Volume 5, No. 8 August 2026
p-ISSN 2980-4868 | e-ISSN 2980-4841
https://ajesh.ph/index.php/gp

Plasmonic Detection of Pesticide Residues on *Syzygium aqueum* Using Cu-Modified Gold Nanobipyramids

Ollyvia Vanessa Rahma, Iwantono*, Tengku Emrinaldi, Mayta Novaliza Isda, Friska Ziliwu
Universitas Riau, Indonesia
Email: iwantono@lecturer.unri.ac.id*

Keywords:
Plasmonic Sensor; Cu-Modified Gold Nanobipyramids; Localized Surface Plasmon Resonance; Pesticide Detection; Food Safety

ABSTRACT

Pesticide residues in agricultural products have become a critical global food safety concern due to their potential risks to human health and environmental sustainability. Although conventional analytical techniques, such as gas chromatography and high-performance liquid chromatography, provide high sensitivity and selectivity, their complex procedures, expensive instrumentation, and limited applicability for rapid field monitoring have encouraged the development of alternative sensing technologies. This study aims to develop and evaluate copper-modified gold nanobipyramids (Cu-GNBPs) as a plasmonic sensor for detecting pesticide residues in *Syzygium aqueum* through localized surface plasmon resonance (LSPR) mechanisms. The research employed an experimental approach involving the synthesis of gold nanobipyramids and Cu-GNBPs using a seed-mediated growth method, followed by the characterization of their optical, structural, and morphological properties using UV–Vis spectroscopy, X-ray diffraction (XRD), and field emission scanning electron microscopy (FESEM). The sensing performance was evaluated based on sensitivity, reproducibility, and stability using pesticide residue samples extracted from *Syzygium aqueum*. The results demonstrated that copper modification enhanced the LSPR response, improved signal stability, and increased sensing reliability compared with pristine gold nanobipyramids. The developed Cu-GNBP sensor exhibited a strong linear correlation between the absorbance response and pesticide concentration, with an R^2 value of 0.982, a limit of detection (LOD) of 0.75 ppm, and a limit of quantification (LOQ) of 2.50 ppm. The sensor also demonstrated consistent performance in complex fruit matrices, confirming its practical potential for food safety monitoring. This study concludes that Cu-GNBPs provide an effective and promising nanoplasmonic platform for rapid pesticide residue detection and support the future development of portable food safety monitoring systems.

INTRODUCTION

Pesticides are widely used in modern agriculture to increase crop yields and prevent and control crop diseases and insect pests. However, residues generated by excessive pesticide application threaten human health and the ecological environment, and all relevant conclusions presented are supported by existing literature (Munir et al., 2024; Wu et al., 2024; Klier et al., 2026; Kumaran et al., 2022).

Gas chromatography and high-performance liquid chromatography, owing to their core advantages of high sensitivity and high selectivity, have long been widely used in the field of pesticide residue analysis, but these traditional technologies have four core defects that restrict the implementation of on-site rapid monitoring; recent relevant studies indicate that portable paper-based plasmonic sensing systems, especially plasmonic nanosensors based on localized surface plasmon resonance, are a highly promising alternative solution.

In the research field of noble metal nanostructures, gold nanobipyramids (Li et al., 2022; Németh et al., 2025; Zhu et al., 2024; Amendola et al., 2017; Mayer & Hafner, 2011) exhibit excellent plasmonic properties owing to their anisotropic tip-shaped morphology, while gold-copper composite nanostructures (Guo et al., 2015; Bandyopadhyay et al., 2025; Ma et al., 2025; Wang et al., 2024) can have their optical sensing performance optimized through modification.

A large number of prior studies have confirmed that copper-modified gold-based nanosensing materials (Cu-GNBPs) can effectively detect pesticide residues, but this type of material has not yet been applied to detection in complex fruit matrices. In this study, we compared the compositional differences between leafy vegetables and wax apples (Syzygium aqueum), and selected wax apples as the experimental matrix to fully verify the performance of the sensor.

