

Detection of Malathion in Eggplant Using a Plasmonic Sensor Based on Gold Nanobipyramids

Andhini Zafira*, Iwantono

Universitas Riau, Indonesia

Email: andhini.zafira0186@student.unri.ac.id*, iwantono@lecturer.unri.ac.id

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Abstract

Malathion is an organophosphate pesticide that is widely used in agriculture, but excessive use can leave harmful residues on food products and the environment. This research aims to develop a plasmonic sensor based on gold nanobipyramids (GNBPs) to detect malathion residues in eggplant (*Solanum melongena* L.). GNBPs were synthesized using the seed-mediated growth method and characterized using UV-Vis spectroscopy, X-ray diffraction (XRD), and field emission scanning electron microscopy (FESEM). The UV-Vis spectrum shows peaks of transverse and longitudinal localized surface plasmon resonance (LSPR) in the range of 500–600 nm and 700–900 nm, indicating the formation of anisotropic structures of GNBPs. Variations in growth time affect the optical properties of nanoparticles, with optimal conditions obtained at a growth time of 2 hours. Sensitivity testing showed a decrease in absorbance intensity of approximately 17.8% after interaction with eggplant extract containing malathion, demonstrating changes in the plasmonic response of GNBPs. In addition, repeatability and stability testing showed consistent and stable sensor responses during repeated measurements. The results show that GNPB-based plasmonic sensors have good potential for rapid and sensitive detection of pesticide residues in agricultural products. In conclusion, the GNPB-based plasmonic sensor exhibits high sensitivity, good repeatability, and excellent stability, making it a promising rapid detection tool for malathion residues in agricultural products.

INTRODUCTION

The use of pesticides in modern agriculture is one of the main factors contributing to increased crop yields, but it is also a serious threat to food security and human health (Gupta, 2023; Wahab et al., 2022). Pesticide residues can seep into the food chain and cause a variety of health problems (Gai et al., 2023). Organophosphate pesticides are known to be neurotoxic because they are able to inhibit the enzyme acetylcholinesterase (Selvolini et al., 2018). In addition, pesticide residues in the environment are a source of contamination that needs to be monitored effectively (Feng et al., 2025). Therefore, fast, sensitive, and accurate detection methods are needed to ensure food and environmental safety. Conventional methods such as gas chromatography (GC) and high-performance liquid chromatography (HPLC), especially in combination with mass spectrometry (GC–MS/LC–MS), have high sensitivity and selectivity (Wahab et al., 2022; Umer et al., 2025), but require complex sample preparation, high cost, long analysis time, and reliance on laboratory equipment and experts (Gai et al., 2023).

Alternatively, nanomaterials-based nanosensors, especially gold nanoparticles (AuNPs), are growing rapidly as they offer high sensitivity, fast response, and potential in situ applications for monitoring environmental contaminants (Feng et al., 2025; Wang et al., 2024).

The unique optical properties of AuNPs, especially localized surface plasmon resonance (LSPR), allow their use in colorimetric sensors, surface-enhanced Raman scattering (SERS), and electrochemical sensors to improve signal intensity and electron transfer efficiency (Altaf et al., 2024; Li et al., 2018; Huang et al., 2020; Liu et al., 2026). The plasmonic effects of AuNPs, including the formation of SERS hotspots due to the distribution and spacing between particles, are known to improve detection sensitivity (Ghanashyam et al., 2025; Tu et al., 2026). The performance of AuNPs-based nanosensors is strongly influenced by the morphology of nanoparticles, such as spherical AuNPs, nanorods, nanostars, core-shell structures, and bimetallic nanostructures (He et al., 2019; Liu et al., 2022; Moram et al., 2023; Ke et al., 2023; Xu et al., 2023). These various morphologies affect the plasmonic properties, active surface area, electron transfer efficiency, and sensor sensitivity and detection limits (Huang et al., 2020; Iwantono et al., 2024; Jammee et al., 2026).

