



Green Synthesis of Silver Nanoparticles Using *Andrographis paniculata* Leaf Extract and Poly (vinyl alcohol) as a Capping Agent for Colorimetric Detection of Hg^{2+} Ions

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A B S T R A C T

Mercury (Hg^{2+}) contamination is a major environmental concern due to its toxicity, persistence, and bioaccumulation. This study reports the green synthesis of silver nanoparticles (AgNPs) using *Andrographis paniculata* leaf extract as a reducing agent and poly(vinyl alcohol) (PVA) as a capping agent, and explores their potential for qualitative colorimetric detection of Hg^{2+} . AgNPs were synthesized using AgNO_3 (0.5–2.5 mM) and PVA (0.1–1.0%) and characterized by FTIR and UV–Vis spectroscopy. FTIR indicated the involvement of hydroxyl and carbonyl groups in the reduction of Ag^+ to Ag^0 , while UV–Vis spectra showed LSPR peaks at 411–448.5 nm, confirming nanoparticle formation. The optimum condition was obtained at 2 mM AgNO_3 and 0.4% PVA, with a maximum absorbance of 0.710 at 435.5 nm. Qualitative testing with Hg^{2+} (1 ppb–1 ppm) showed a clear color change from yellowish-brown to colorless. Although quantitative performance was not evaluated, these results demonstrate a preliminary proof-of-concept for AgNP-based colorimetric detection of Hg^{2+} .

Contribution to Sustainable Development Goals (SDGs):

SDG 3: Good Health and Well-being

SDG 6: Clean Water and Sanitation

SDG 9: Industry, Innovation and Infrastructure

SDG 12: Responsible Consumption and Production

SDG 14: Life Below Water

1. INTRODUCTION

1.1. Research Background

Heavy metal pollution remains one of the major global environmental problems, particularly in developing countries. Heavy metals are persistent, non-biodegradable, and capable of accumulating within the food chain, thereby posing serious risks to human health and ecosystems. Mercury (Hg), especially in the form of Hg^{2+} ions, is considered one of the most toxic heavy metals due to its high toxicity even at low concentrations. Mercury contamination can originate from various anthropogenic activities, including gold mining, chlor-alkali industries, coal combustion, industrial wastewater, and the use of mercury-containing chemicals in illegal cosmetic and pharmaceutical

products [16]. Therefore, the development of practical, low-cost mercury detection methods is essential for supporting environmental monitoring and public health protection.

Several conventional analytical methods, such as Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), and Cold Vapor Atomic Fluorescence Spectrometry (CV-AFS), have been widely used for Hg^{2+} detection due to their high sensitivity and accuracy. However, these methods require expensive instrumentation, skilled personnel, and labor-intensive sample preparation, limiting their applicability for rapid on-site environmental monitoring [10]. Consequently, colorimetric sensors based on metal nanoparticles have attracted considerable attention as alternative detection systems because they are simple, rapid, and cost-effective. Among various noble metal nanomaterials, AgNPs have emerged as particularly attractive candidates because their



localized surface plasmon resonance (LSPR) is highly responsive to changes in the surrounding chemical environment, enabling direct visual detection of target analytes without sophisticated instrumentation.

Silver nanoparticles (AgNPs) exhibit unique optical properties known as localized surface plasmon resonance (LSPR), where the UV–Vis absorption peak is highly sensitive to particle size, morphology, and surrounding environmental conditions. Interactions between Hg^{2+} ions and AgNP surfaces may induce aggregation or morphological changes, resulting in shifts or decreases in LSPR intensity that can be utilized for colorimetric sensing applications [16]. AgNP synthesis can be performed through chemical, physical, or green synthesis approaches. Compared to conventional methods that employ hazardous reducing agents such as sodium borohydride and hydrazine, green synthesis utilizes naturally occurring phytochemicals as reducing and stabilizing agents, making the synthesis process more environmentally benign, sustainable, and compatible with green chemistry principles. In addition to minimizing the use of hazardous chemicals, plant-mediated synthesis offers a simple one-pot approach in which phytochemicals simultaneously function as reducing, stabilizing, and surface-functionalizing agents, thereby improving the sustainability and practicality of nanoparticle production.

Various studies have reported the successful synthesis of AgNPs using plant extracts containing secondary metabolites as bioreductors. [6] reported that Pelawan leaf extract produced AgNPs with a maximum UV–Vis absorption peak at 400 nm and particle sizes of 10–14 nm. Meanwhile, [17] synthesized AgNPs using ketapang leaf extract with absorption peaks at 420–450 nm and an average particle size of 79.7 nm. These studies demonstrate that plant-derived phytochemicals can effectively mediate AgNP synthesis; however, the resulting nanoparticle characteristics vary considerably depending on the biochemical composition of the plant extract. Consequently, identifying alternative plant sources with distinct phytochemical compositions remains essential for tailoring nanoparticle properties toward specific analytical applications, including colorimetric heavy metal detection. Despite the growing number of plant-mediated AgNP studies, the utilization of *Andrographis paniculata* for AgNP synthesis, particularly for Hg^{2+} colorimetric detection, remains limited. In this study, *Andrographis paniculata* leaf extract was selected as a natural bioreductor due to its bioactive compounds, including andrographolide, flavonoids, phenolics, and terpenoids. These phytochemicals possess hydroxyl and carbonyl functional groups with high redox activity, enabling efficient reduction of Ag^+ to Ag^0 while contributing to the initial stabilization of the synthesized nanoparticles [15]. Compared with many plant extracts previously reported for AgNP synthesis, the high abundance of andrographolide and antioxidant phytochemicals in *A. paniculata* provides a promising biochemical environment for efficient nanoparticle formation and stable colloidal systems, making this plant a compelling candidate for green nanomaterial synthesis.

