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## Citrus aurantifolia-mediated AuNPs: Microplastic detection achieved, pesticide sensing explored

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### ABSTRACT

Green synthesis of AuNPs (gold nanoparticles) is increasingly gaining importance for producing nanoparticles with high stability and strong optical activity, as current research focuses not only on feasibility but also on sustainability. In this study, AuNPs were synthesized using *Citrus aurantifolia* extract. Optimization was performed by varying extract concentration, precursor concentration, extract pH, synthesis time, and temperature. The optimum conditions were 10% extract, 0.6 mM precursor, pH 7, and a 10-min synthesis under boiling conditions. These conditions produced homogeneous nanomaterials, characterized by a high, narrow surface plasmon resonance (SPR) peak at ~530 nm. The characterization results revealed predominantly spherical AuNP morphology via field emission scanning electron microscopy (FESEM), an average particle size of 35.51 nm (PSA-Size), and a negative surface charge of -23.29 mV (PSA-Zeta Potential), all of which contribute to the stability of the AuNP colloid. Fourier transform infrared spectroscopy (FTIR) analysis further indicated the presence of secondary metabolite functional groups from *C. aurantifolia* extract on the nanoparticle surface. The synthesized AuNPs were then applied for microplastic detection using a precipitation-based method, enabling simple and direct visual identification. The system successfully detected PS microplastics at concentrations as low as 5 mg/L. Additionally, this study assessed the potential of AuNPs for pesticide detection via surface interaction mechanisms that induce SPR peak shifts. Overall, AuNPs-CA offers a sustainable synthesis route while providing opportunities for the development of low-cost, rapid, easy-to-apply, and environmentally friendly chemical sensors for environmental pollutant monitoring.

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## 1. Introduction

Modern analytical methods are beginning to consider the use of real-time detection systems, and the use of nanotechnology is one of the most crucial pathways [1,2]. AuNPs, one of the most frequently studied nanoparticles, possess fundamental properties that significantly facilitate real-time detection. AuNPs exhibit high chemical stability, unique optical properties through strong localized surface plasmon resonance (LSPR) phenomena, biocompatibility, surface modifiability, and the ability to interact with a wide range of organic and inorganic molecules. These characteristics make AuNPs suitable for a variety of monitoring applications, such as biosensing, pollutant detection, and health-monitoring analysis [3,4]. However, the widespread use of synthetic reducing agents, such as sodium citrate and sodium borohydride, and stabilizing agents such as EDTA, tartaric acid, and surfactants, results in the generation of hazardous waste during and after production [4-6]. Therefore, synthesis methods that consider the principles of green chemistry are needed to create safer, more sustainable, energy-efficient, non-toxic, and economical alternatives [7]. Recently, green synthesis has become a highly sought-after approach to substitute conventional synthesis routes. Renewable sources of reducing and stabilizing agents are obtained from plant extracts, cells, enzymes, and other biomass. Specifically, plant extracts act as reducing and stabilizing agents because they contain secondary metabolites such as flavonoids, terpenoids, and alkaloids. These metabolites are electron-rich, enabling them to perform reductions, and their combination of hydrophilic and lipophilic components simultaneously stabilizes nanoparticles after synthesis [3].

*Citrus aurantifolia* is a plant abundantly found in tropical regions like Indonesia and is attracting considerable attention due to its rich chemical composition, which shows strong potential as a substitute for synthetic reducing and stabilizing agents. Metabolic compounds contained in *C. aurantifolia* include ascorbic acid, limonene, tannins, flavonoids, and various phenolic groups, all of which are effective in reducing metal ions and

stabilizing nanoparticles. Furthermore, utilizing citrus—particularly its peel—in the green synthesis of AuNPs helps reduce agricultural waste [8,9].

AuNP synthesis requires careful consideration of several factors, as they directly affect the size, morphology, distribution, shape, and stability of the product. In other words, the properties and structure of synthesized AuNPs can be controlled. Several significant parameters in the synthesis include extract concentration, gold precursor concentration, pH, reaction time, and heating temperature [10,11]. In addition to determining synthesis yield, these variations also influence the reduction rate. In this study, these five parameters were optimized to obtain AuNPs synthesized from *C. aurantifolia* with characteristics suitable for future applications. Furthermore, fundamental indicators of nanoparticle formation, such as an SPR peak around 530 nm, are also key benchmarks in the optimization process [4].

The use of AuNPs as a detection medium is further supported by concerning environmental conditions. East Java Province, Indonesia, is a leading agricultural production region, relying heavily on two major rivers, the Solo and Brantas Rivers. Unfortunately, numerous pollutants, such as microplastics and pesticide residues, are increasingly found in these water systems. This situation will ultimately threaten rice production, a major commodity of the region. Microplastic pollution and pesticide residues in agricultural water reduce crop quality and productivity. Therefore, developing detection methods for microplastic and pesticide pollutants is crucial [12-14]. Moreover, efforts to create real-time environmental monitoring technology using environmentally friendly synthesis routes are urgently needed [15].

Green AuNPs synthesized from *C. aurantifolia* extract have significant potential as a detection medium due to their stability, ability to agglomerate under changing conditions, and optical properties. This stability can be utilized for microplastic detection, while the surface chemistry contributed by secondary metabolites offers interaction sites useful for pesticide sensing. Pesticides—particularly organophosphate and carbamate classes—can interact with AuNP surfaces through coordination or aggregation

mechanisms. This potential study is highly relevant considering the increasing use of pesticides in agriculture and the negative health and environmental impacts caused by their residues [3]. Thus, this research aims to explore the possibility of utilizing AuNPs fabricated with *C. aurantifolia* extract as a sensing platform for microplastics and pesticides.

