

The Role of the plant "*Rosmarinus officinalis*" active components in the Green Synthesis of Gold Nanoparticles: A Review Article

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ABSTRACT: The plant-based approach are most environmentally friendly method for manufacturing nanomaterials, as it does not use harmful byproducts, simple, not expensive. Rosemary (*Rosmarinus officinalis* Linn.) is an aromatic medicinal plant rich in various active compounds, such as phenolic acids, polyphenols, terpenoids, and flavonoids etc., which performance as effective us a reducing and stabilizing agents during the synthesis process of nanoparticles. This research focuses on *R. officinalis*, identifying its active components, their proportions, and their mechanisms of action in the synthesis of the gold nanoparticles (AuNPs). The research concludes by outlining the most important submissions of gold nanoparticles in various arenas.



Keywords: Green synthesis. *Rosmarinus officinalis*, Nanotechnology, Gold Nanoparticles

1. INTRODUCTION

Nanotechnology is defined as the field concerned with the design, development, application, and structure of materials at the nanoscale. Nanoparticles typically have sizes that range in diameter from 1 to 100 nanometers. As is well known, nanoparticles differ significantly from larger particles in their unique physical and chemical properties, as well as their large surface area [1]. These distinctive characteristic and properties of nanomaterials have been supported to contribute their use in various industrial and scientific fields, including chemical, biological, physical, biomedical and even engineering applications [2, 3]. These combined properties (chemical, optical, electronic, etc.), which depend on the size and structural characteristics of the nanoparticles, have gathered significant attention due to their increasing roles in various applications, including biomedical and nutritional ones [4, 5].

Metallic nanoparticles, amid other nanomaterials, have attracted considered attention to have very potent antimicrobial properties and relatively low toxicity [6]. Of these, gold nanoparticles (AuNPs) have received the most research and study due to their exceptional surface Plasmon resonance properties, tenability of size- and shape-dependent physical and chemical behavior and is their minimal-to-non toxicity and chemically inactive character, and is commonly deliberated benign to the human body [7, 8]. Furthermore, the gold nanoparticles are characterized by their high stability and durability, and their superior ability to bind to targets both quantitatively and qualitatively, making them highly suitable for a varied range of medical and biotechnological presentations [9]. Like other nanoparticles, the size and shape of gold nanoparticles are the two main factors that control the chemical, physical, and electrical properties of gold nanoparticles [10].

There are several techniques have been established for preparation of the gold nanoparticles (AuNPs), and can generally be ordered into two approaches (top – down) and (bottom – up) approaches [11]. In the first approach, the bottom–up approach, in contrast, involves the formation of nanoparticles from atomic or molecular precursors, whereas the second methods, large materials (bulk materials) are reduced to nanoscale dimensions using physical techniques

such as laser ablation and spray thermal decomposition, these approaches often encompassing physical techniques such as spray pyrolysis and laser ablation, have been broadly employed due to their high purity, simplicity, constancy, and competency. Size and shape of the resulting AuNPs [12, 13]. In contrast, bottom-up, have dominated recent studies particularly chemical reduction methods, in view of the fact that of their lower cost and reduced energy requirements, effectiveness producing diverse morphologies. In view of the fact that of physical and chemical synthesis protocols used toxic reagents and high-temperature conditions, This poses many concerns regarding environmental safety as well as health risks. These limitations have sparked interest in green synthesis approaches, which seek to find environmentally friendly, sustainable, and biocompatible methods for producing gold nanoparticles [14] (figure1).

In response to growing concerns regarding the environmental and biological hazards associated with conventional physicochemical nanoparticle synthesis methods, increasing attention has been directed toward green synthesis approaches, encompasses by means of biological objects like plants, bacteria, fungi, and algae [15]. Biological systems, particularly medicinal plants, are natural sources rich in reducing, stabilizing, and coating agents necessary for the manufacturing process, thus helping to avoid the use of toxic substances and harsh conditions employed in traditional methods [16]. Furthermore, plant-based synthesis offers unique advantages as it is biologically friendly, cost-effective, and highly biocompatible [17]. Among various medicinal plants, rosemary (*Rosmarinus officinalis* Linn.) has shown remarkable potential in the synthesis of stable and bioavailable AuNPs [18].