One of the major challenges in plant-mediated nanoparticle synthesis is particle agglomeration due to poor control of the particle size distribution. To overcome this limitation, poly(vinyl alcohol) (PVA) was used as a capping agent because of its non-toxic, hydrophilic, and water-soluble properties. PVA can form hydrogen bonds with AgNP surfaces, thereby preventing agglomeration and improving colloidal stability [2]. Maintaining

colloidal stability is particularly important for colorimetric sensing because the optical response of AgNPs strongly depends on particle dispersion, surface characteristics, and the preservation of LSPR properties throughout the sensing process. However, the combined effect of AgNO_3 precursor concentration and PVA content on the optical characteristics of *A. paniculata*-mediated AgNPs has not been systematically investigated. Moreover, previous studies have predominantly emphasized nanoparticle synthesis or biological applications, whereas systematic optimization of synthesis parameters for Hg^{2+} colorimetric detection has received comparatively limited attention. This knowledge gap highlights the need to better understand how synthesis variables influence the optical characteristics of AgNPs and their subsequent sensing performance. Accordingly, this study systematically investigates the influence of AgNO_3 precursor concentration and poly(vinyl alcohol) content on the optical characteristics of green-synthesized AgNPs derived from *A. paniculata* leaf extract. Furthermore, a preliminary qualitative colorimetric evaluation toward Hg^{2+} ions was performed to establish a proof-of-concept for developing an environmentally friendly and low-cost AgNP-based sensing platform for mercury detection.

1.2. Literature Review

Nanoparticles are materials with dimensions below 100 nm that exhibit unique physicochemical properties compared to their bulk counterparts. These distinctive characteristics arise primarily from quantum confinement effects and the increased surface area-to-volume ratio at the nanoscale. As a result, nanoparticles often demonstrate enhanced optical, electrical, magnetic, mechanical, and catalytic properties, making them attractive for a wide range of applications. Their utilization has expanded across various fields, including biomedicine, environmental monitoring, food technology, catalysis, and electronic devices. Among the different types of nanomaterials, silver nanoparticles (AgNPs) have received considerable attention due to their remarkable optical properties, high surface reactivity, and potential applications in sensing technologies [16]. To provide a comprehensive scientific basis for the present study, the following sections discuss the fundamental principles of silver nanoparticles, green synthesis, the phytochemical characteristics of *Andrographis paniculata*, the stabilizing role of poly(vinyl alcohol), UV–Visible characterization, and the colorimetric detection mechanism of Hg^{2+} ions.

1.2.1. Silver Nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) are nanostructured silver particles typically 1 to 100 nm in size, exhibiting unique optical, chemical, and catalytic properties. One of their most distinctive characteristics is *localized surface plasmon resonance* (LSPR), which arises from the collective oscillation of conduction electrons upon interaction with electromagnetic radiation. The LSPR phenomenon generates a characteristic absorption band in the UV–Vis region that is highly sensitive to particle size, morphology, and environmental changes. Due to these optical properties, AgNPs have been widely applied in biomedical, catalytic, and sensing applications, particularly in colorimetric detection systems. Their ability to undergo measurable optical changes upon interaction with metal ions makes AgNPs promising materials for the development of simple, rapid, and

cost-effective Hg^{2+} sensors [12]. The physicochemical characteristics of AgNPs, particularly particle size, morphology, and surface chemistry, directly determine their optical response and sensing performance. Consequently, precise control over nanoparticle synthesis is essential to obtain reproducible optical properties suitable for analytical applications.

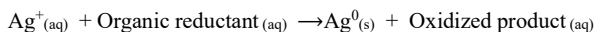
1.2.2. Green Synthesis of AgNPs

Green synthesis is an environmentally friendly approach for nanoparticle production that employs biological resources, particularly plant extracts, as reducing and stabilizing agents [9]. Compared with conventional chemical and physical methods, green synthesis reduces the use of hazardous chemicals, lowers energy consumption, and provides a simple and cost-effective route for nanoparticle. Plant extracts contain various bioactive compounds, such as flavonoids, phenolics, terpenoids, alkaloids, and tannins, which play important roles in the reduction of metal ions and stabilization of the resulting nanoparticles. Owing to these advantages, green-synthesized silver nanoparticles (AgNPs) have gained significant attention for applications in catalysis, biomedicine, environmental remediation, and chemical sensing [7]. Despite its environmental advantages, the properties of green-synthesized AgNPs are highly dependent on extraction conditions, phytochemical composition, precursor concentration, and reaction parameters. Consequently, achieving reproducible nanoparticle characteristics remains one of the principal challenges in plant-mediated synthesis.

The formation of AgNPs through green synthesis mainly involves the reduction of silver ions (Ag^+) into metallic silver (Ag^0) by phytochemicals present in plant extracts. Initially, silver nitrate dissociates in aqueous solution according to the following reaction:



Subsequently, bioactive compounds donate electrons to reduce Ag^+ into Ag^0 , which can be represented as:



The generated Ag^0 atoms undergo nucleation and growth, resulting in stable silver nanoparticles [5]. The nucleation and growth stages are strongly governed by the balance between the reduction rate of Ag^+ ions and the stabilization of newly formed nuclei. An uncontrolled reduction process may produce broad particle size distributions and nanoparticle aggregation, thereby affecting the optical properties required for sensing applications. During this process, phytochemicals adsorbed on the nanoparticle surface act as natural capping and stabilizing agents, preventing excessive aggregation and enhancing nanoparticle stability. The successful formation of AgNPs is commonly indicated by a visible color change from a colorless solution to yellowish-brown due to the localized surface plasmon resonance (LSPR) phenomenon. When light interacts with AgNPs, the conduction electrons on the nanoparticle surface collectively oscillate, producing a characteristic absorption band in the UV-Vis region, typically between 400 and 450 nm depending on particle size, shape, and surrounding medium. Therefore, visual color changes and the appearance of characteristic UV-Vis absorption peaks are widely used as preliminary indicators of AgNP formation prior to further characterization and application studies [13].

