syzygium sp.*, whereas active terpenoids were detected in the leaves of *Memecylon caeruleum* and *A. octandra* [26].

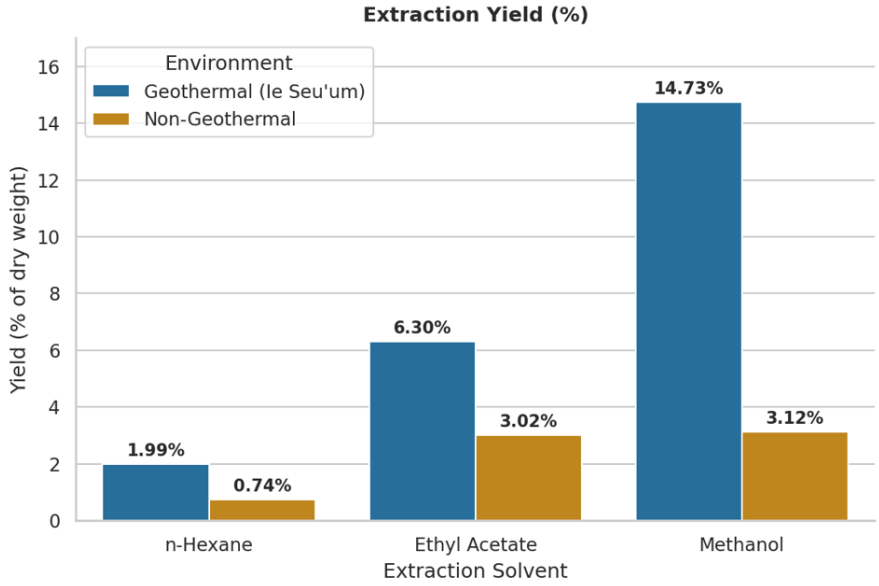


Figure 1. Comparison of extract yields from laban (*Vitex pinnata* L.) leaves collected from geothermal (Ie Seu'um) and non-geothermal areas.

Table 1. Metabolites identified in the Mount Seulawah Agam and Jaboi geothermal areas, Aceh Province.

Researchers	Plant Species	Location	Plant Part	Metabolites
Kemala, P. et al.[42]	Calotropis gigantea	Ie Seu-Um geothermal area, Aceh Besar	Leaves	Alkaloids, saponins, phenolics, tannins, steroids, phytol, n-hexadecanoic acid
			Flowers	Alkaloids, saponins, phenolics, tannins, flavonoids, terpenoids
Idroes, G. M. et al.[43]	Calotropis gigantea	Ie Brouk geothermal area, Lamteuba, Aceh Besar	Leaves	Urs-12-en-24-oic acid 3-oxo methyl ester, Lupenyl acetate, Beta-amyrenyl acetate, Alpha-amyrin, Beta-amyrin, Psi-taraxasterol acetate, Beta-sitosterol, Squalene, Methyl tetracosanoate
			Latex	Lignan glycoside compounds
Ningsih, D. S. & Idroes, R. [44]	Calotropis gigantea	Ie Jue geothermal area, Aceh	Leaves	Alkaloids
Pati Kemala et al.1]	Lantana camara	Ie Seu-Um geothermal area, Aceh Besar	Leaves, twigs, and flowers	Flavonoids, phenolics, saponins, tannins, steroids
Azhari, S. et al. [46]	Vitex pinnata (Laban)	Ie Jue, Ie Seu'um, and Ie Brouk geothermal areas	Leaves	Secondary metabolites (identified via IR-PCA and GC-MS)
Nuraskin, C. et al.[40]	Vitex pinnata (Laban)	Ie Seu'um geothermal area, Aceh Besar	Leaves and stem bark	Alkaloids, steroids, terpenoids, saponins, flavonoids, phenolics, tannins
Imelda, E. et al. [47]	Isotoma longiflora L.	Ie Seu-um geothermal manifestation, Aceh Besar	Leaves	Polysaccharides, proteins, phenolics, flavonoids, tannins
Maulydia, N. B. et al.[36,38,48]	Antidesma montanum	Ie Brouk geothermal area, Aceh	Leaves, stem bark, and flowers	Steroids, tannins, saponins, phytol, hexadecanoic acid methyl ester, sitosterol, terpenoids, flavonoids