Plasmonic nanostructures with elongated morphologies, such as gold nanobipyramids (GNBPs), attract attention because they have tunable surface plasmon resonance. The sharp tip structure of GNBPs is capable of producing strong local electron fields as well as sharper LSPR peaks than gold nanorods, thus providing higher refractive index sensitivity for plasmonic sensor applications (Nafisah et al., 2021). In addition, GNBPs are known to have a high plasmonic quality factor and are able to amplify local electromagnetic fields (Hanqi et al., 2022). Previous research has reported the use of gold nanoparticles for the detection of pesticide residues using UV-Vis and Raman spectroscopy with good sensitivity. Iwantono et al. (2022) developed a gold nanoparticle-based biosensor for the detection of chlorpyrifos residues in lettuce with a sensitivity of 0.1 ppm and 95% accuracy, while follow-up research demonstrated the effectiveness of GNBPs in Raman spectroscopy for rapid detection of pesticide residues with up to 10-fold signal enhancement (Iwantono et al., 2024; Iwantono et al., 2025).

Eggplant (*Solanum melongena* L.) is one of the food crops that is susceptible to pest attacks, so the use of pesticides, including malathion, is still widely used by farmers. Excessive use of pesticides can leave harmful residues on food products and the environment (Tudi et al., 2021). Malathion is an organophosphate insecticide that is widely used in the agricultural sector and can accumulate in living organisms (Toropova et al., 2023). Therefore, this study aims to utilize gold nanobipyramids as plasmonic nanosensors to detect malathion insecticide residues in eggplants. The synthesis of GNBPs is carried out using the seed-mediated growth (SMG) method because this method has a simple procedure and allows control of the morphology of nanoparticles (Nafisah et al., 2021). Growth time variations were used to study their effect on morphology, LSPR position, sensitivity, and sensor performance in malathion detection. This research offers a rapid, sensitive, and cost-effective GGBP-based plasmonic sensor for on-site malathion detection in eggplant, contributing to food safety and the development of nanosensor technology for agricultural contaminants.

RESEARCH METHOD

Material

Materials used in the synthesis of gold nanobipyramids (GNBPs) include gold(III) chloride hydrate ($\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$), chlorplatinic acid ($\text{H}_2\text{PtCl}_4 \cdot \text{H}_2\text{O}$), cetyltrimethylammonium bromide ($\text{CTAB} \geq 99\%$), sodium borohydride (NaBH_4), ascorbic acid

(C₆H₈O₆), silver nitrate (AgNO₃≥99.5%), and hydrochloric acid (HCl). All chemical solutions are prepared using de-ionized water (DIW). Before use, the entire glassware is washed using decon and water. Next, the glassware is sonicated in DIW for 15 minutes. The sonication process is repeated using ethanol and DIW in succession. After that, the glassware is dried in the oven at 60 °C for 1 hour. The pesticide malathion was used as the target analyte, while eggplant (*Solanum melongena* L.) was used as a test sample.

Sintesis

The synthesis of anisotropic nanomaterials uses the Seed-Mediated Growth (SMG) method which consists of two main stages, namely seed formation and the growth process. At the seed formation stage, small nanoparticles (seeds) are synthesized through the reduction method as nucleation centers for the formation of larger nanomaterial structures. The seed formation process is carried out by mixing 0.15 mL (HAuCl₄·3H₂O) 0.01 M and 0.1 mL (H₂PtCl₄) 0.01 M into 9.75 mL (CTAB) 0.1 M, then gently whipped until a homogeneous solution. Next, as much as 0.9 mL (NaBH₄) 0.01 M that had been cooled in ice was added to the solution and gently shaken. The seed formation process is carried out for 2 hours at room temperature.

In the growth stage, seed nanoparticles are developed into larger or more complex structures through the addition of metal ions or other precursors that undergo reduction and deposition on the surface of the seed. The growth process is carried out by sequentially adding 0.875 mL (HAuCl₄·3H₂O) 0.01 M, 0.025 mL (H₂PtCl₄) 0.01 M, 0.2 mL (AgNO₃) 0.01 M, 20 mL CTAB 0.1 M, 0.4 mL (HCl) 1 M, and 0.16 mL (C₆H₈O₆) 0.1 M. The solution is then gently shaken before adding 0.05 mL of pre-prepared seed solution. The mixture is then left undisturbed for 2 hours.