1.2.3. *Andrographis paniculata* Extract

Andrographis paniculata is a medicinal plant widely distributed in Indonesia and is known to contain a variety of bioactive secondary metabolites, including flavonoids, phenolic compounds, terpenoids, alkaloids, saponins, and tannins. These phytochemicals have attracted considerable attention in green nanoparticle synthesis due to their ability to act as natural reducing and stabilizing agents. In particular, phenolic and flavonoid compounds possess hydroxyl groups capable of donating electrons, thereby facilitating the reduction of silver ions (Ag^+) into metallic silver (Ag^0) during nanoparticle formation [15]. The abundance of these bioactive compounds makes *A. paniculata* a promising plant source for environmentally friendly synthesis of silver nanoparticles. Compared with many medicinal plants previously employed for AgNP synthesis, *A. paniculata* is distinguished by its high andrographolide content together with abundant phenolic and flavonoid compounds, providing a favorable phytochemical profile for efficient electron transfer during nanoparticle formation [14].

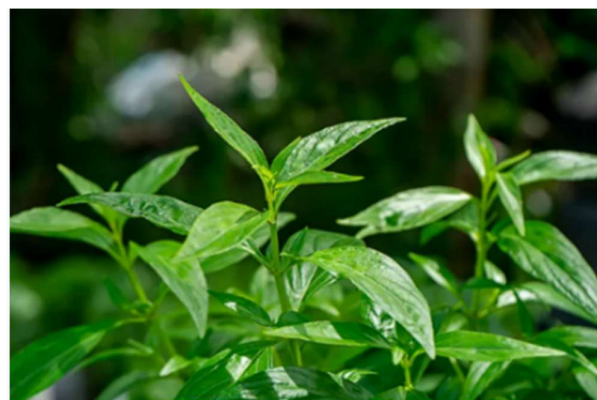


Fig. 1. *Andrographis paniculata*

Among the major bioactive constituents of *A. paniculata*, andrographolide is recognized as the dominant diterpenoid lactone and serves as a chemical marker of the plant. The presence of hydroxyl groups and unsaturated bonds within the andrographolide structure contributes to its redox activity and may support the reduction of Ag^+ ions during nanoparticle synthesis. In addition, the relatively high phenolic and flavonoid contents of *A. paniculata* extract provide strong antioxidant activity, which is closely associated with electron transfer processes involved in the conversion of Ag^+ into Ag^0 . Consequently, these compounds not only participate in nanoparticle formation but may also contribute to the initial stabilization of the synthesized nanoparticles. These characteristics suggest that *A. paniculata* is not only capable of reducing Ag^+ ions but may also enhance colloidal stability by adsorbing phytochemicals onto the nanoparticle surface, thereby supporting its application in green nanomaterial synthesis.

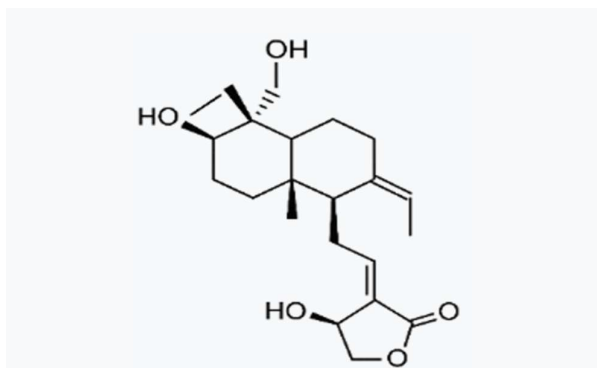


Fig. 2 Molecular structure of andrographolide, the principal bioactive diterpenoid lactone present in *Andrographis paniculata* leaf extract.

The extract also contains chlorophyll, the primary photosynthetic pigment responsible for the characteristic green color of the leaves. Although chlorophyll is not considered the primary reducing agent in AgNP synthesis, it can influence the extract's optical appearance and the reaction system's visual characteristics [8]. Chlorophyll is susceptible to degradation when exposed to heat, light, oxygen, and pH changes, producing pheophytin and related derivatives that cause a color transition from green to olive-green or brownish tones [20]. Therefore, slight color changes observed during extraction may be associated with chlorophyll degradation and oxidation of phenolic compounds. Nevertheless, the successful synthesis of AgNPs remains primarily governed by the reducing capabilities of andrographolide, phenolic compounds, flavonoids, and other phytochemicals present in the extract rather than by chlorophyll itself [14].

1.2.4. Poly(vinyl alcohol) as Capping Agent

Silver nanoparticles synthesized through green synthesis are prone to aggregation due to their high surface energy and strong interparticle attractive forces. Aggregation can significantly alter nanoparticle size distribution, reduce colloidal stability, and affect the optical properties required for sensing applications. To overcome this limitation, capping agents are commonly introduced to form a protective layer around the nanoparticle surface, thereby preventing excessive particle growth and aggregation. Among various stabilizing polymers, poly(vinyl alcohol) (PVA) has been widely employed because of its excellent water solubility, biocompatibility, and stabilizing capability [11].

PVA contains abundant hydroxyl (–OH) groups that can interact with the surface of AgNPs through hydrogen bonding and physical adsorption. These interactions create a steric barrier that enhances nanoparticle dispersion and improves colloidal stability over extended storage periods. In addition, the presence of PVA may contribute to a narrower particle size distribution, resulting in more defined localized surface plasmon resonance (LSPR) absorption bands and improved optical reproducibility. However, excessive PVA concentrations may partially cover the nanoparticle surface and reduce the accessibility of active sites, which can negatively influence the sensitivity of AgNP-based colorimetric sensors toward target ions such as Hg^{2+} [3]. Therefore, optimization of PVA concentration is crucial because insufficient surface coverage may promote nanoparticle

aggregation, whereas excessive polymer adsorption can hinder analyte accessibility and reduce sensing performance.