Researchers	Plant Species	Location	Plant Part	Metabolites
	Baccaurea pyriformis		Leaves, twigs, and flowers	Steroids, saponins, tannins, phytol, hexadecanoic acid methyl ester, ethyl 13-methyl-tetradecanoate
	Streblus asper		Leaves, twigs, and flowers	Saponins, tannins, alkaloids, terpenoids, flavonoids
	Blumea balsamifera	Ie Jue geothermal area, Aceh	Leaves, twigs, and flowers	Flavonoids, tannins, proximadiol, stigmasterol, terpenoids, alkaloids
	Chromolaena odorata	Ie Jue, Ie Brouk, and Ie Seu-um areas	Leaves, twigs, and flowers	Steroids, tannins, flavonoids, terpenoids, alkaloids
	Ocimum americanum	Ie Jue geothermal area, Aceh	Leaves, twigs, and flowers	Alkaloids, saponins, tannins, terpenoids, flavonoids
	Tephrosia noctiflora		Leaves, twigs, and flowers	Saponins, tannins, terpenoids, flavonoids, alkaloids
	Ziziphus rufula		Leaves, twigs, and flowers	Tannins, terpenoids, flavonoids, alkaloids
	Tridax procumbens	Ie Seu-um geothermal area, Aceh	Leaves, twigs, and flowers	Flavonoids, saponins, steroids, tannins, terpenoids
	Acrostichum aureum		Leaves, twigs, and flowers	Tannins, terpenoids, flavonoids, alkaloids
	Sumbaviopsis albicans	Ie Brouk geothermal area, Aceh	Leaves, twigs, and flowers	Saponins, tannins, terpenoids, flavonoids, alkaloids
Khairan, K. et al.[26]	Garcinia dioica	Jaboi Sabang (JK2)	Leaves and stem bark	Phenolics, Alkaloids
	Aporosa octandra		Leaves	Terpenoids, 5-HMF, furfural
	Syzygium sp.		Leaves	Phenolics, Phytol, methyl elaidate
	Memecylon edule		Leaves	Phenolics, ethyl oleate, acetic acid
	Memecylon caeruleum		Leaves	Terpenoids, Furfural, 5-methyl furfural
Suryawati, S. et al.[41]	Hydnophytum formicarum	Jaboi crater, Sabang	Roots	Methyl ricinoleate, furfural, methyl palmitate
Abubakar, A. et al.[41]	Chromolaena odorata	Ie Seu-um geothermal area, Aceh	Leaves	Tannins, phenols, pinene, cadinene, camphora, limonene
Muhammad Doudi et al.[37]	Amaranthus spinosus	Ie Jue hot springs, Aceh	Leaves	Alkaloids, tannins, essential oils
	Alstonia scholaris		Stem bark	Alkaloids, tannins
	Desmodium triflorum		Leaves	Flavonoids, saponins, polyphenols, trigonelline
	Melia azedarach		Stem bark and leaves	Alkaloids, tannins
	Stachytarpheta jamaicensis		Flowers, leaves, and roots	Secondary metabolites
	Acalypha indica		Roots and leaves	Flavonoids
	Urena lobata		Roots	Anti-inflammatory and anti-malarial compounds

Comparison of the Reduction Efficiency, Particle Size, and Stability of AgNPs Produced Using Geothermal versus Non-Geothermal Bioreductants

Alterations in plant biosynthetic pathways induced by geothermal growing conditions have been shown to affect the physical characteristics of the resulting nanoparticles. For example, AgNP synthesis using leaf extract of *Lantana camara*, a weed collected from the Ie Seu'um geothermal area, produced considerably smaller and more uniform nanoparticles, ranging from 31 to 63 nm with a mean size of 44 nm. By contrast, *L. camara* from non-geothermal environments yielded substantially larger nanoparticles, ranging from 50 to 90 nm and, in some reports, reaching 425 nm. The loss of specific phytochemicals, such as alkaloids and terpenoids, from geothermal *L. camara* samples as a consequence of geothermal stress is strongly

suspected to alter the composition of natural reducing agents and facilitate the formation of smaller, more compact, and more stable silver-particle nuclei [1].

Challenges and Future Research Directions

The conclusions section serves as a succinct summary of the primary findings and their implications. It should revisit the research question(s) or hypothesis(es), indicating whether they were substantiated or not. Furthermore, this section should delve into the significance of these findings for the respective field of study, offering insights into the broader implications and potential contributions to the existing body of knowledge.