Characterization

Characterization of the optical properties, crystal structure, and surface morphology of gold nanobipyramids (GNBPs) was carried out using several characterization techniques. Analysis of optical properties was performed using Ultraviolet-Visible Spectroscopy (UV-Vis) in the wavelength range of 200–1000 nm to observe the absorbance and response characteristics of the Localized Surface Plasmon Resonance (LSPR) of GNBPs (Sukelan et al., 2024). Crystal structure characterization was carried out using X-Ray Diffraction (XRD) at an angle range of 2θ of 20°–60° to determine the crystal phase and the level of crystallinity of the material (Huynh et al., 2023). Meanwhile, surface morphology and particle shape analysis was carried out using the Field Emission Scanning Electron Microscope (FESEM) with magnification of 50,000× to 100,000× (Sukelan et al., 2024).

Target analysis preparation

The target analysis was prepared by applying malathion to eggplant plants (*Solanum melongena* L.) aged 3 weeks. A total of 0.2 g of malathion was dissolved in 500 mL of DIW to produce an insecticide solution. After the pesticide application process, eggplant fruits are harvested and processed for systemic malathion residue analysis. The eggplant fruit sample is mashed until homogeneous, then filtered and 30 mL of DIW is added. The results of the analysis showed a concentration of systemic malathion residue of 3598 ppm before further testing was carried out using a plasmonic sensor. The high concentration of malathion residues obtained is thought to be due to a systemic application mechanism, in which the pesticide is

not only on the surface of the plant but also absorbed into the plant tissue. These conditions lead to higher residue accumulation in eggplant extract samples used in sensor testing.

LSPR sensor testing

After a 2-hour growth process, GNBP are used as sensing materials on LSPR sensors. Sensor testing was carried out using a system consisting of a light source, cuvette holder, spectrometer, and computer equipped with Ocean View software. The GNBP-based sensor is then tested using pre-prepared analytes. During testing, the sensor is placed on the test cell and illuminated with light. The spectrum response is observed through changes in absorbance intensity at a given wavelength indicating the interaction between the analyte and the nanoparticle surface. The shift in localized surface plasmon resonance (LSPR) is affected by changes in the local refractive index around the nanoparticles due to the adsorption of analyte molecules on the sensor surface. In addition, anisotropic nanoparticles such as GNBP have transverse and longitudinal modes that are sensitive to changes in the dielectric environment, making them effective in LSPR-based plasmonic sensor applications. These characteristics allow for increased detection sensitivity to changes in the local environment around the nanoparticles (Tian et al., 2020; Dos Santos et al., 2021).

RESULTS AND DISCUSSION

Optical Characteristics, Structure, and Morphology of GNBP

Characterization of GNBP was carried out using UV-Vis spectroscopy, FESEM, and XRD to evaluate the optical properties, morphology, and crystal structure of the nanoparticles formed. The effect of growth time variation on the formation of GNBP was analyzed based on changes in the plasmonic spectrum, particle shape, and crystal diffraction pattern.