Overall, the synthesis of AuNPs using *C. aurantifolia* extract (hereinafter referred to as AuNPs-CA) offers a simple, environmentally friendly, and economical approach, while also opening opportunities for detecting environmental pollutants such as microplastics and pesticides. The development of this approach aligns with the global trend toward green technology and more accessible analytical methods. By combining synthesis optimization, comprehensive characterization, and potential application studies, this research is expected to contribute significantly to environmental chemistry, nanotechnology, and nanoparticle-based sensing technology.

## 2. Materials and methods

### 2.1. Materials

The main materials used in this study included *Citrus aurantifolia* fruit obtained from the traditional market of Bojonegoro. The gold precursor ( $\text{HAuCl}_4$ ) was prepared by dissolving pure gold from MiniGold using hydrochloric acid ( $\text{HCl}$ ) and nitric acid ( $\text{HNO}_3$ ), both purchased from Merck. Additional reagents used were sodium hydroxide ( $\text{NaOH}$ ), ascorbic acid ( $\text{C}_6\text{H}_8\text{O}_6$ ), sodium citrate ( $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$ ), and acetone ( $\text{C}_3\text{H}_8\text{O}$ ), all obtained from Merck. Distilled water (aquabidest) was supplied by Ikapfarmindo Putramas, and the polystyrene (PS) microplastic standard ( $(\text{C}_6\text{H}_8)_n$ ) was obtained from Macklin.

### 2.2. Instrumentation

AuNPs-CA characterization was performed using several analytical instruments. An ultraviolet-visible (UV-Vis) spectrophotometer (Agilent Technologies Cary 60) was used to observe the SPR absorption and to assess the absorbance intensity, particle size tendencies, and the homogeneity of the synthesized nanoparticles. Functional group analysis of the *Citrus aurantifolia* extract and

AuNPs-CA was conducted using FTIR (Agilent Technologies). Particle size distribution and surface charge were measured using a particle size analyzer (PSA; Malvern Panalytical). Meanwhile, particle morphology and size were further examined using a Field Emission Scanning Electron Microscope (FESEM-Hitachi 8400).

### 2.3. Citrus aurantifolia Extraction

Extraction began with cleaning the *Citrus aurantifolia* fruit and grinding it to increase the surface area. A total of 100 mL of distilled water was brought to a boil, and once boiling, 10 grams of finely ground *C. aurantifolia* was added. The mixture was allowed to infuse for 10 minutes. The extract was then cooled to room temperature, centrifuged, and filtered. The obtained extract was stored in a refrigerator and used within two weeks; afterward, it must be regenerated.

### 2.4. Green Synthesis of Citrus aurantifolia-Mediated Gold Nanoparticles (AuNPs-CA)

The green synthesis of gold nanoparticles was carried out by mixing an  $\text{HAuCl}_4$  precursor solution with *C. aurantifolia* extract at a specific ratio while stirring under controlled temperature. A color change from yellow to wine red indicated the formation of gold nanoparticles. The synthesis process began by heating the gold precursor to boiling, followed by the rapid addition of the extract. During the synthesis,  $\text{Au}^{3+}$  ions were reduced to  $\text{Au}^0$  by biomolecules present in the extract.

Several synthesis variations were investigated, including extract concentration (0.2; 0.4; 0.6; 0.8; 1.0; 2.0; 4.0; 6.0; 8.0; and 10.0%), precursor concentration (0.03; 0.15; 0.30; 0.45; and 0.60 mM), synthesis time (2.5; 5.0; 10.0; 20.0; and 40.0 minutes), pH (3, 5, 7, 9, and 11), and applied synthesis temperature (50, 60, 70, 80, 90°C, and boiling).

Determination of the optimum synthesis conditions was performed using a UV-Vis spectrophotometer by evaluating spectra in the characteristic SPR region of gold nanoparticles, around 530 nm.

### 2.5. AuNPs-CA Characterization

Characterization of the *Citrus aurantifolia*-mediated colloidal gold nanoparticles was performed on the optimally synthesized AuNPs-CA.

A UV-Vis spectrophotometer was used to examine the position, sharpness, and slenderness of the SPR peaks as indicators of successful nanoparticle formation and size homogeneity. FTIR analysis was conducted to identify functional groups from the *C. aurantifolia* extract that interact with and stabilize the nanoparticle surface. Particle size distribution and surface charge were evaluated using a particle size analyzer. Meanwhile, FESEM was used to directly observe nanoparticle morphology and estimate particle size.

## 2.6. Microplastic Testing and Pesticide Detection Potential Study

The application of AuNPs-CA for PS microplastic detection was carried out using a back-detection approach with acetone as an agglomerating agent. The process began by determining the acetone-induced agglomeration point of AuNPs-CA. Microplastic detection was then performed by mixing AuNPs-CA with PS microplastics, followed by intentional agglomeration through acetone addition. The presence of microplastics increased the stability of the AuNPs-CA suspension, and this change in colloidal behavior served as an indicator for PS microplastic detection. Meanwhile, the potential application of AuNPs-CA for pesticide detection was evaluated based on a literature review and preliminary exploratory observations.

## 3. Results and discussion

### 3.1. Synthesis of Gold Nanoparticles (AuNPs) Using *Citrus aurantifolia* Extract

The synthesis of gold nanoparticles using *Citrus aurantifolia* extract (AuNPs-CA) was successfully carried out, as indicated by a color change from pale yellow to wine red. This color transition represented the most direct visual evidence of the reduction of  $\text{Au}^{3+}$  ions to  $\text{Au}^0$  [16]. In addition, the appearance of the Tyndall effect when the colloidal suspension was exposed to laser light further confirmed nanoparticle formation. UV-Vis spectrophotometric analysis also verified the presence of localized surface plasmon resonance (SPR) absorption around ~530 nm, which is characteristic of gold nanoparticles [17].