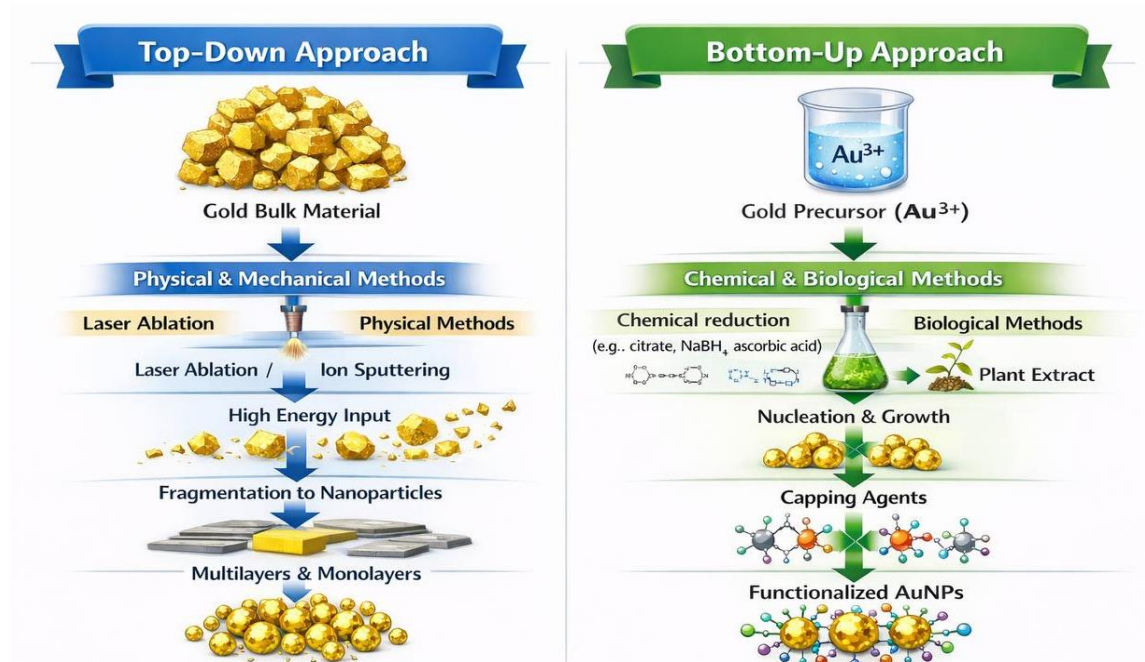


FIGURE 1. -Schematic representation of (top-down) and (bottom-up) strategies for gold nanoparticles (AuNPs) synthesis

2. ROSMARINUS OFFICINALIS LINN.

The usage of medicinal plants is increasing globally year after year, due to their beneficial effects in the production of medicines and dietary supplements. Research indicates that only 10% of the more than 250,000 plant species have actually been studied [19, 20]. Among these plants is rosemary (*Rosmarinus officinalis* Linn.), of which more than 20 distinct species and varieties of *R. officinalis* have been previously identified and classified based on their morphological characteristics [21]. This aromatic, evergreen plant, belonging to the mint family (Lamiaceae), has a long history deeply rooted in various culinary, medicinal, and even cultural traditions [22] (figure2). Rosemary grows wild in the Mediterranean region and is widely cultivated throughout the world due to its multifaceted nature and diverse applications [23]. It is considered the most generally used medicinal herb amongst spices in recent times in medicines, food, and also in cosmetics, making it essential in both the medical and food fields [24].