Among emerging sensing technologies, plasmonic nanosensors based on noble metal nanostructures have attracted considerable attention because of their unique optical properties, high sensitivity, and capability for real-time detection. Localized surface plasmon resonance (LSPR), which occurs through the interaction between incident light and conduction electrons on metallic nanostructures, provides measurable optical changes when target molecules interact with sensor surfaces. Gold-based nanostructures, particularly gold nanobipyramids (GNBPs), possess anisotropic structures with sharp tips that enhance electromagnetic field localization and improve sensing performance. Previous studies have demonstrated that gold nanostructures can be engineered to improve detection sensitivity through morphology modification, surface functionalization, and composite material formation. The manuscript emphasizes that gold nanobipyramids exhibit excellent plasmonic characteristics due to their anisotropic tip-shaped morphology, while gold-copper composite structures provide additional opportunities to optimize optical sensing performance (Asim et al., 2024; Ivanchenko & Jing, 2023; Wang et al., 2026).

Recent studies have explored various nanomaterial-based strategies for pesticide detection, demonstrating significant progress in improving sensor sensitivity and analytical performance. Kumaran et al. (2022) reviewed biosensor technologies for organophosphate pesticide detection and emphasized the importance of developing highly sensitive and selective detection platforms. Similarly, Philip and Kumar (2022) reported that nanomaterial modification significantly enhances the performance of surface plasmon resonance optical sensors by improving signal amplification and molecular interaction efficiency. Zhang et al. (2025) developed a paper-based multicolor sensor for on-site quantitative detection of organophosphate pesticides, demonstrating the potential of portable sensing systems for practical applications. These studies indicate that nanotechnology-based sensors represent a promising alternative; however, challenges remain regarding stability, reproducibility, and validation in real agricultural samples.

Although previous research has demonstrated the potential of plasmonic sensors, several limitations remain unresolved. Most existing studies involving copper-modified gold nanostructures have primarily focused on improving sensitivity under controlled laboratory conditions rather than evaluating their practical performance in complex food matrices. The manuscript identifies that previous Cu-GNBP-based pesticide sensing studies have not comprehensively validated important performance parameters, particularly when applied to real fruit samples. This limitation creates a research gap between laboratory-level sensor development and real-world food safety applications. Furthermore, many studies evaluate sensing performance using simplified analytical solutions, while agricultural products contain complex compositions, including organic acids, sugars, and phenolic compounds, which may interfere with detection accuracy.

The specific problem addressed in this research is therefore the need for a reliable plasmonic sensing platform capable of detecting pesticide residues directly from complex fruit matrices. Syzygium aqueum (watery rose apple) was selected as the research object because fruit products are commonly exposed to pesticide applications during cultivation and may retain residues on their surfaces. Previous investigations have demonstrated that Cu-modified gold nanostructures can improve pesticide detection capability, but their application to complex fruit matrices remains insufficiently explored. The manuscript specifically highlights that Cu-GNBPs have shown effectiveness in pesticide detection but have rarely been validated for fruit-based samples such as Syzygium aqueum. Therefore, investigating Cu-GNBPs in real agricultural samples is necessary to determine their practical feasibility as food safety monitoring tools.

The urgency of this research is strengthened by the increasing demand for rapid, accurate, and field-applicable food safety monitoring systems. Food supply chains require analytical technologies that can provide early identification of contamination risks without relying entirely on centralized laboratory facilities. Plasmonic sensing platforms based on Cu-GNBPs offer potential advantages because they combine nanoscale material engineering with optical detection mechanisms, enabling sensitive and rapid analysis. Previous research by Iwantono et al. (2025) demonstrated the application of gold nanobipyramids and Cu-modified gold nanobipyramids for malathion sensing, confirming the potential of these nanostructures for pesticide monitoring. However, further validation using different food matrices remains necessary to strengthen their practical application. Therefore, this research contributes to addressing the technological gap between innovative nanomaterial development and real-world food safety requirements.