1.2.5. Optimization of AgNP Synthesis

The physicochemical characteristics of silver nanoparticles (AgNPs) are governed not only by the choice of reducing and stabilizing agents but also by the synthesis conditions employed during nanoparticle formation. Among the most influential parameters are the concentration of the silver precursor and the amount of capping agent, as both directly affect the nucleation, growth, and stabilization processes. Variations in these parameters alter the reduction kinetics of Ag^+ ions, resulting in differences in nanoparticle concentration, particle size distribution, colloidal stability, and optical characteristics. Consequently, systematic optimization of synthesis conditions is essential to obtain AgNPs with reproducible physicochemical properties suitable for sensing applications.

The concentration of silver nitrate (AgNO_3) determines the availability of Ag^+ ions for reduction and therefore plays a pivotal role in nanoparticle formation. At relatively low precursor concentrations, the number of nucleation sites may be insufficient to generate an adequate nanoparticle population, leading to weak localized surface plasmon resonance (LSPR) signals. Conversely, excessive AgNO_3 concentrations may accelerate particle growth beyond the stabilizing capacity of the reducing and capping agents, promoting particle aggregation and broader size distributions. Therefore, an appropriate precursor concentration is required to balance nucleation and particle growth, yielding stable nanoparticles with desirable optical properties [5].

In addition to precursor concentration, the amount of capping agent strongly influences nanoparticle stability and surface characteristics. Poly(vinyl alcohol) (PVA) adsorbs onto the AgNP surface through hydroxyl groups, generating steric stabilization that suppresses particle agglomeration and maintains colloidal dispersion. However, the protective effect of PVA is concentration dependent. Insufficient polymer coverage may fail to prevent nanoparticle aggregation, whereas excessive PVA adsorption may partially block the nanoparticle surface, thereby reducing the accessibility of target analytes and diminishing the optical response during colorimetric detection [3]. Consequently, optimizing the PVA concentration is essential to achieve a balance between colloidal stability and sensing performance.

Since the optical properties of AgNPs are highly sensitive to nanoparticle size, morphology, and dispersion state, optimization of AgNO_3 and PVA concentrations is commonly evaluated through UV–Visible spectroscopy by monitoring changes in LSPR absorption characteristics. Variations in absorbance intensity and maximum absorption wavelength (λ_{max}) provide valuable information regarding nanoparticle formation efficiency and optical behavior under different synthesis conditions. Therefore, systematic optimization of these parameters constitutes a fundamental step in developing reproducible green-synthesized AgNPs with favorable optical characteristics for qualitative colorimetric detection of Hg^{2+} ions.

1.2.6. UV–Visible Spectroscopic Characterization of AgNPs

The formation of silver nanoparticles (AgNPs) can be preliminarily identified through qualitative visual observation of color changes during the synthesis process. Silver ions (Ag^+) in

aqueous solution are initially colorless because they do not significantly absorb visible light. Following reduction to metallic silver (Ag^0), the resulting nanoparticles impart a yellow to yellowish-brown color to the solution due to the emergence of localized surface plasmon resonance (LSPR). Although qualitative visual observation provides a rapid indication of nanoparticle formation, quantitative characterization is commonly performed using UV–Visible spectroscopy to evaluate the optical properties of the synthesized AgNPs [17]. Compared with microscopic characterization techniques, UV–Visible spectroscopy offers a rapid and non-destructive approach for monitoring nanoparticle formation and evaluating changes in optical properties throughout the synthesis process.

LSPR is a unique optical phenomenon exhibited by noble metal nanoparticles, including silver and gold nanoparticles. It occurs when conduction electrons on the nanoparticle surface collectively oscillate in response to incident electromagnetic radiation. At a specific resonant frequency, strong light absorption occurs, producing a characteristic absorption band in the UV–Vis spectrum. For AgNPs, this absorption band is typically observed within the range of 400–450 nm, depending on particle size, morphology, aggregation state, and the dielectric properties of the surrounding medium [16]. Besides confirming nanoparticle formation, UV–Visible spectroscopy has been extensively employed to optimize synthesis conditions because subtle variations in LSPR characteristics reflect changes in nanoparticle size, morphology, dispersion state, and surface interactions.

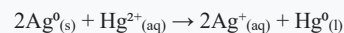
The position and intensity of the LSPR absorption band provide valuable information regarding nanoparticle characteristics. An increase in absorbance generally indicates a greater concentration of dispersed nanoparticles, whereas shifts in the maximum absorption wavelength (λ_{max}) are often associated with changes in particle size and aggregation behavior. A red shift toward longer wavelengths is commonly related to larger particle sizes or increased aggregation, while a blue shift suggests smaller and more uniformly dispersed nanoparticles [10]. Owing to its high sensitivity to surface interactions, LSPR also serves as the fundamental mechanism for AgNP-based colorimetric sensors. In the presence of Hg^{2+} ions, changes in absorbance intensity or LSPR band position may occur due to surface oxidation or Ag–Hg interactions, making UV–Vis spectroscopy a powerful tool for evaluating the sensing performance of AgNPs toward mercury ions [19]. Consequently, UV–Visible spectroscopy served as the principal analytical technique in the present study to evaluate the influence of synthesis parameters on AgNP optical characteristics and their qualitative response toward Hg^{2+} ions.

1.2.7. Colorimetric Detection of Hg^{2+}

Colorimetric sensing is based on observable optical changes that occur when nanoparticles interact with target analytes. In AgNP-based sensing systems, the interaction between Hg^{2+} ions and nanoparticle surfaces alters the localized surface plasmon resonance (LSPR) behavior, resulting in measurable changes in absorbance intensity and solution color. These optical responses enable rapid and cost-effective detection of mercury contamination without requiring sophisticated analytical instruments [4].

The sensing mechanism has been widely proposed to involve the redox reaction between metallic silver (Ag^0) and Hg^{2+} ions.