FIGURE 2. – (*Rosmarinus officinalis*) plant

2.1 ROSMARINUS OFFICINALIS BIOACTIVE COMPONENTS

Previous investigation using GC-MS technique (gas chromatography-mass spectrometry) and HPLC technique (high-performance liquid chromatography) on rosemary plant (*R. officinalis*) have shown that the plant is rich in biologically active secondary metabolites compounds, including both phenolic and terpenoid compounds. These constituents are considered important contributors to the biological activities of the plant. The most abundant and comprehensive phenolic compounds include rosmanol, carnosic acid, rosmadillo, and carnosol, in addition to phenolic diterpenes, which are also the most abundant. The less comprehensive major phenolic acids include rosmarinic acid and caffeic acid. As for flavonoid compounds, the predominant component is phenolic. Flavonoids include apigenin, luteolin, ginkgoanis, cercimarates, and others [25]. In addition to the above, essential oils, which are the volatile component, typically constitute 1-2% of the dry matter. They are usually quantified along with the plant's diterpenes during chemical analysis and play a important role in determining the plant's sensory characteristics. This fraction is rich in monoterpenes and sesquiterpenes, with 1,8-cineole (15–55%), camphor (5–31%), α -pinene (9–26%), β -pinene (2.0–9.0%), camphene (2.5–12.0%), limonene (1.5–5.0%), borneol (1.5–5.0%), and verbenone (2.2–11.1%) as predominant monoterpenes, alongside sesquiterpenes such as β -caryophyllene (1.8–5.1%), δ -cadinene (4.75%), α -copaene (3.55%), and α -humulene (3.11%) [26, 27, 28] (figure 3). In addition to these biologically active compounds, rosemary contains trace elements present in low concentrations, and minerals such as calcium, magnesium, iron, zinc, manganese, copper, selenium, potassium, and phosphorus [29], as well as some vitamins such as ascorbic acid, niacin, riboflavin, thiamine, and vitamins A, B6, B12, D, and E, among others [30]. These nutrients play a role in balancing redox reactions and in the ability of rosemary extracts to chelate minerals. Numerous studies have reported that these compounds possess a range of properties: they are potent antioxidants, anti-inflammatories, antimicrobials, anticoagulants, analgesics, anti-ulcer agents, antidepressants, and play an important role as anticancer agents, highlighting their therapeutic potential in medicine [31, 32].

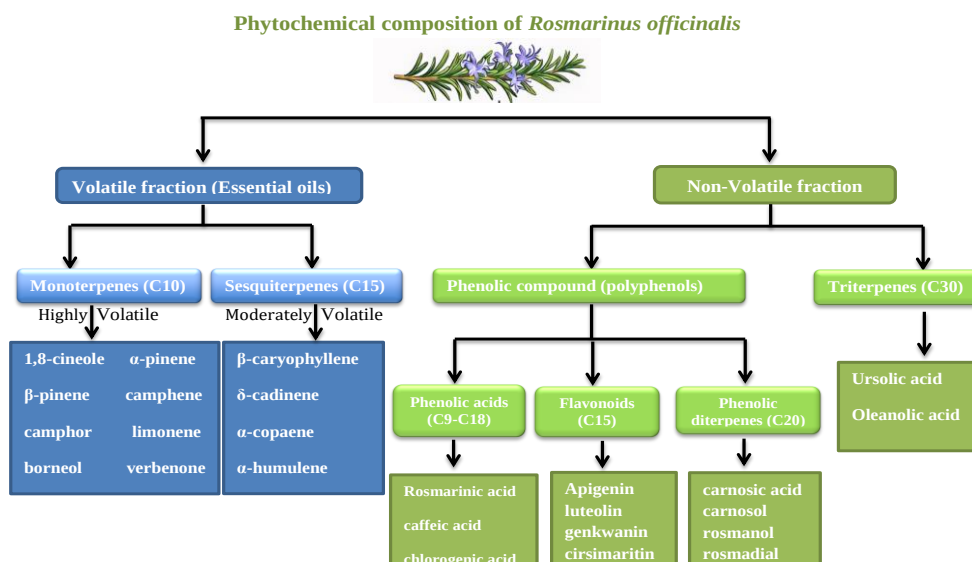


FIGURE 3. - Phytochemical composition of *Rosmarinus officinalis*

2.2 MECHANISM OF PLANTS IN SYNTHESIS OF GOLD NANOPARTICLE:

Recently, plants have been considered the best and most widely used option in the biosynthesis of nanoparticles compared to additional living organisms such as bacteria and fungi [33]. Plant extracts are rich sources of a wide diversity of primary and secondary active metabolites compound, including alkaloids, flavonoids, phenolic composites, proteins, polysaccharides, cellulose, and other biomolecules, which play crucial roles in nanoparticle synthesis [34]. These phytochemicals can catalyze the bio-reduction of metal ions into nanoparticles, while simultaneously acting as natural stabilizing and encapsulating agents [35]. All parts of a plant, including roots, fruits, and stems, can synthesize gold nanoparticles; however, leaves are preferred because they are rich in phenolic compounds, which accelerates the synthesis process. The varying levels of compounds in different plants and their portions affect the synthesis of gold nanoparticles. Nevertheless, identifying the active components in plants can be challenging due to their wide range of bioactive compounds [36].