Aceh's geothermal manifestation areas, including Ie Seu'um, Ie Jue, Ie Brôuk, and Jaboi Crater, are distinctive ecosystems characterized by extreme abiotic stress, including soil temperatures of 150-316 °C at Ie Jue and up to 96 °C at Jaboi, soil acidity, and high sulfur and mineral concentrations. These environmental pressures drive local flora to undergo metabolic adaptation by increasing the diversity and accumulation of secondary metabolites, with tannins consistently dominating phytochemical profiles as an adaptive biochemical defense mechanism. This abundance of reducing compounds provides a significant advantage for the biosynthesis of silver nanoparticles (AgNPs), as by aqueous leaf extracts of geothermal *Lantana camara*, which yield AgNPs with a substantially smaller and more uniform mean size (44 nm) than those produced using conspecific plants from non-geothermal areas (50-90 nm).

Despite this highly promising biosynthetic potential, scaling the technology from the laboratory to industry remains constrained by the inherent chemical variability of crude plant extracts. Fluctuations in soil temperature, mineralogy, moisture, and geographic position across geothermal manifestation sites lead to inconsistent phytochemical profiles and extract yields, as illustrated by the 11.59% difference between the yields of methanolic extracts from geothermal and non-geothermal laban (*Vitex pinnata*) leaves. To address this problem, future research should integrate advanced chemometric techniques based on Fourier transform infrared (FTIR) or near-infrared (NIR) spectroscopy with multivariate analyses such as principal component analysis (PCA), hierarchical cluster analysis (HCA), and linear discriminant analysis (LDA). These approaches have successfully classified geographic origins and differentiated metabolite profiles in plants such as *Chromolaena odorata* and *Isotoma longiflora* with predictive accuracies of up to 100%, while providing an essential quality-control method for the pharmaceutical industry to authenticate and stabilize herbal raw-material supply chains.

Beyond raw-material standardization, future research should move from qualitative phytochemical screening toward validated quantitative modeling and reaction optimization. Statistical optimization methods such as Response Surface Methodology (RSM) coupled with Central Composite Design (CCD) should be applied more extensively to control critical reaction parameters, including silver-salt concentration, extract-to-precursor volume ratio, pH, and temperature, thereby enabling precise control of uniform and stable AgNP morphologies. Bioactivity testing also requires rigorous standardization. Rapid screening methods such as TLC bioautography, which link chromatographic bands of specific compounds to zones of inhibition against pathogenic bacteria such as *Escherichia coli*, should be complemented by comprehensive quantitative testing, including determination of the minimum inhibitory concentration (MIC) and mathematical modeling of dose-response curves to measure antioxidant capacity (IC50). These measures are necessary to ensure the reproducibility and therapeutic safety of AgNPs before their formulation into clinical products.

From a sustainability perspective, future research must also address the need to protect vulnerable geothermal flora from overexploitation and the potential ecotoxicity of AgNPs if they accumulate in aquatic environments or induce reactive oxygen species (ROS) formation in non-target organisms. To address these concerns, research should adopt circular-economy

principles by using abundant, inexpensive agro-industrial solid waste, such as grape stalks or fruit-extraction residues, as alternative bioreducing agents, while adhering to green-chemistry principles through the optimization of environmentally benign solvents such as water and reactions conducted at room temperature. To reduce the risk of uncontrolled silver-ion release into ecosystems, research should also focus on developing decorated nanocomposites or nanohybrids. Encapsulating or dispersing AgNPs within an organic support matrix such as chitosan or an inorganic matrix such as hydroxyapatite can physically stabilize the nanoparticles, limit the release of toxic substances into the environment, and sustainably enhance antimicrobial efficacy.

Conclusions

Overall, the synergy between chemometrics-based quality control and circular hybrid-material design will provide a central foundation for commercializing this technology. Once product reproducibility can be assured and environmental toxicity risks mitigated, environmentally friendly AgNPs derived from geothermal flora could not only transform biomedical applications, including acute-wound management, antiviral agents, and inhibition of biofilms produced by drug-resistant bacteria such as *S. aureus* and *P. aeruginosa*, but also expand into other green-technology sectors. Potential applications include photocatalytic degradation of industrial dye pollutants, sensitive biosensors for detecting heavy-metal contaminants, and renewable-energy storage devices. Through this holistic approach, the unique biodiversity of Aceh's geothermal areas can be translated into scientifically validated industrial solutions that are safe for ecosystems and highly beneficial to human life.

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