The reduction process is strongly influenced by the secondary metabolites naturally present in *C. aurantifolia*, including phenolics, terpenoids, and

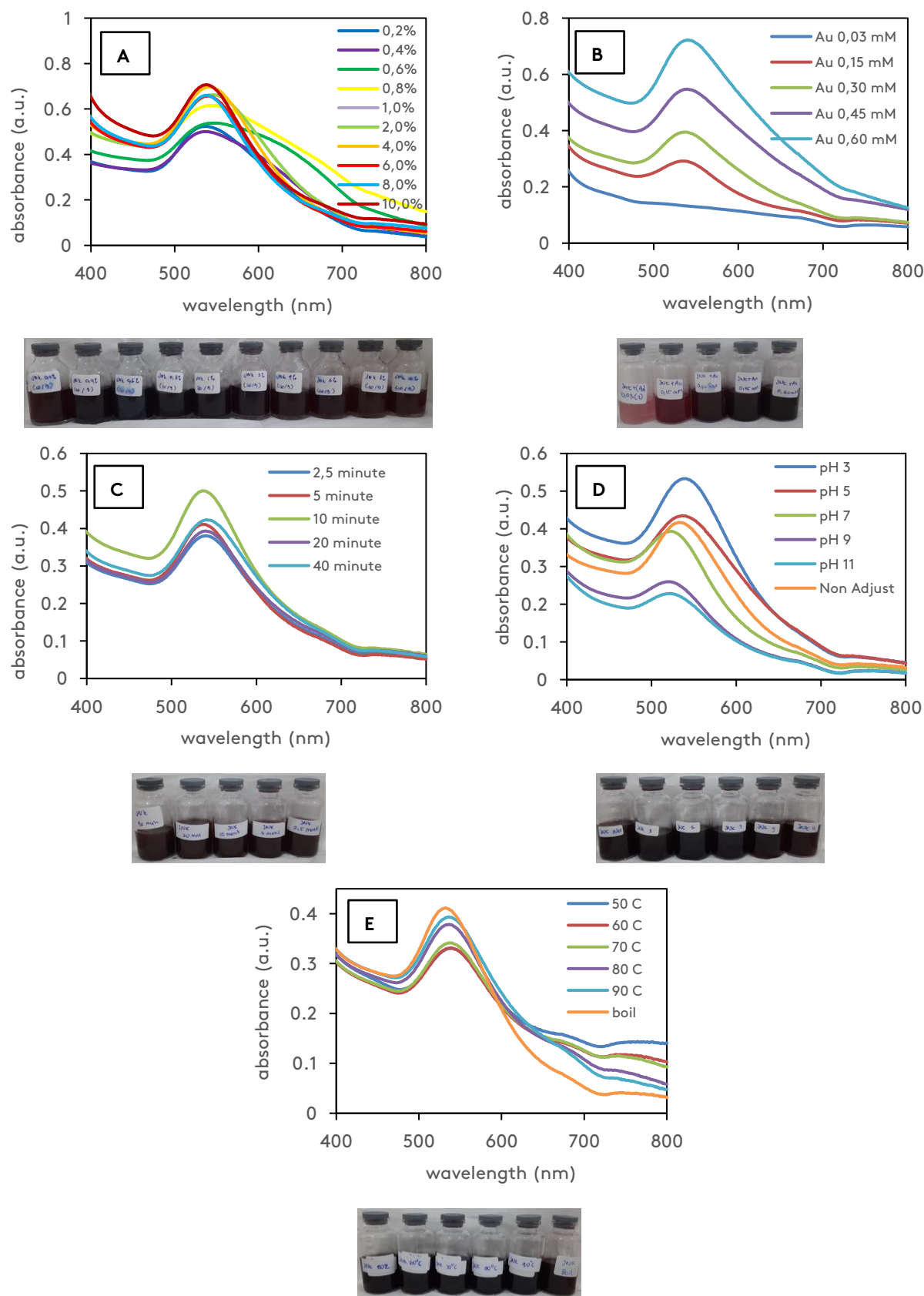
alkaloids [18]. Phenolic compounds contain alcohol groups, terpenoids are composed of five-carbon alkyl chains, and alkaloids feature nitrogen-rich structures. These functional characteristics make the metabolites highly electron-rich, enabling them to function as antioxidants [19]. Ascorbic acid, one of the strongest natural antioxidants, is abundant in *C. aurantifolia* and plays a central role in the reduction of  $\text{Au}^{3+}$  to  $\text{Au}^0$  [20].

These metabolites not only act as reducing agents but also as stabilizers. Long-chain terpenes coat the nanoparticle surface, preventing rapid aggregation [3]. Because each component plays a specific function, determining the optimal synthesis conditions—precursor concentration, bioreductant concentration, pH, temperature, and reaction time—is crucial for producing AuNPs with controlled size, quantity, morphology, and stability [4].