Proteins found in plant extracts contain functional amino groups ($-\text{NH}_2$) that show activity in the reduction process of gold ions during the creation of gold nanoparticles (AuNPs) [37]. In addition, there are other functional groups, such as $-\text{C}-\text{O}-\text{C}-$, $-\text{C}-\text{O}-$, $-\text{C}=\text{C}-$, and $-\text{C}=\text{O}-$, found in phytochemicals, including flavonoids, alkaloids, phenols, and anthracene derivatives, also play a significant role in the formation and stabilization of gold nanoparticles. Carboxyl groups in alkaline environments also play a vital role, as the hydroxyl group ($-\text{OH}$) in a carboxylic acid can reduce Au^{3+} ions to Au^0 , foremost to the creation of gold nanoparticles. It is important to note that different biomolecules exhibit varying reduction capacities, which should be evaluated before use [38]. It is noteworthy that this vital process does not necessitate external stabilizing or covering agents, as basic phytochemicals replace toxic reducing chemicals such as sodium borohydride thus reducing environmental and biological risks [39].

The bioreduction mechanism converts metal ions from their mono- and di-oxidized states to their non-oxidized state. Subsequently, the formation of nuclei of the reduced metal atoms begins [39]. In green synthesis, gold salts are reduced within minutes to hours from Au^{3+} to Au^0 using a simple and environmentally friendly one-step method [40]. Because plant extracts are chemically complex, no single universal mechanism for the synthesis process has been identified. This leads to the creation of different sizes, shapes, and structures of the resulting nanoparticles, primarily due to variations in the type, composition, and concentration of reducing managers in the plant extracts [41]. Furthermore, the synthesis process of nanoparticles is influenced by several variables, such as metal concentration, pH, and temperature, which in turn affect the physical and chemical possessions of the nanoparticles [42].

2.3 ROSEMARY-MEDIATED GOLD NANOPARTICLE SYNTHESIS

Several studies conducted in previous years have demonstrated the effectiveness of the aromatic plant *R. officinalis* in using an environmentally benign approach to synthesize gold nanoparticles, confirming the conducting role of plant secondary metabolites (active components) in nanoparticle formation and stability [43]. Plant analysis by FT-IR (Fourier transform infrared) spectroscopy revealed distinct absorption bands corresponding to hydroxyl ($-\text{OH}$) groups, aliphatic $\text{C}-\text{H}$ groups (CH_2 and CH_3), carbonyl ($\text{C}=\text{O}$) groups, aromatic $\text{C}=\text{C}$ groups, and functional $\text{C}-\text{O}$ groups. These functional groups are primarily attributed to flavonoids, phenolic acids, amino acids, and other naturally occurring bioactive components in *R. officinalis* [44].

These secondary metabolites are known for their high reducing capacity, enabling the bioreduction of trivalent gold ions (Au^{3+}) to their zero-valent metallic form (Au^0), while simultaneously being absorbed onto the surface of nanoparticles and acting as natural coatings and stabilizing agents [45].

Al-Shahrani and colleagues synthesized gold nanoparticles using an acetone extract of *R. officinalis* leaves collected from As-Soudah, Saudi Arabia. The successful synthesis of gold nanoparticles was promoted by UV-Vis spectroscopy and scanning electron microscopy (SEM), revealing predominantly spherical nanoparticles with an diameter of approximately 79 nm. (FT-IR) was used to analyze both the crude plant extract and the gold nanoparticles synthesized using the extract, providing crucial insights into the functional groups responsible for nanoparticle synthesis [46].

Onmaz's study absorbed on the green approach in synthesis of gold nanoparticles (AuNFs) by means of the bioactive components of rosemary (*Rosmarinus officinalis*). STEM and DLS analysis inveterate the flower-like shape of the 20–130 nm *R. officinalis*-AuNF gold nanoparticle aggregates [18].

Further evidence supporting the role of rosemary phytochemicals in nanoparticle formation was provided by transmission electron microscopy (TEM) analyses, and these findings were further corroborated by energy-dispersive X-ray (EDX) analysis, as reported in Supplementary Studies. TEM examination showed that gold nanoparticles (AuNPs) synthesized using rosemary (*R. officinalis*) extracts exhibited size distributions ranging from 60.7 ± 60.6 nm to 8.66 ± 2.03 nm using essential oils and leaf extracts, respectively. In the EDX spectra, strong characteristic signals of elemental gold were detected, confirming the efficacious bio-reduction of the gold precursor. In addition to gold, signals corresponding to oxygen (O), carbon (C), and potassium (K), elements naturally occurring in the essential oils and leaf extracts, were also detected. The presence of these elements indicates their binding to the superficial of the biosynthesized gold nanoparticles, supporting the starring role of plant-derived biomolecules in binding and stabilization [47], (Table 1).