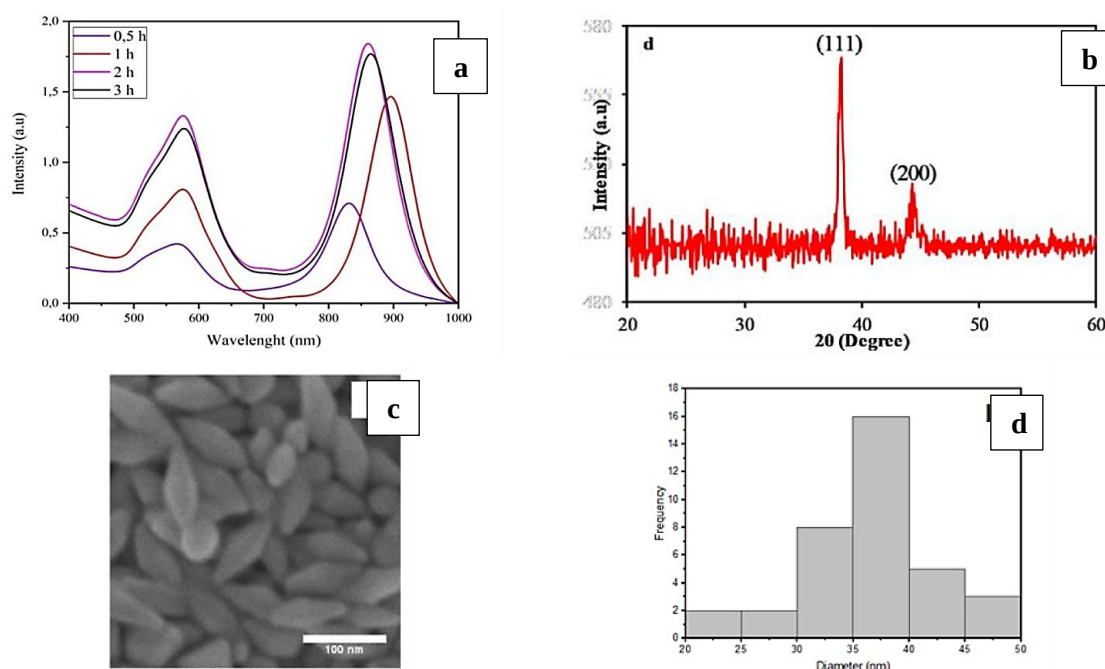


Fig 1. (a) Spektrum UV-Vis, adapted from Iwantono et al. (2024); (b) pola XRD, adapted from Nafisah et al. (2021); (c) citra FESEM, adapted from Iwantono et al. (2024); dan (d) histogram of the distribution of GNBP sizes, adapted from Iwantono et al. (2024).

Source: Research data, 2026

The UV-Vis spectrum in Figure 1(a) shows the absorbance distribution of GNBPs at various growth times, namely 0.5 hours, 1 hour, 2 hours, and 3 hours. The spectrum shows two plasmonic bands related to transverse surface plasmon resonance (t-SPR) in the range of 500–600 nm and longitudinal surface plasmon resonance (l-SPR) in the range of 700–900 nm, indicating the formation of anisotropic structures of GNBPs. As the growth time increases, the intensity of absorbance increases and reaches a maximum at a growth time of 2 hours, indicating a more optimal formation of bipyramidal structures. However, at the 3-hour growth time, there was a slight decrease in intensity which was thought to be caused by morphological changes, increased nanoparticle density, and changes in the aspect ratio of GNBPs during the growth process. The changes affect the plasmonic response and optical properties of nanoparticles. Therefore, a growth time of 2 hours is chosen as the optimal condition for advanced characterization and sensor applications.

Table 1. Absorbance values of t-SPR and l-SPR GNBPs at growth time variation

Growth Time	t-SPR (nm)	l-SPR (nm)
0,5jam	~570	~830
1 jam	~580	~900
2 jam	~580	~880
3 jam	~575	~870

Source: Research data, 2026

The XRD pattern in Figure 1(b) shows the peak of the main diffraction at an angle of 2θ of about 38° and 44° . The peak at $2\theta \approx 38^\circ$ corresponds to the crystal plane (111) of gold (Au), while the other peak indicates another crystalline plane corresponding to the face-centered cubic structure (FCC) typical of gold (Nafisah et al., 2021). The sharp and clear peak intensity indicates good crystallinity of the nanoparticles as well as confirms the successful synthesis of GNBPs. The dominance of the peak (111) indicates that crystal growth tends to occur in the field during the synthesis process.

Figure 1(c) shows the FESEM image of GNBPs that were successfully synthesized using *the seed-mediated growth method*. The morphology of the nanoparticles shows a bipyramidal structure with a relatively homogeneous particle distribution and a low agglomeration rate. Anisotropic structures with sharp tips are clearly visible, which indicates the success of longitudinal growth of nanoparticles during the synthesis process. In addition, the bipyramidal shape that forms has the potential to result in high local electromagnetic field reinforcement due to charge accumulation in areas with high curvature. Based on the histogram of the size distribution in Figure 1(d), most GNBPs have diameters in the range of 35–40 nm. The relatively narrow size distribution indicates a fairly uniform and stable growth of the nanoparticles.

Performance of GNBPs-Based LSPR Sensors

The evaluation of sensor performance includes three main parameters, namely sensitivity, stability, and repeatability. Sensitivity indicates the sensor's ability to detect changes in the concentration of the analyte through changes in the analytical signal. Stability describes the sensor's ability to maintain a consistent response during testing, while repeatability indicates the consistency of measurement results under the same conditions over

and over again. Evaluation of these three parameters is important to ensure the reliability and performance of the sensor in practical applications. The following figure shows the results of the sensitivity, stability, and repeatability tests of the developed sensor.