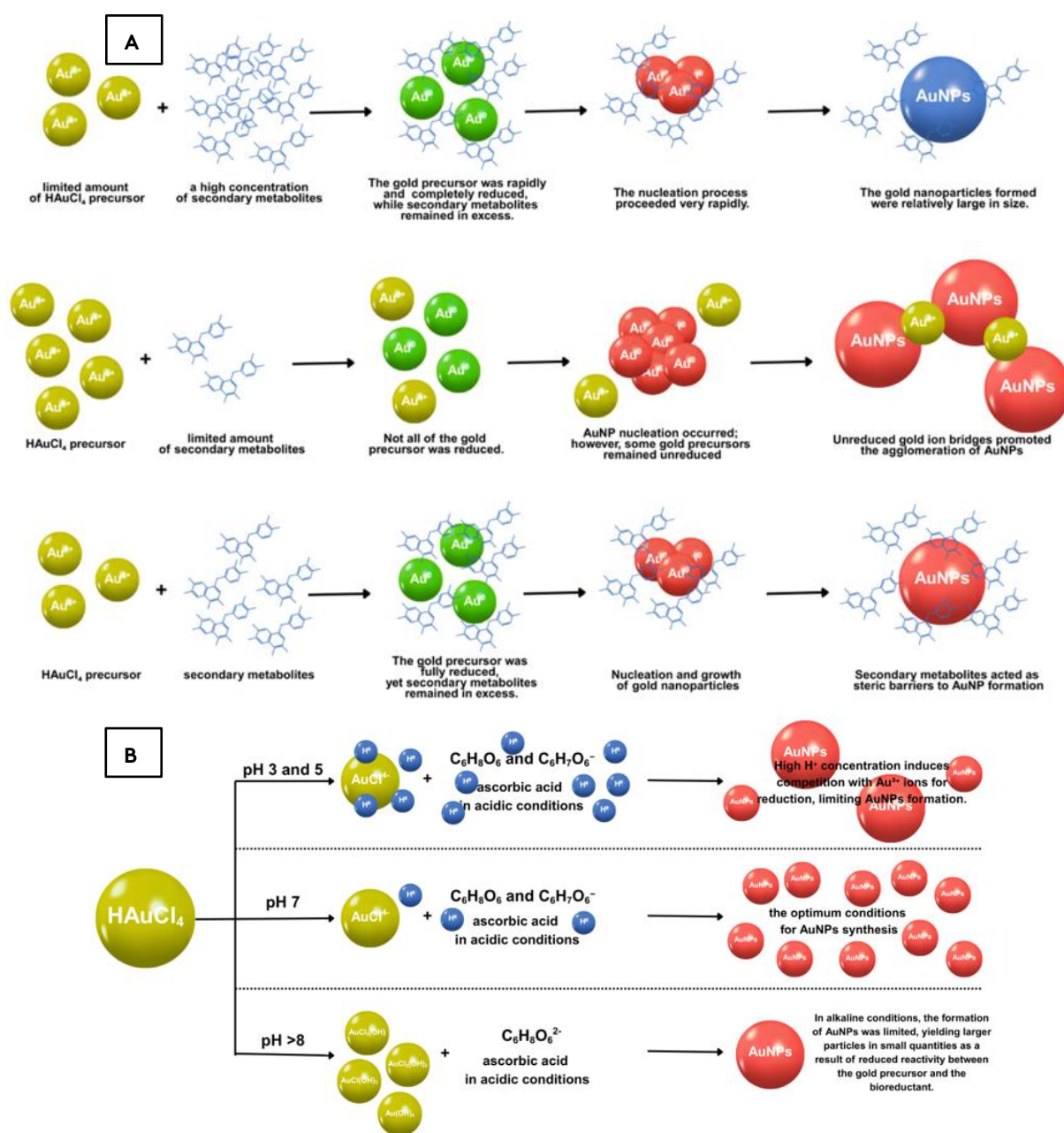
Across various extract concentrations, nearly all conditions resulted in AuNP formation, but with differing spectral characteristics. The SPR peak shape—sharp, tall, broad, or tailed—indicates nanoparticle quantity, size, and homogeneity. High peak intensity corresponds to a larger number of nanoparticles; a leftward shift (blue shift) indicates smaller nanoparticle size; and sharp peaks reflect better size uniformity [5,6].

Among the tested concentrations, only the 10% extract resulted in the sharpest and most symmetrical SPR peak, indicating a more homogeneous size distribution. When the extract concentration is too low, the reduction becomes incomplete, leaving residual  $\text{Au}^{3+}$  ions that can act as ionic bridges and promote particle growth. Results are shown in Figures 1A and 2A. Conversely, excessively high reducing agent concentrations cause the reduction to occur too rapidly, creating kinetic instability that may hinder nucleation and nanoparticle formation. This phenomenon is seen more clearly in the precursor concentration variation, especially at 0.03 mM Au, as shown in Figures 1B and 2A [21-23].

Variation in precursor concentration showed optimal results at 0.6 mM. Higher precursor concentrations yielded more intense red coloration of the colloids, consistent with UV-Vis data. Reaction time variation, however, showed minimal differences in colloid color.



**Fig. 1.** SPR spectra of AuNPs-CA obtained using a UV-Vis spectrophotometer: (A) variation in bioreductant concentration, (B) variation in gold precursor concentration, (C) variation in synthesis time, (D) variation in reducing agent pH, and (E) variation in synthesis temperature.



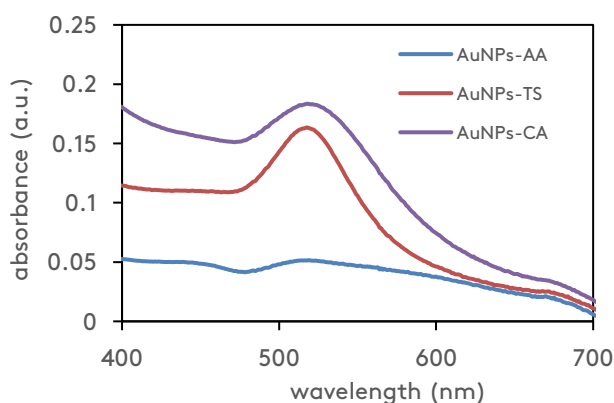
**Fig. 2.** Proposed mechanism illustrating the formation of gold nanoparticles: (A) variation in gold precursor and bioreductant concentrations, and (B) variation in the applied pH.