Table 1. - Comparative analysis of the size of AuNPs biosynthesized with *R. officinalis* plant extracts and their essential oils

Plant extract	part/	Method of measurement (analysis)	Nanoparticle size (nm)	shape	Study (ref.)
Leaf (acetone)	extract	UV-Vis, SEM, FT-IR	~79 nm	spherical	Al-Shahrani et al., (45)
Leaf (aqueous extracts)		STEM, UV-Vis, DLS, ZETA, FESEM-EDX, and FTIR techniques.	20-130nm	flower-like	Onmaz et al., (18)
essential oils		UV/Vis, TEM, EDX, ATR-FITR	60.7 ± 60.6 nm	spherical	Dzimitrowicz, et al., (46)
leaf extracts			8.66 ± 2.03 nm		

2.4 APPLICATIONS OF ROSEMARY-MEDIATED AUNPS

R. officinalis is an edible medicinal plant that might help in formulating anticancer drugs, either lone or in combination with green-synthesized gold nanoparticles. Research has shown that these formulations trigger apoptotic mechanisms (programmed cell death) in cancer cells, rather than necrosis [48]. Moreover, gold nanoparticles from plants have exhibited significant antimicrobial potential. Antimicrobial possible of plant-mediated synthesis of gold nanoparticles against pathogenic microorganisms was proved in numerous studies [49, 50]. As an example, antibacterial effects of gold nanoparticles were realized by biosynthesis using extract of the leaves from *Alternanthera bettzickiana*, implying their possible development as effective antibacterial agents. Of note, biosynthesized gold nanoparticles have shown higher antibacterial activities versus the chemically synthesized counterparts possibly due to synergistic contributions from the bioactive compounds of the plant extract [51]. Gold Nanoparticles also have generated much interest in their catalytic uses, allowing them to be applied as photo-catalysts for the deprivation of organic pollutants. This actually happens primarily for the reason that of their high surface area, and quantum confinement effects [52]. Utilizing plant biosynthesized gold nanoparticles as an eco-friendly approach can be a low-cost and necessity to environmental pollution issues [53]. Furthermore, plant-derived gold nanoparticles exhibit remarkable antioxidant activity, with the occurrence of secondary active metabolites in plant extracts being linked to their antioxidant capacity [54]. Previous studies have shown that the specific surface area, concentration, and size of nanoparticles influence the communication of gold nanoparticles with free radicals [55, 56].

3. CHALLENGES AND FUTURE PERSPECTIVES

The determining factors and the concentrations of active ingredients present in future studies handling these compounds alone (weighing their pure form) at In which the flow process in material application, such as manufacturing processes can increase control of that synthesis process and increase reproducibility. Optimal reaction circumstances, such as pH, temperature, ionic strength, and storage conditions, should also be systematically investigated, as these factors can significantly influence nanoparticle aggregation, surface charge, and overall functionality.

Furthermore, scaling up the production of green nanoparticles presents a significant challenge. The variability in the composition of plant extracts, the difficulty in maintaining reaction conditions, and the lack of standardized and reproducible parameters all significantly affect nanoparticle size, shape, and yield. Therefore, improving reaction parameters is crucial for achieving consistent and reproducible results.

4. CONCLUSION

Green synthesis methods one of the most efficient methods for producing gold nanoparticles distinguishing qualities like low cost, high scalability, eco-friendliness, reproducibility and ease of operation. This approach also provides controlled tunable properties achieved at molecular level and improve biocompatibility. *R. officinalis* is a competent candidate for the green bio-synthesis of gold nanoparticles in this perspective, for the reason that its rich bioactive components facilitate the reduction of Au ions and encapsulate the It provides the nanoparticles and acting a title role in their stability. Overall gold nanoparticles are multi-functional large surface area, controllable, safe to use , multiple medical and industrial applications.

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CONFLICTS OF INTEREST

The authors announce that they have no conflict of interest.

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