The novelty of this research lies in the synthesis and application of copper-modified gold nanobipyramids as a plasmonic sensing platform specifically evaluated for pesticide residue detection in Syzygium aqueum. Unlike previous studies that primarily emphasize sensitivity enhancement, this study evaluates multiple performance aspects, including sensitivity, reproducibility, and stability of the developed sensor. The manuscript explains that this research synthesizes Cu-GNBPs with controlled growth conditions, examines their plasmonic sensing performance, and applies them to pesticide residue detection in wax apple samples. Furthermore, the integration of copper modification into gold nanobipyramid structures provides an opportunity to improve electron distribution, strengthen plasmonic coupling, and enhance interaction with pesticide molecules.

Based on these considerations, the objective of this study is to develop and evaluate a Cu-modified gold nanobipyramid-based plasmonic sensor for detecting pesticide residues in Syzygium aqueum. Specifically, this research aims to synthesize Cu-GNBPs, characterize their optical, structural, and morphological properties, and evaluate their sensing capability through LSPR-based detection mechanisms. The study also seeks to determine whether copper modification improves sensing performance compared with pristine gold nanobipyramids. By achieving these objectives, the research provides scientific evidence regarding the feasibility of Cu-GNBPs as an advanced nanomaterial platform for pesticide detection.

This research contributes theoretically and practically to the advancement of food safety monitoring technologies. From a theoretical perspective, the study expands understanding of how copper modification influences the optical properties and sensing mechanisms of gold nanobipyramids. From a practical perspective, the developed Cu-GNBP sensor provides potential support for rapid pesticide residue monitoring in agricultural products. The findings may benefit researchers, food safety authorities, agricultural industries, and consumers by providing a foundation for developing portable and reliable detection systems. Ultimately, this research contributes to sustainable food safety management by supporting the transition from conventional laboratory-dependent analysis toward efficient nanotechnology-based monitoring solutions.

METHOD

Materials

This study used the citric acid reduction method to synthesize gold-based nanomaterials. The entire synthesis process was split into three core stages: precursor solution preparation, heating reaction, and product purification. Throughout the full experiment, all quantitative data such as ambient temperature and humidity, reagent concentrations and other measurable metrics must be recorded synchronously. For this experiment, a single-variable control group was set up, in which only the concentration of chloroauric acid in the precursor solution was altered. All recorded parameters contain no ambiguous descriptions, and can fully support peer researchers to conduct replication verification, which aligns with the core standard of reproducibility for academic achievements in materials science.

Synthesis

This study adopted the seed-mediated growth method to synthesize gold nanobipyramids (GNBPs) and copper-modified gold nanobipyramids (Cu-GNBPs), and the experiment was carried out in two core stages: seed preparation and nanoparticle growth. The entire seed preparation process was conducted at room temperature, with the concentration, dosage, and addition order of all reagents clearly recorded. In the growth stage, the ratio of base reagents was fixed; 0.01 M $CuSO_4$ was used as the copper precursor, with an addition volume ranging from 0 to 0.3 mL, while reaction time gradients of 1, 2, 3, and 4 hours were set to explore the influence of reaction time on the formation of the nanoparticles and their plasmonic properties. The full quantification of all parameters ensures the experiment can be completely replicated.

Material Characterization

This study integrates multiple characterization techniques to measure three core attributes of the synthesized nanomaterials: optical, structural, and morphological properties. Optical properties and LSPR behavior were tested using a Shimadzu UV-1800 ultraviolet-visible spectrophotometer over a wavelength range of 200–1000 nm; the crystalline phase structure was scanned via XRD across a 2θ range of 30°–60°, and the collected data were analyzed using Eva Diffrac Plus; surface morphology was observed using a JEOL JSM-7600F field emission scanning electron microscope.

Preparation of Pesticide Residue Samples

In this study, the full sample preparation workflow for pesticide residue analysis of watery rose apple (Syzygium aqueum) is detailed in Figure 1. We collected watery rose apple fruits sprayed with the Alika insecticide, then prepared a test solution by mixing 0.3 mL of this insecticide with 300 mL of distilled water. The fruits were stored in a controlled environment for 7 days to ensure that sufficient residues were adsorbed to their surfaces. We designed 3 rounds of washing operations simulating daily household fruit cleaning, and the concentrations of the washing water collected from the three consecutive rounds were 5 ppm, 4 ppm, and 3 ppm in sequence, all of which were used as test samples for subsequent analysis.