UV-Vis spectra indicated that nanoparticles were even formed at 2.5 minutes, but in lower quantities. The optimal time was 10 minutes, where sharper spectral peaks appeared. Longer synthesis times eventually led to decreased nanoparticle concentration, likely due to progressive agglomeration during extended heating, as shown in Figure 1C [16]. pH plays a significant role in AuNP stability. At low pH, ascorbic acid is highly reactive and efficiently reduces  $\text{Au}^{3+}$ , whereas under alkaline conditions, its reducing ability decreases

markedly. Although colloidal color alone did not show drastic differences, UV-Vis spectra revealed clear trends: acidic pH produced high yields, and basic pH produced lower yields. pH 7 was chosen as optimal because its spectral peak appeared slightly shifted to the left, indicating smaller nanoparticle size, without sacrificing overall yield (Figures 1D and 2B) [11]. Temperature is another critical factor, as higher temperatures accelerate reaction kinetics and facilitate more frequent collisions between reducing molecules and gold ions.

Although AuNPs can be synthesized without heating, the process requires 24–48 hours. Heating significantly reduces reaction time. UV–Vis results confirmed that increasing the precursor temperature to boiling produced higher yields and more homogeneous nanoparticles [11,16,17]. These findings also suggest that the phytochemicals in *C. aurantifolia* remain stable under heating, as they continued to reduce  $\text{Au}^{3+}$  ions effectively.

Overall, AuNP synthesis using *C. aurantifolia* extract successfully produced high-quality and stable nanoparticles. The synthesis process was simple, safe, non-toxic, renewable, and rapid. The stability of AuNPs-CA was demonstrated by the suspension's resistance to agglomeration for up to one month while maintaining its burgundy color. Compared to the standard Turkevich method (using sodium citrate or ascorbic acid), AuNPs-CA yielded significantly more nanoparticles, even at the same precursor concentration. Although its homogeneity was inferior to citrate-reduced AuNPs, its stability was markedly superior to ascorbic-acid-reduced AuNPs, as demonstrated by UV-vis spectrophotometry results shown in Figure 3 [4]. These findings strongly support the potential of *C. aurantifolia* as an effective biomaterial substitute for synthetic reagents in AuNP synthesis.



**Fig. 3.** Comparison of SPR spectra for AuNPs-AA (ascorbic acid), AuNPs-TS (trisodium citrate), and AuNPs-CA (*C. aurantifolia*).

### 3.2. AuNPs-CA Characterization Study

Characterization was conducted to understand the physicochemical properties of AuNPs produced through the green synthesis process using *Citrus aurantifolia* extract. Spectroscopic analysis,

particle size measurement, surface charge evaluation, and morphology observation provided insight into nanoparticle characteristics, degree of homogeneity, and stabilization mechanisms. The optical properties of the AuNPs were confirmed using UV–Vis spectroscopy, as presented in the previous section. A key indication of successful nanoparticle synthesis is the appearance of an SPR peak around 530 nm. SPR is a unique optical phenomenon that occurs when incident light interacts with the surface electrons of metallic nanoparticles. A narrow and symmetrical SPR peak under optimum conditions indicates uniform particle size and good colloidal stability. The SPR position also provides an indication of nanoparticle size: shorter wavelength absorption corresponds to smaller particle size (wine-red colloid), while longer wavelength absorption (purple colloid) indicates larger nanoparticles, often exceeding 100 nm [3,4]. Following UV–Vis analysis, FTIR characterization was performed because it provides important information regarding the functional groups present in both the *C. aurantifolia* extract and the resulting AuNPs-CA (Figure 4). The FTIR spectrum of the extract shows absorption bands attributed to O–H stretching (around  $3280\text{ cm}^{-1}$ ), alkyne functional groups (around  $2100\text{ cm}^{-1}$ , very weak), and C=C or C=O stretching (around  $1628\text{ cm}^{-1}$ ). Meanwhile, the FTIR spectrum of AuNPs-CA shows similar features: O–H (around  $3272\text{ cm}^{-1}$ ), alkynes (around  $2100\text{ cm}^{-1}$ ), and alkenes (around  $1632\text{ cm}^{-1}$ ). The similarity between the extract and nanoparticle spectra can be explained by the fact that both systems consist predominantly of water, while the extract (10%) and gold precursor (0.6 mM) are present only in minor quantities. Thus, the dominant FTIR absorption is contributed by water, overshadowing other signals [24,25].

Nevertheless, the subtle peaks that do appear reflect the presence of secondary metabolites that participate in nanoparticle formation. These functional groups—originating from phenolics, terpenoids, and alkaloids—remain on the nanoparticle surface, indicating that *C. aurantifolia* extract acts both as a reducing agent and as a stabilizer by forming a capping layer around the nanoparticles [3,9]. Particle size analysis using a PSA revealed that AuNPs-CA have a size distribution in the range of 10–100 nm, with

an average of 35.51 nm (Figure 5A). Two size populations appeared across several synthesis variations. This distribution is consistent with the broader SPR spectra typically observed in green synthesis compared to the more uniform spectra of the Turkevich method. The broader distribution is characteristic of plant-based synthesis due to the diverse biomolecular content, which leads to complex reaction kinetics and varied nucleation rates. Improved extract purification processes may reduce this variability in future work [24]. Zeta potential measurements showed that AuNPs-CA carry a negative surface charge, with an average of  $-23.29$  mV, as shown in Figure 5B. This negative charge contributes to electrostatic repulsion between particles, helping maintain colloidal stability by preventing aggregation. The surface charge originates from phenolic, alkaloid, and terpene groups that surround the nanoparticles.