Because the standard reduction potential of $\text{Hg}^{2+}/\text{Hg}^0$ (+0.85 V) is slightly higher than that of Ag^+/Ag^0 (+0.80 V), Hg^{2+} can oxidize surface silver atoms according to the following reaction:



Although both redox reactions and Ag–Hg amalgam formation have been extensively reported in the literature, the relative contributions of each mechanism may vary with nanoparticle composition, surface chemistry, and synthesis conditions. In addition, the reduced mercury atoms may form Ag–Hg amalgams on the nanoparticle surface. Both processes modify the electronic structure and dielectric environment surrounding the nanoparticles, leading to attenuation or disappearance of the characteristic LSPR absorption band. Consequently, the solution color changes from yellowish-brown to pale yellow or colorless, providing a visual indication of Hg^{2+} presence [16].

The performance of AgNP-based colorimetric sensors is strongly influenced by nanoparticle size, colloidal stability, and surface accessibility. Appropriate optimization of AgNO_3 concentration and poly(vinyl alcohol) (PVA) content is essential to maintain nanoparticle stability while preserving active sites for Hg^{2+} interaction [2]. Furthermore, green-synthesized AgNPs have demonstrated high selectivity toward Hg^{2+} compared with other metal ions, largely due to the specific redox and amalgamation processes occurring at the nanoparticle surface [19]. Therefore, optimization of nanoparticle synthesis parameters is essential to maximize the optical response while maintaining sufficient colloidal stability for reliable qualitative colorimetric detection.

1.3. Research Objective

This study aims to systematically investigate the influence of AgNO_3 precursor concentration and poly(vinyl alcohol) (PVA) content on the green synthesis of silver nanoparticles (AgNPs) mediated by *Andrographis paniculata* leaf extract and to establish a preliminary proof-of-concept for their qualitative colorimetric detection of Hg^{2+} ions through optical characterization.

2. MATERIALS AND METHODS

This study employed an experimental approach to investigate the influence of AgNO_3 precursor concentration and poly(vinyl alcohol) (PVA) content on the green synthesis of silver nanoparticles (AgNPs) mediated by *Andrographis paniculata* leaf extract, followed by a preliminary qualitative evaluation of their colorimetric response toward Hg^{2+} ions. The research was conducted from April to May 2026 at the Advanced Materials Laboratory, Department of Chemical Engineering, Universitas Pembangunan Nasional “Veteran” Jawa Timur, Surabaya, Indonesia. All synthesis procedures, sample preparation, and characterization analyses, including Fourier transform infrared spectroscopy (FTIR) and UV–Visible spectroscopy, were carried out in the same laboratory.

Fresh *Andrographis paniculata* leaves, collected in April 2026 from Surabaya, East Java, Indonesia, were taxonomically identified based on morphological characteristics and subsequently used as the natural source of reducing phytochemicals for AgNP synthesis. Silver nitrate (AgNO_3 , $\geq 99\%$, analytical grade) was used as the silver precursor, whereas poly(vinyl alcohol) (PVA, medium molecular weight, technical grade) served as the capping agent. Mercury(II) chloride (HgCl_2 ,

analytical grade) was used for preparing Hg^{2+} stock solutions. All solutions were prepared using double distilled water (aquabidest) without further purification. The *A. paniculata* leaves were washed, air-dried at room temperature, ground, and sieved through a 60-mesh screen. Leaf extract was prepared by mixing 30 g of powdered leaves with 300 mL of double distilled water (1:10 w/v), followed by extraction at 60 °C for 60 min under continuous stirring. The filtrate was diluted with distilled water at a ratio of 1:6 (v/v) and stored at 4 °C prior to use.

Silver nanoparticles (AgNPs) were synthesized via a green synthesis approach by mixing 20 mL of AgNO_3 solution, 3 mL of diluted leaf extract, and 5 mL of PVA solution. The reaction mixture was stirred at 270 rpm and maintained at 35 °C for 6 min. AgNO_3 concentrations of 0.5, 1.0, 1.5, 2.0, and 2.5 mM and PVA concentrations of 0.1, 0.2, 0.4, 0.5, and 1.0% (w/v) were systematically investigated to evaluate their influence on nanoparticle formation. A total of twenty-five synthesis conditions were generated by combining five AgNO_3 concentrations with five PVA concentrations while maintaining all other synthesis parameters constant. Owing to the exploratory nature of this study, each synthesis condition was evaluated through a single experimental run, and the resulting optical characteristics were comparatively analyzed to identify the optimum synthesis condition. The synthesis was conducted at the natural pH of the reaction mixture under ambient laboratory conditions and protected from direct sunlight to minimize undesired photo-induced silver reduction. UV–Visible spectra were recorded between 250 and 800 nm using quartz cuvettes with a 1 cm optical path length. The maximum absorbance and corresponding wavelength (λ_{max}) were used as the principal parameters for evaluating nanoparticle formation and optical characteristics.

For colorimetric sensing, Hg^{2+} solutions with concentrations of 1 ppb, 10 ppb, 100 ppb, and 1 ppm were prepared by serial dilution of a 100 ppm stock solution. For each sensing experiment, 1 mL of the optimum AgNP suspension was mixed with 3–10 mL of Hg^{2+} solution depending on the tested concentration and allowed to react for 5 min at room temperature. The sensing response was evaluated qualitatively through visual color observation and by monitoring changes in UV–Visible absorption spectra after Hg^{2+} addition. The overall experimental workflow consisted of extract preparation, AgNP synthesis, optical characterization, optimization of synthesis conditions, and preliminary qualitative evaluation toward Hg^{2+} ions.

3. RESULT AND DISCUSSION

3.1. Characterization of *Andrographis paniculata* Extract

The FTIR spectrum of *Andrographis paniculata* leaf extract is presented in Fig. 3. Several characteristic absorption bands were observed at 3464.106, 2082.919, and 1641.387 cm^{-1} , indicating the presence of functional groups potentially involved in the green synthesis of silver nanoparticles. The broad absorption band at 3464.106 cm^{-1} is assigned to the O–H stretching vibration of hydroxyl groups, which are commonly associated with phenolic compounds and flavonoids known to participate in the reduction of Ag^+ ions [15]. Meanwhile, the absorption band at 1641.387 cm^{-1} corresponds to C=O stretching and/or C=C

skeletal vibrations originating from phenolic constituents and diterpenoid compounds such as andrographolide [15].