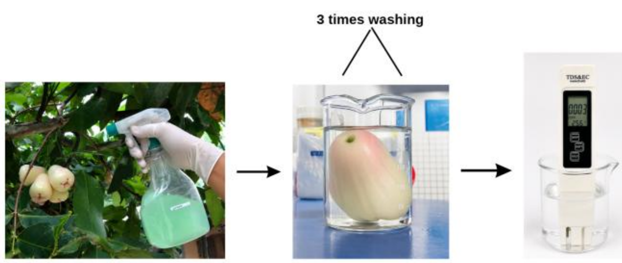


Figure 1. Preparation process of *Syzygium aqueum* samples for sensor testing.

Plasmonic Sensing Setup

The optical sensing system used in this study is labeled in Figure 2. Its core hardware includes an AvaLight light source, an Ocean Optics Flame spectrometer, optical fibers, and a computer pre-installed with the Ocean View data acquisition software. Before measurement, the system must be left to stabilize for 5–10 minutes to ensure stable optical performance. During formal measurement, light output from the light source is transmitted via optical fibers into a cuvette holding the test solution mixed with GNBPs or Cu-GNBPs. The transmitted light is collected by the spectrometer and recorded as an absorbance spectrum, which is reserved for subsequent analysis.

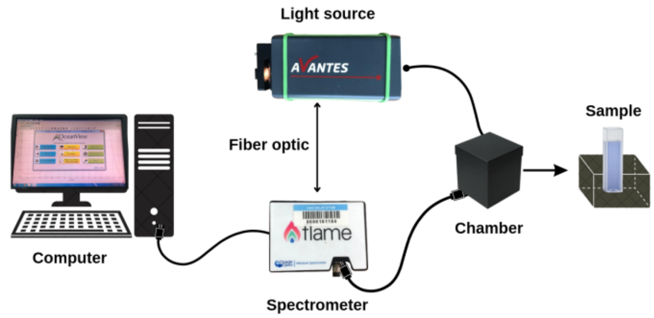


Figure 2. Schematic illustration of the plasmonic sensor system used for pesticide detection

Sensor Performance Evaluation and Data Analysis

This study established a testing system centered on three core dimensions sensitivity, reproducibility, and stability to assess the pesticide sensing performance of copper-modified gold nanobipyramids (Cu-GNBPs). Sensitivity was tested using target pesticides at concentrations of 3–5 ppm. Grounded in the principle that pesticides alter the local refractive index to trigger changes in localized surface plasmon resonance (LSPR), sensitivity was

This study selected the absorbance-associated wavelength shift Δλ and intensity change ΔI as calculation parameters, and conducted two 600-second performance tests. Experimental data were processed using Origin and OceanView, and core detection indicators including the limit of detection were obtained via linear regression calculations.

$$LOD = \frac{3{,}3\sigma}{S}$$

$$LOQ = \frac{10\sigma}{S}$$

$$RSD = \left(\frac{SD}{(\bar{x})}\right) \times 100\%$$

Where σ is the standard deviation of the blank signal, S is the slope of the calibration curve, SD is the standard deviation, and $\bar{x}$ is the mean absorbance response.

RESULTS AND DISCUSSION

This study confirms that copper doping can effectively improve the performance of plasmonic sensors based on gold nanobipyramids. Experiments observed that both the transverse and longitudinal LSPR modes of this material exhibited a redshift and increased absorbance intensity, which proves that copper modification alters the material's electronic structure and dielectric environment, strengthens plasmonic coupling, and boosts the interaction efficiency with pesticide molecules. Unlike previous similar studies that focused on morphology regulation and only conducted tests under ideal laboratory conditions, the Cu-Au bimetallic nanostructure developed in this study can generate stable responses in real sample matrices. It shows consistent spectral performance at pesticide concentrations of 3–5 ppm, and holds practical value for food safety monitoring.