The presence of electron-rich functional groups is consistent with the FTIR results. While plant-extract-based AuNPs often show variability in zeta potential due to their complex biomolecular matrix, the values obtained remain within a stability range ( $-40$  to  $+40$  mV), confirming that the AuNPs-CA suspension is stable [24]. Morphological analysis using FESEM confirmed that the synthesized nanoparticles are predominantly spherical, although size variation and small aggregates are visible. This morphology aligns with the UV-Vis data, which show a single SPR peak near 530 nm. FESEM images also visually confirm that nanoparticles synthesized under optimal conditions display better uniformity compared to those produced under non-optimal synthesis variations, reinforcing the importance of synthesis parameters in determining nanoparticle quality (Figure 6) [26].

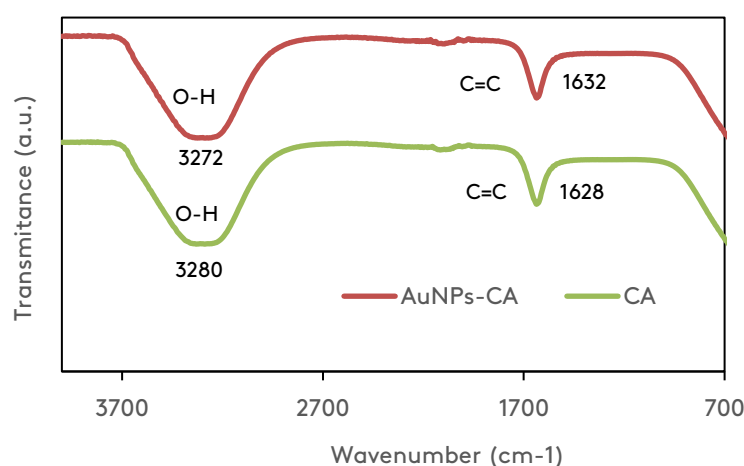


Fig. 4. FTIR spectra of *C. aurantifolia* extract and AuNPs-CA.

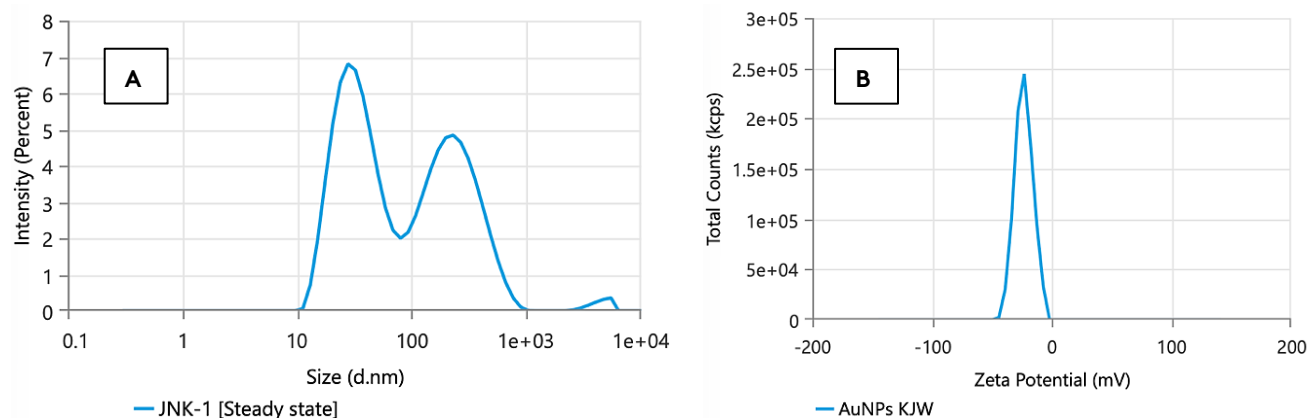
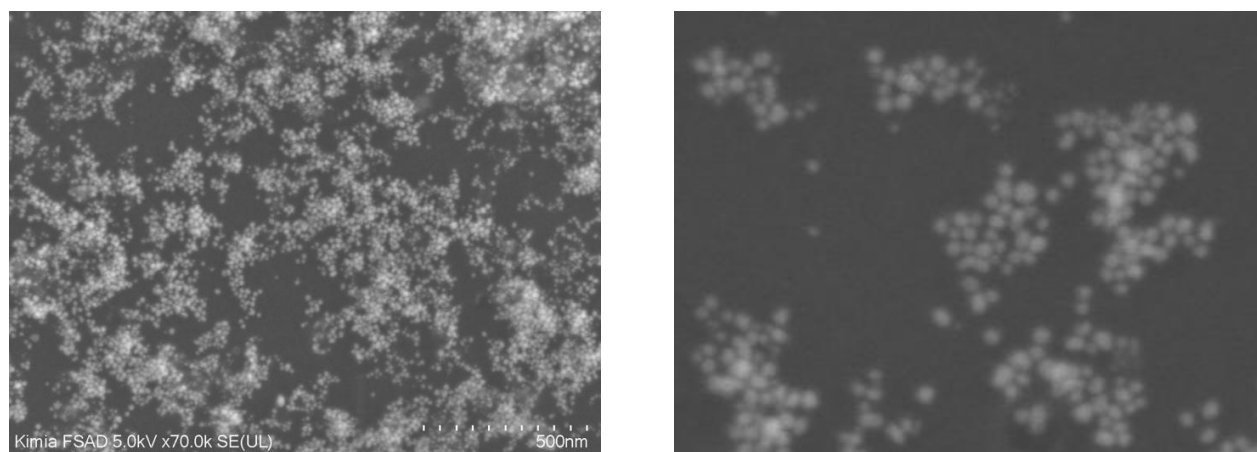


Fig. 5. PSA spectra showing (A) particle size distribution and (B) zeta potential of AuNPs-CA.



**Fig. 6.** Morphology of AuNPs-CA characterized using FESEM.

Overall, the characterization results indicate that *C. aurantifolia* extract is capable of producing AuNPs with suitable optical characteristics, particle size, morphology, and stability for sensing applications. The presence of naturally bound biomolecules on the nanoparticle surface enhances biocompatibility and presents opportunities for selective interactions with target analytes. These physicochemical characteristics form a strong foundation for the implementation of AuNPs in microplastic detection and for evaluating their potential for pesticide sensing, which are discussed in the next subsection.