1. Sensitivity

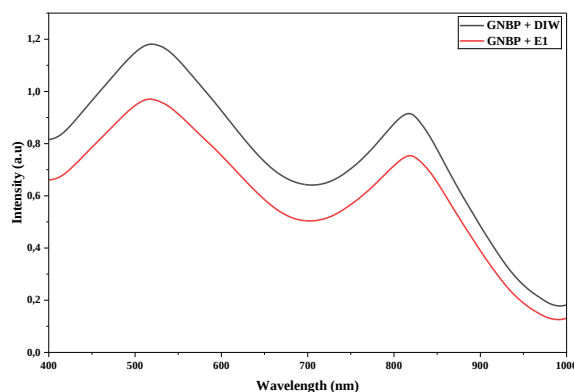


Figure 2. Sensitivity GNPB

Source: Research data, 2026

Figure 3 shows the spectrum of absorbance of gold nanobipyramids (GNBPs) in the DIW medium and E1 extract. Both samples showed two main absorption peaks in the visible to near-infrared regions that showed the LSPR characteristics of GNBPs. GNBPs + DIW samples had a higher absorbance intensity than GNBPs + E1 over the entire wavelength range. The main peak of GNPB+DIW appears at about 520 nm with an intensity of about 1.18 a.u., while GNPB+E1 shows a lower intensity, which is about 0.97 a.u. In addition, the second peak appears at about 810 nm related to the longitudinal mode of plasmon resonance of anisotropic nanoparticles.

A decrease in absorbance intensity after the addition of E1 extract indicates an interaction between biomolecules and malathion residues with the surface of GNBPs. These interactions cause changes in the dielectric environment and local refractive index around the nanoparticles, thus influencing the plasmonic response. Nonetheless, the peak position of absorbance remains relatively stable, indicating that the anisotropic structure of GNBPs is maintained after interaction with the extract. The intensity of GNBPs + E1 absorbance decreased by around 17.8% compared to GNBPs + DIW. In addition, the anisotropic morphology of GNBPs with sharp tips also increases sensor sensitivity through local electromagnetic field amplification.

Overall, these results suggest that the dispersing medium has a significant influence on the optical properties and plasmonic response of GNBPs. Higher intensities in DIW indicate stronger plasmonic resonance, while decreased intensity in E1 indicates successful interactions between extract compounds and nanoparticle surfaces.