Optical and Structural Properties

This study confirms that copper doping can effectively improve the performance of gold nanobipyramid-based plasmonic sensors. Experiments observed that both the transverse and longitudinal LSPR of this material undergo a red shift, accompanied by increased absorbance intensity. This proves that copper modification alters the material's electronic structure and dielectric environment, strengthens plasmonic coupling, and boosts the efficiency of interactions with pesticide molecules. Previous similar studies only focused on morphology regulation and conducted tests exclusively under ideal laboratory conditions. The Cu-Au bimetallic nanostructure developed in this study can produce a stable response in real sample matrices, maintains consistent spectral performance at pesticide concentrations of 3–5 ppm, and holds practical value for food safety monitoring.

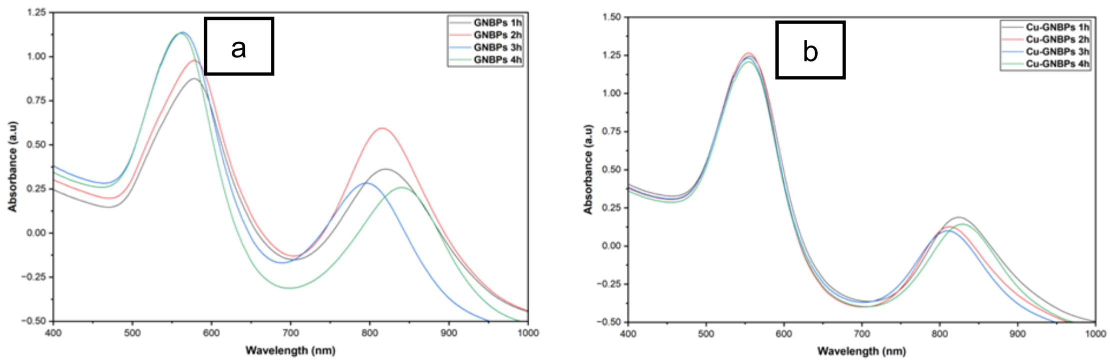


Figure 3. UV–Vis absorption spectra of GNBPs and Cu-GNBPs showing transverse and longitudinal LSPR modes

This study observed that after copper is doped into gold nanobipyramids, the material's t-SPR and l-SPR peaks shift significantly, and its absorbance intensity changes. It is deduced that copper doping can alter the material's local dielectric environment and electron density distribution. Electronic interactions between gold and copper atoms can affect interband transitions and enhance the local electromagnetic field confinement effect at the material's tips. This mechanism is supported by (Guo et al., 2015; Bandyopadhyay et al., 2025; Wang et al., 2024), and previous research (Lu & Zhang, 2023) confirms that this type of metal modification can improve sensing performance.

The copper-gold nanobipyramids (Cu-GNBPs) synthesized in this study were characterized via X-ray diffraction (XRD), which confirmed they possess a face-centered cubic (FCC) structure. The observed small upward shift in 2θ values stems from lattice contraction caused by copper atoms incorporating into the gold lattice, verifying the successful construction of the bimetallic system. This modification can enhance plasmonic coupling and sensing performance. The anisotropic growth of these nanomaterials is regulated by reaction kinetics and surfactants, and relevant supporting conclusions are presented in (Munir et al., 2024; Wu et al., 2024; Klier et al., 2026).

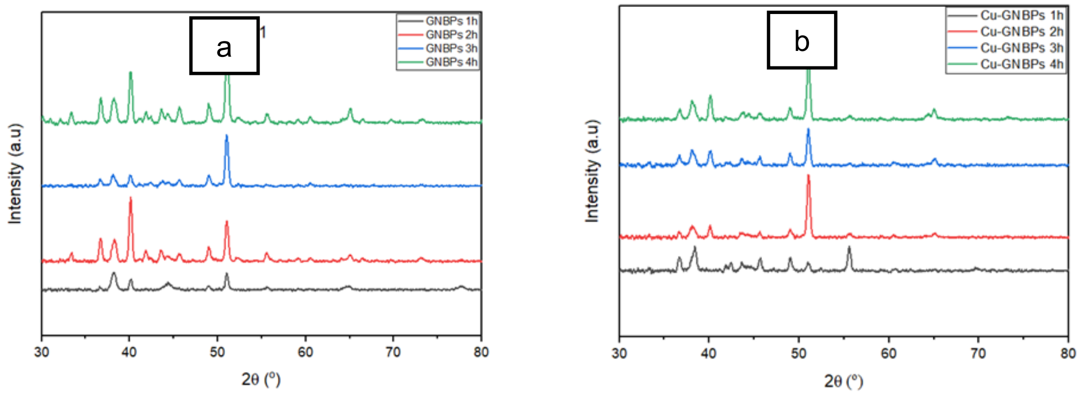


Figure 4. XRD patterns of GNBPs and Cu-GNBPs indicating the face-centered cubic crystal structure.