### 3.3. Microplastic Back-Detection with Acetone

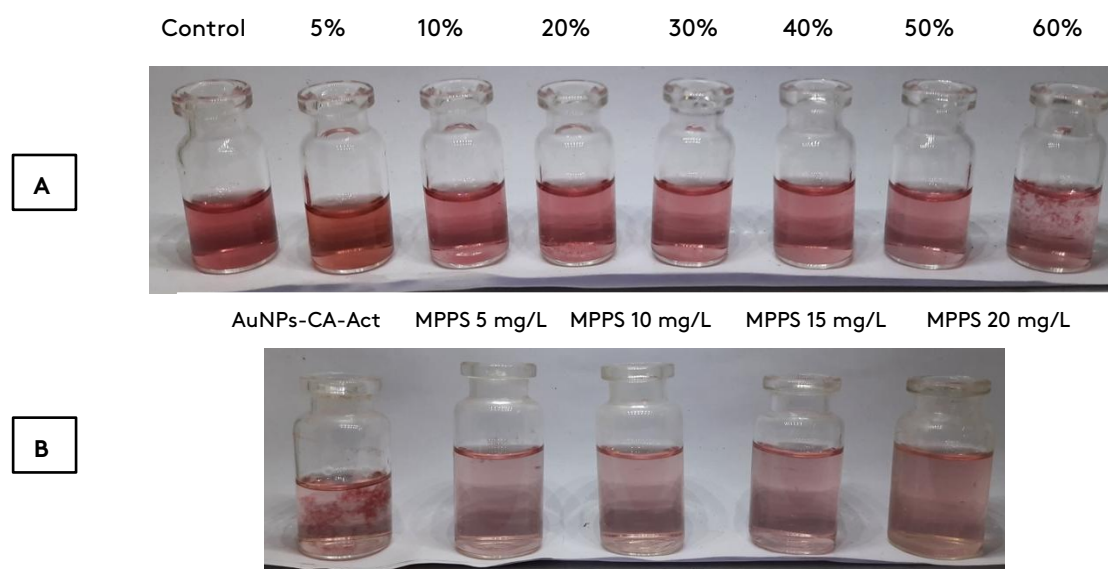
Testing the ability of AuNPs-CA to detect microplastics provides a clear illustration of their potential for environmental monitoring. The microplastic used in this study was polystyrene (PS), one of the most common polymers found in the environment. Microplastics, which are typically composed of hydrophobic polymers, have a low tendency to interact with aqueous media. Consequently, their detection generally relies on instrument-based methods such as FTIR or Raman spectroscopy. The ability of AuNPs-CA to induce precipitation in the presence of microplastics offers a simpler and faster alternative to conventional methods, which are expensive, preparation-intensive, and energy-demanding (Figure 7) [27,28]. This research used the basic logic that stable AuNPs typically require stabilizing agents. Gold nanoparticles synthesized using natural materials often do not require additional stabilizers because their surfaces are naturally coated with

both hydrophobic and hydrophilic components from plant-based matrices. Based on this concept, we deliberately attempted to destabilize AuNPs-CA by introducing a substance capable of inducing agglomeration—acetone. Due to its strong effect on solution polarity, acetone reduces the stability of AuNPs-CA at certain concentrations.

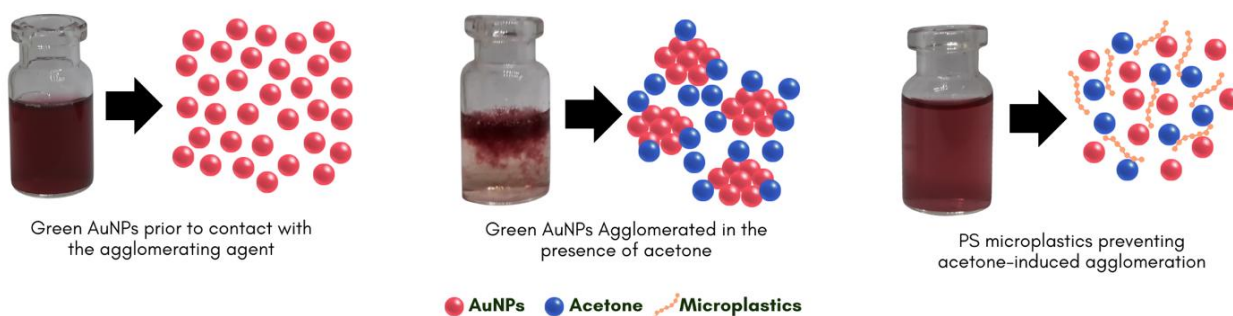
As the fraction of acetone increases, the polarity of the medium shifts away from that of water, weakening solvent-nanoparticle interactions. We varied the acetone volume fraction from 5 to 60% (v/v), and AuNPs-CA began to precipitate at 60% (v/v) [29,30].

After identifying the acetone concentration that induces nanoparticle precipitation, the hydrophobic nature of microplastics was used. Polymers—including microplastics—can act as stabilizing agents for nanoparticles by providing steric hindrance and altering interparticle interactions. When PS microplastics were added at concentrations ranging from 5 to 20 mg/L and subsequently treated with 60% (v/v) acetone, even the lowest concentration of PS microplastics (5 mg/L) was able to maintain the stability of AuNPs-CA. In contrast, the AuNPs-CA control sample (without microplastics) immediately underwent precipitation. These results demonstrate that AuNPs-CA can detect the presence of microplastics at very low concentrations, namely 5 mg/L. We refer to this mechanism as reverse detection, in which microplastics act as stabilizing agents that prevent acetone-induced agglomeration of AuNPs-CA. This back-detection strategy offers a simple, rapid, and accessible approach for identifying

microplastics in aqueous media. The proposed schematic is shown in Figure 8.