A relatively weak absorption band was also observed at 2082.919 cm^{-1} . Unlike the hydroxyl and carbonyl bands, this absorption is not typically regarded as a characteristic feature of phenolic compounds. It may be attributed to minor organic constituents or combination/overtone vibrations present in the plant extract, although its contribution to the nanoparticle synthesis mechanism is considered less significant than those of the O–H and C=O functional groups [15]. Consequently, the interpretation of this band should be made with caution.

The predominance of hydroxyl- and carbonyl-containing phytochemicals suggests that *A. paniculata* extract provides the essential functional groups required for AgNP synthesis. Hydroxyl groups serve as electron donors during the reduction of Ag^+ to metallic Ag^0 , whereas oxygen-containing functional groups may adsorb onto the nanoparticle surface, contributing to the initial stabilization of the resulting colloidal system [18]. Therefore, the FTIR results provide spectroscopic evidence supporting the role of *A. paniculata* extract as both a natural reducing agent and an intrinsic stabilizing matrix during the green synthesis process.

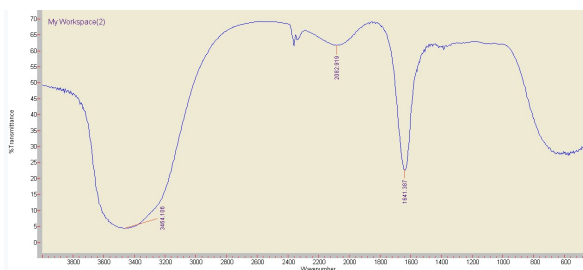


Fig. 3 FTIR spectrum of *Andrographis paniculata* leaf extract showing the major functional groups involved in AgNP synthesis.

3.2. Green Synthesis of Silver Nanoparticles

The initial formation of silver nanoparticles (AgNPs) was qualitatively indicated through visual observation of the reaction mixture. As illustrated in Fig. 4, the solution gradually changed from colorless to yellowish-brown following the addition of *Andrographis paniculata* leaf extract and poly(vinyl alcohol) (PVA) to the AgNO_3 solution. The appearance of this characteristic color suggests the reduction of Ag^+ ions into metallic silver (Ag^0) and the subsequent formation of colloidal AgNPs. This optical transition is attributed to the emergence of localized surface plasmon resonance (LSPR), which originates from the collective oscillation of conduction electrons on the nanoparticle surface upon interaction with incident light [16]. The FTIR results demonstrated the presence of hydroxyl- and carbonyl-containing phytochemicals, particularly phenolic compounds, flavonoids, and andrographolide, which facilitate electron transfer during Ag^+ reduction while contributing to the initial stabilization of the synthesized nanoparticles [15].



Fig. 4. Visual color change from colorless AgNO_3 solution to yellowish-brown AgNP colloid during the green synthesis process.

Meanwhile, PVA acted as a capping agent by forming a steric protective layer around the nanoparticles, thereby suppressing excessive particle growth and aggregation throughout the synthesis process [3]. Although the observed color change provides preliminary evidence of AgNP formation, qualitative visual observation alone is insufficient to verify nanoparticle characteristics. Therefore, UV-Visible spectroscopy was employed as the principal characterization technique to confirm AgNP formation and systematically evaluate the influence of synthesis parameters on their optical properties.

3.3. Effect of AgNO_3 and PVA Concentrations on AgNP Characteristics

The optical characteristics of the synthesized AgNPs were investigated using UV-Visible spectroscopy, and the corresponding results are summarized in Table 1. All representative samples exhibited localized surface plasmon resonance (LSPR) absorption bands within the range of 411–448.5 nm, confirming the successful reduction of Ag^+ ions into metallic silver (Ag^0) by phytochemicals present in the *Andrographis paniculata* extract. A secondary absorption band was consistently observed at approximately 290–305 nm, which is likely associated with the absorption of residual phytochemicals and/or PVA present in the colloidal system rather than the LSPR of AgNPs. Nevertheless, noticeable variations in both maximum absorbance and absorption wavelength (λ_{max}) were observed among the synthesis conditions, indicating that AgNO_3 precursor concentration and PVA content substantially influenced nanoparticle formation and optical behavior. In addition to peak position and intensity, slight differences in spectral bandwidth were observed, suggesting variations in particle-size distribution and the extent of nanoparticle aggregation under different synthesis conditions [18].

To provide an overall comparison of the synthesized AgNPs, representative UV-Vis spectra obtained under different AgNO_3 and PVA concentrations are presented in Fig. 5, whereas the corresponding λ_{max} and maximum absorbance values are summarized in Table 1. The combined evaluation of these parameters enables assessment of nanoparticle formation efficiency, optical response, and changes in plasmonic characteristics arising from variations in synthesis conditions.

Table 1. Maximum absorption wavelength (λ_{max}) and absorbance values of AgNPs synthesized under different AgNO_3

and poly(vinyl alcohol) (PVA) concentrations as determined by UV-Visible spectroscopy.