2. Repeatability

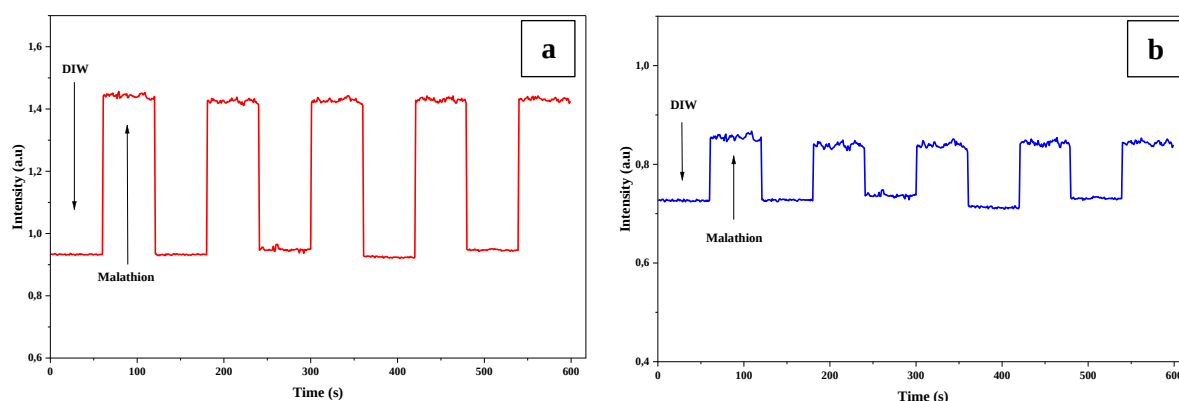


Figure 3. Repeatability GNBPs (a) t-SPR GNBPs (b) l-SPR GNBPs

Source: Research data, 2026

The results of the repeatability tests in Figures 3(a) and (b) show that the GNBPs sensor is capable of producing a consistent response over multiple repeated measurement cycles. The change in intensity during the transition of the medium from DIW to malathion showed a relatively uniform response pattern at each repetition. The t-SPR GNBPs sensor exhibits a higher intensity change than the l-SPR GNBPs, which indicates a stronger sensitivity of the plasmonic response to the presence of malathion. Meanwhile, the l-SPR GNBPs sensor still shows good signal stability even with lower intensity changes. The consistency of the response on both sensors indicates good repeatability as well as stable malathion detection capability under the same test conditions. These results show that GNBPs sensors have good reliability for repeated plasmonic sensor applications.

3. Stability

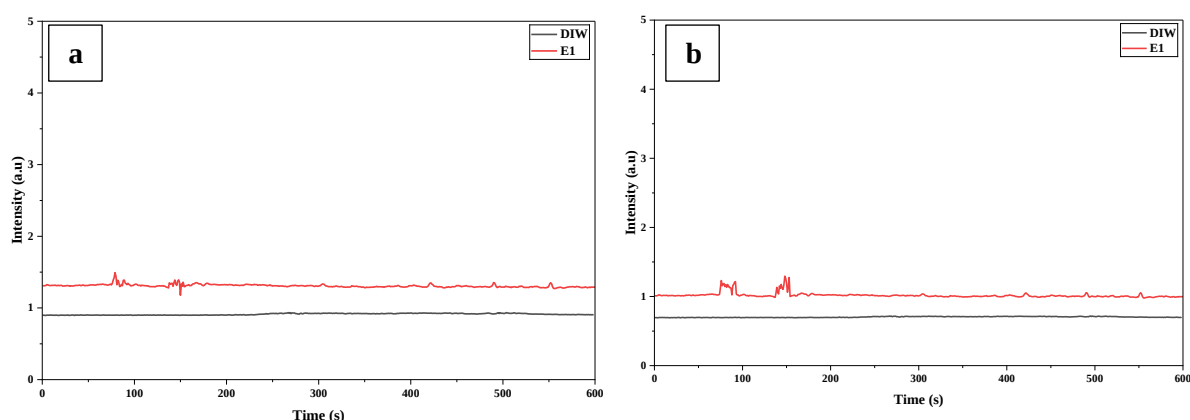


Figure 4. Stability GNBPs (a) t-SPR GNBPs (b) l-SPR GNBPs

Source: Research data, 2026

Figures 4(a) and (b) show the results of the GNBPs sensor stability test at the peak of transverse surface plasmon resonance (t-SPR) and longitudinal surface plasmon resonance (l-SPR). Tests were performed to evaluate the stability of the sensor's plasmonic response to the DIW medium and E1 extract during the observation time. Based on the measurement results,

both sensors showed relatively stable intensity of up to 600 s with small signal fluctuations. In the t-SPR GNPB sensor, the intensity of GNPB+E1 was seen to be higher than that of DIW with a constant response pattern, while the l-SPR GNPB sensor also showed good signal stability despite slight fluctuations at the beginning of the measurement. The stability of this response suggests that the interaction between the analyte and the surface of the GNBPB occurs consistently without a significant decrease in plasmonic performance. These results indicate that GNPB sensors have good stability and have the potential to be used in plasmonic sensor applications with reliably repeated measurements.

CONCLUSION

This research has succeeded in developing a plasmonic sensor based on gold nanobipyramids (GNBPB) for the detection of malathion residues in eggplant (*Solanum melongena* L.). Characterization of UV-Vis, XRD, and FESEM showed the successful synthesis of GNPBs with anisotropic structure and good localized surface plasmon resonance (LSPR) response. Variations in growth time affect the optical properties of the nanoparticles, with optimum conditions obtained at a growth time of 2 hours.

Sensitivity testing showed a 17.8% decrease in absorbance intensity after interaction with eggplant extract containing malathion. In addition, repeatability and stability tests show consistent and stable sensor response during repeated measurements. These results show that GNPBs-based sensors have good potential for rapid and sensitive pesticide residue detection applications. Further research can be focused on testing malathion concentration variations and additional characterization to improve sensor performance.

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