**Fig. 7.** (A) AuNPs-CA intentionally contacted with acetone to induce agglomeration, from left to right: control; 5, 10, 20, 30, 40, 50, and 60% (v/v) acetone. (B) Reverse microplastic detection using AuNPs-CA and acetone, from left to right: AuNPs-CA-acetone control and AuNPs-CA with PS microplastics at 5, 10, 15, and 20 mg/L.



**Fig. 8.** Proposed schematic of the precipitation-based detection process using acetone as an agglomerating agent.

### 3.4. Study of the Potential of Pesticide Detection Using AuNPs-CA

The use of AuNPs-CA for pesticide detection demonstrates strong potential for future analytical applications. Previous studies have shown that pesticides can be detected using gold nanoparticles through three primary mechanisms: (i) direct interaction between pesticides and AuNPs, (ii) modification of the AuNP surface with specific ligands, and (iii) chemical preparation of pesticide molecules so that they are more readily attracted to AuNPs. In all approaches, pesticide-induced aggregation typically results in a visible color change from wine-red to purplish blue [14,31,32]. In AuNPs-CA, the nanoparticles are naturally stabilized by secondary metabolites such

as flavonoids, terpenoids, ascorbic acid, and phenolic compounds, which function not only as reducing agents but also as surface-stabilizing ligands.

These biomolecules provide a surface rich in functional groups capable of selectively interacting with various classes of pesticides. However, it is important to note that different plant-derived reducing agents will produce nanoparticles with different surface chemistries, and each pesticide will exhibit unique interaction behavior depending on its molecular structure [14,31,32].

A study by Fahimi-Kashani demonstrated that organophosphate pesticides—such as azinphos-methyl, chlorpyrifos, and phosalone—can directly interact with AuNPs through a combination of

chemical interactions, electrostatic forces, and ionic conformation changes induced by pH variations. These interactions lead to AuNP aggregation, which is visible as a distinct color change [14]. As mentioned earlier, each pesticide generates a specific aggregation pattern depending on environmental conditions and its chemical properties. This analytical behavior forms the basis for selective sensing systems, where sensor preparation conditions may vary depending on the pesticide class. Because AuNPs-CA possess biomolecular surface ligands that are sensitive to environmental changes, it is highly probable that similar direct aggregation mechanisms can be reproduced. Furthermore, the electron-rich surface of AuNPs-CA may interact with polar or partially positive sites on pesticide molecules, enhancing sensing performance [31].

In contrast, Zhao et al. proposed a more advanced method involving enzymatic preparation to improve sensitivity and selectivity. Their system employs acetylcholinesterase (AChE) to generate thiocholine, which binds strongly to AuNPs via Au-S interactions, inducing aggregation and causing the suspension to turn blue. In the presence of organophosphate pesticides, AChE activity is inhibited, reducing thiocholine production and preventing AuNP aggregation, causing the solution to remain red. Conceptually, this preparative strategy mirrors the back-detection method developed in this study for microplastics, where agglomeration behavior is intentionally modulated [32]. Based on these comparisons, AuNPs-CA show strong promise for pesticide detection, especially for simplified sensing formats or device-based applications. Their natural stabilization layer, electron-rich functional groups, and sensitivity to environmental perturbations make AuNPs-CA viable candidates for future development in rapid, low-cost, and environmentally friendly pesticide sensing platforms.

#### 4. Conclusion

This research successfully produced stable, safe, and easily synthesized AuNPs-CA that are capable of detecting PS microplastics and show strong potential as detectors for various classes of pesticides. Optimization of synthesis parameters demonstrated that a 10% extract concentration,

0.6 mM precursor concentration, pH 7, a very short reaction time of 10 minutes, and boiling temperature produced a narrow and intense localized surface plasmon resonance (SPR) peak. Characterization using UV-Vis, FTIR, PSA, zeta potential, and FESEM confirmed that the synthesized AuNPs possessed a predominantly spherical morphology, a size distribution centered at 35.52 nm, and a surface charge of  $-23.29$  mV. This negative charge, originating from surface-bound metabolites, contributed to excellent colloidal stability, as also supported by the FTIR results.

The application of AuNPs-CA for PS microplastic detection using precipitation with acetone as an agglomerating agent demonstrated a rapid and effective response, enabling the detection of microplastics at low concentrations. The back-detection mechanism using acetone allowed microplastics to stabilize AuNPs-CA, making color and stability changes easily observable. In addition, AuNPs-CA show strong potential for pesticide detection through three possible mechanisms: direct detection via van der Waals interactions between AuNPs and pesticide molecules; surface modification to enhance selectivity; and enzymatic preparation methods that rely on Au-S interactions, analogous to established AChE-based systems.

Overall, the findings of this study demonstrate that the green synthesis of AuNPs using *C. aurantifolia* extract provides not only a sustainable and economical production route but also yields nanoparticles with physicochemical characteristics suitable for microplastic detection and highly promising for pesticide sensing applications.

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#### Author's contribution

**Muhammad Bakhru Thohir:** Conceptualization, Methodology, Data Collection, Data Curation, Visualization, Writing—Original Draft, and Analysis. **Grasianto Grasianto:** Methodology, Data Collection, Review, Editing, and Analysis. **Anggi Tri**

**Nurhaliza:** Editing and Data Collection. **Heru Dwi Lestari:** Visualization and Data Collection. All authors have read and approved the final version of the manuscript.

### Conflict of interest

No potential conflict of interest was reported by the authors.

### Data availability

Not Applicable.

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