Code	AgNO_3 (mM)	PVA (%)	λ_{max} (nm)	Absorbance
A01	0.5	0.1	441-448.5	0.093
A05	0.5	0.5	419.5-426.5	0.15
A10	0.5	1.0	411-417.5	0.152
B04	1	0.4	435.5-440.5	0.282
B05	1	0.5	433.5-440.5	0.336
B10	1	1.0	434-435.5	0.392
C01	1.5	0.1	439.5-444.5	0.215
C05	1.5	0.5	441.5-445	0.342
D01	2	0.1	443-444.5	0.433
D04	2	0.4	435.5	0.71
D05	2	0.5	438.5-445	0.352
E01	2.5	0.1	441.5-443.5	0.344
E10	2.5	1.0	436.5-441.5	0.473

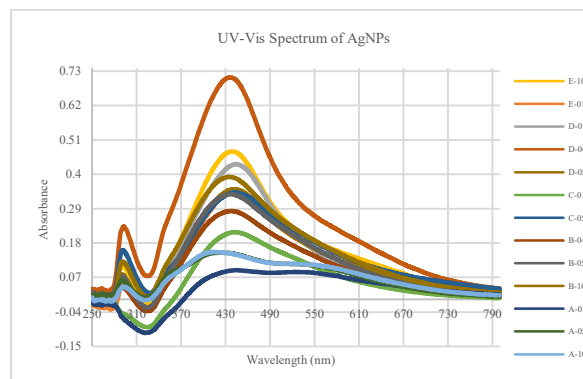


Fig. 5. Representative UV-Visible absorption spectra of AgNPs synthesized under different AgNO_3 precursor and poly(vinyl alcohol) (PVA) concentrations, showing variations in localized surface plasmon resonance (LSPR) characteristics.

Despite variations in absorbance intensity and λ_{max} , all representative spectra exhibited a single dominant LSPR band without obvious peak splitting, indicating that AgNP formation occurred consistently under all investigated synthesis conditions. Differences among the spectra were primarily reflected by variations in peak intensity and spectral definition, suggesting that AgNO_3 and PVA concentrations mainly influenced nanoparticle growth and colloidal stabilization rather than altering the fundamental plasmonic characteristics of the synthesized AgNPs. Variations in λ_{max} primarily reflect changes in nanoparticle size, interparticle interactions, and the local dielectric environment, whereas differences in absorbance intensity are associated with variations in nanoparticle concentration and plasmonic response. Accordingly, both parameters were evaluated simultaneously to identify synthesis conditions capable of producing AgNPs with favorable optical characteristics. Although quantitative peak-width analysis was not performed, slight differences in spectral broadening among the representative samples suggest variations in particle-size distribution and colloidal uniformity. To specifically evaluate the

role of PVA as a capping agent, UV–Vis spectra were obtained at a fixed AgNO_3 concentration of 2 mM. Samples D01, D04, and D05, corresponding to PVA concentrations of 0.1, 0.4, and 0.5%, respectively, were selected because they capture changes in polymer concentration while eliminating variations due to precursor availability. The resulting spectra are presented in Fig. 6. The LSPR band of sample D04 was characterized by a relatively sharp and well-resolved spectral profile accompanied by the highest absorbance intensity among the investigated samples. Such spectral characteristics generally indicate efficient plasmon excitation and suggest the formation of a comparatively homogeneous colloidal dispersion under the experimental conditions investigated. Nevertheless, quantitative assessment of peak symmetry and full width at half maximum (FWHM) was beyond the scope of the present study; therefore, this interpretation is limited to qualitative spectral observations.

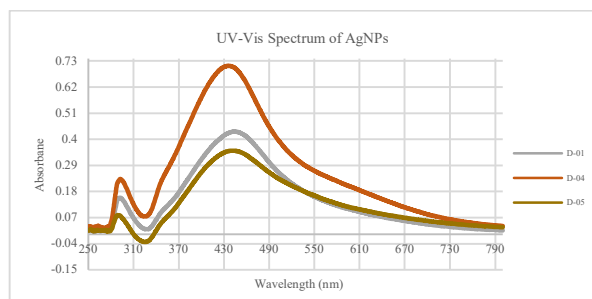


Fig. 6 UV–Visible absorption spectra of AgNPs synthesized at a constant AgNO_3 concentration of 2 mM with different poly(vinyl alcohol) (PVA) concentrations, illustrating the influence of PVA on localized surface plasmon resonance (LSPR) characteristics.

Since sample D04 exhibited the strongest optical response among the evaluated conditions, the influence of silver precursor concentration was subsequently examined to better understand its contribution to nanoparticle formation. The increased absorbance observed for sample D04 suggests that an intermediate PVA concentration provided sufficient steric stabilization to suppress excessive aggregation without substantially hindering nanoparticle growth. At lower PVA concentrations, incomplete surface coverage may reduce colloidal stability, whereas higher polymer concentrations may partially shield the nanoparticle surface, thereby influencing the optical response [3].

Following optimization of the capping agent concentration, the influence of silver precursor concentration was subsequently examined while maintaining the PVA concentration constant at 0.1%. Samples A01, C01, D01, and E01 were therefore compared to investigate the effect of Ag^+ availability on nanoparticle nucleation, growth, and optical characteristics. The corresponding UV–Vis spectra are presented in Fig. 7.

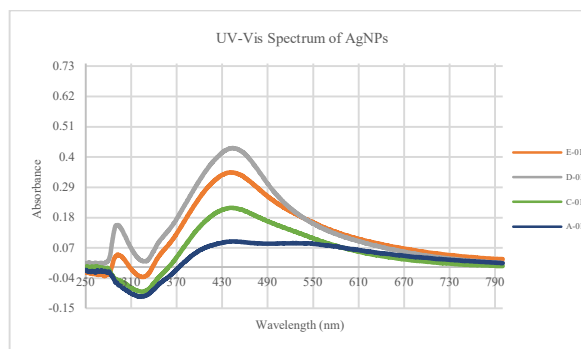


Fig. 7. UV–Visible absorption spectra of AgNPs synthesized at a constant poly(vinyl alcohol) (PVA) concentration of 0.1% with different AgNO_3 concentrations, illustrating the influence of silver precursor concentration on localized surface plasmon resonance (LSPR) characteristics.

Increasing AgNO_3 concentration increased the availability of silver ions for reduction, thereby influencing both nucleation density and subsequent particle growth. However, the optical response did not increase linearly with precursor concentration, indicating that nanoparticle formation was simultaneously governed by the reducing capacity of the plant extract and the stabilizing action of PVA [18].

Collectively, these results demonstrate that the optical characteristics of AgNPs are governed by the synergistic interaction between precursor availability and colloidal stabilization. AgNO_3 concentration primarily influences nucleation and particle growth by regulating silver-ion availability, whereas PVA controls particle dispersion through steric stabilization. Consequently, optimum nanoparticle formation should be evaluated using multiple optical parameters, including absorbance intensity, λ_{max} , and spectral profile, rather than absorbance alone, as these collectively provide a more reliable indication of nanoparticle quality and synthesis efficiency [18].

3.4. Selection of the Optimum Synthesis Condition Based on UV–Visible Spectral Characteristics

The optimum synthesis condition was identified through a comparative evaluation of the UV–Visible spectral profiles, considering the maximum absorbance, the position of the localized surface plasmon resonance (LSPR) band (λ_{max}), and the overall spectral characteristics. Because comprehensive nanoparticle characterization (e.g., particle size distribution, zeta potential, and FWHM analysis) was beyond the scope of the present study, the optimum condition was established based on the optical parameters obtained from UV–Visible spectroscopy. Among all experimental conditions, sample D04, synthesized using 2 mM AgNO_3 and 0.4% PVA, exhibited the highest absorbance (0.710) together with a characteristic LSPR absorption peak centered at 435.5 nm. The corresponding λ_{max} lies within the characteristic absorption region of AgNPs (400–450 nm), indicating successful nanoparticle formation. Furthermore, the absorption profile exhibited a distinct single plasmon band with no obvious secondary features, suggesting the formation of a relatively well-dispersed colloidal system under the conditions investigated [18].

The favorable optical characteristics observed for sample D04 suggest that the selected AgNO_3 and PVA concentrations provided an appropriate balance between silver-ion availability,

phytochemical-mediated reduction, and steric stabilization by PVA. In contrast, although sample A10 exhibited the lowest λ_{max} (411–417.5 nm), which may indicate the formation of relatively small nanoparticles, its substantially lower absorbance suggests a reduced nanoparticle population or a weaker plasmonic response. Consequently, D04 was selected as the optimum synthesis condition because it simultaneously exhibited high absorbance, an LSPR band within the characteristic spectral region of AgNPs, and a well-defined spectral profile. Nevertheless, the present optimization is based exclusively on optical characterization, and additional physicochemical analyses, such as particle size distribution, zeta potential, and long-term colloidal stability, would provide a more comprehensive assessment of nanoparticle quality [5,18].

3.5. Colorimetric Detection of Hg^{2+}

The colorimetric sensing capability of the synthesized AgNPs was preliminarily evaluated through qualitative detection of Hg^{2+} ions. As illustrated in Fig. 8, the characteristic yellowish-brown color of the AgNP colloid gradually disappeared after the addition of Hg^{2+} solution, producing an evident visual transition to a nearly colorless solution. This observation confirms that the synthesized AgNPs exhibit a distinct optical response toward Hg^{2+} and demonstrates the feasibility of employing the nanoparticles as a simple colorimetric probe for mercury detection.

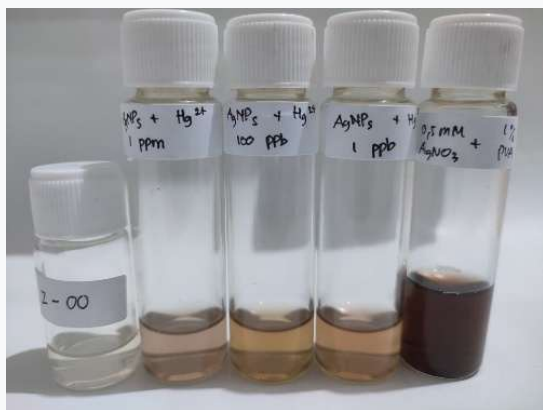


Fig. 8. Color change of AgNP colloids after exposure to different Hg^{2+} concentrations, demonstrating their potential for colorimetric mercury detection.

The observed color change is attributed to the interaction between Hg^{2+} ions and the AgNP surface, which disrupts the localized surface plasmon resonance (LSPR) phenomenon. Owing to the higher standard reduction potential of the $\text{Hg}^{2+}/\text{Hg}^0$ redox couple relative to Ag^+/Ag^0 , Hg^{2+} can oxidize surface Ag^0 atoms while simultaneously promoting the formation of Ag–Hg amalgams. These processes decrease the density of conduction electrons responsible for plasmon resonance, leading to attenuation of the characteristic LSPR absorption band and the accompanying loss of the yellowish-brown coloration [5].

It should be noted that the sensing performance presented in this study was evaluated qualitatively based on visual observation of the colorimetric response. Quantitative analytical parameters, including the limit of detection (LOD), limit of quantification (LOQ), linear detection range, selectivity toward competing metal ions, and long-term sensing stability, were not investigated and therefore remain subjects for future study. Nevertheless, the distinct visual response obtained under the investigated

conditions provides a preliminary proof-of-concept that green-synthesized AgNPs derived from *A. paniculata* leaf extract may serve as an environmentally friendly platform for the development of low-cost colorimetric mercury sensors.

4. CONCLUSION

Silver nanoparticles (AgNPs) were successfully synthesized through a green synthesis approach using *Andrographis paniculata* leaf extract as a reducing agent and poly(vinyl alcohol) (PVA) as a capping agent. FTIR analysis confirmed the presence of bioactive functional groups involved in silver-ion reduction, whereas UV–Visible spectroscopy verified AgNP formation through characteristic localized surface plasmon resonance (LSPR) absorption bands within the range of 411–448.5 nm. Among the investigated synthesis conditions, 2 mM AgNO_3 combined with 0.4% PVA produced the most favorable optical characteristics, exhibiting the highest absorbance (0.710) at 435.5 nm. Preliminary qualitative evaluation further demonstrated a distinct colorimetric response toward Hg^{2+} ions, evidenced by the visible transition of the AgNP colloid from yellowish-brown to colorless. Although quantitative sensing performance was not assessed in the present study, the findings provide proof-of-concept evidence supporting the feasibility of *A. paniculata*-mediated AgNPs as an environmentally friendly platform for future development of colorimetric mercury sensors.

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