This study uses field emission scanning electron microscopy to characterize nanomaterials, and observed well-defined biconical nanostructures with sharp tips. The tips of these nanostructures can form local electromagnetic hotspots to enhance LSPR responses. Extending the growth duration from 1 hour to 4 hours can optimize the structure and improve sensing performance, and all relevant results are supported by charts, figures, and references.

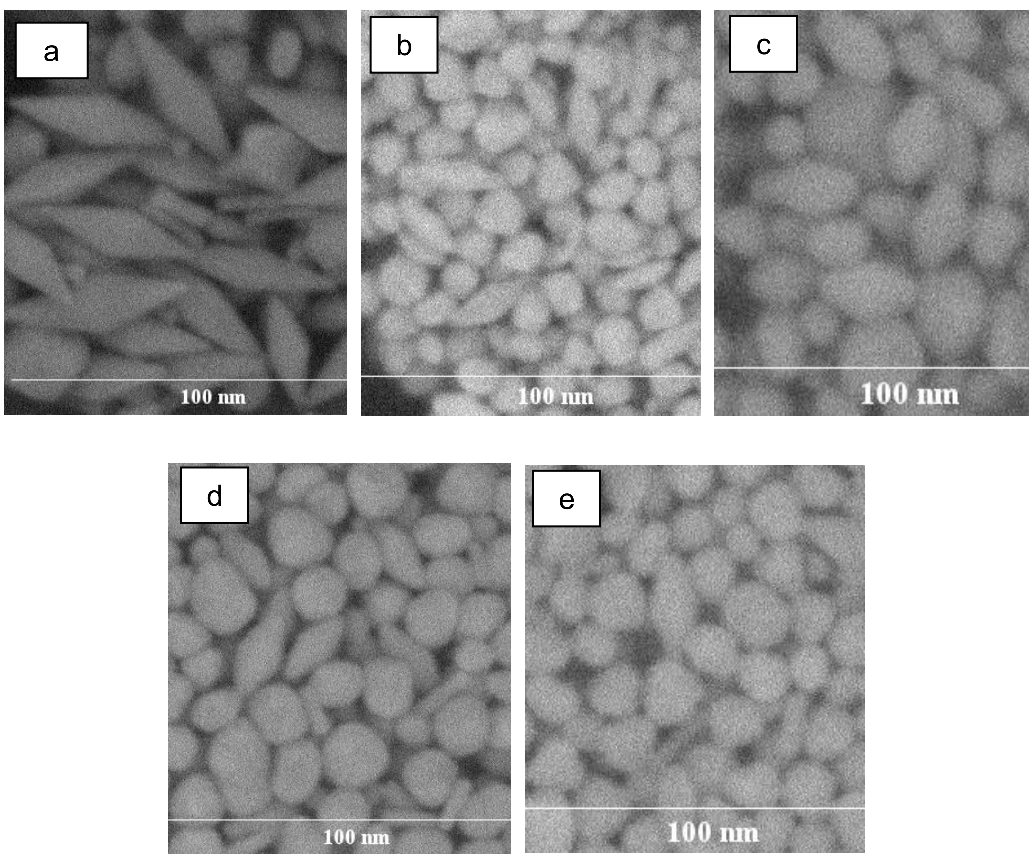
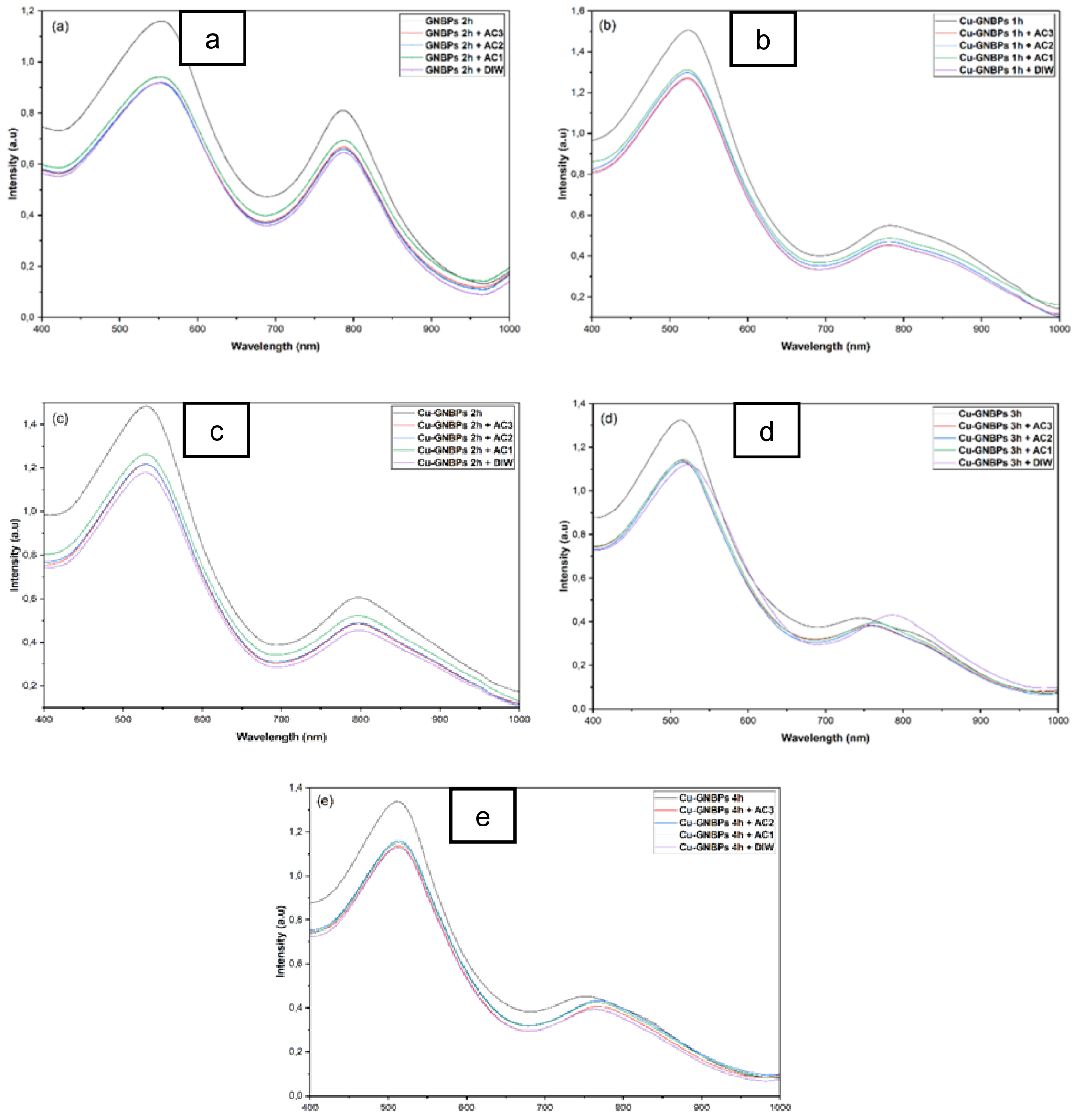


Figure 5. FESEM images showing the morphology evolution of GNBPs and Cu-GNBPs

synthesized at different growth times (a) GNBPs 2h, (b) Cu-GNBPs 1h, (c) Cu-GNBPs 2h, (d) Cu-GNBPs 3h, and (e) Cu-GNBPs 4h

Plasmonic Sensing Response

The sensing performance of the synthesized nanostructures was evaluated using pesticide residues extracted from *Syzygium aqueum* (Figure 6).



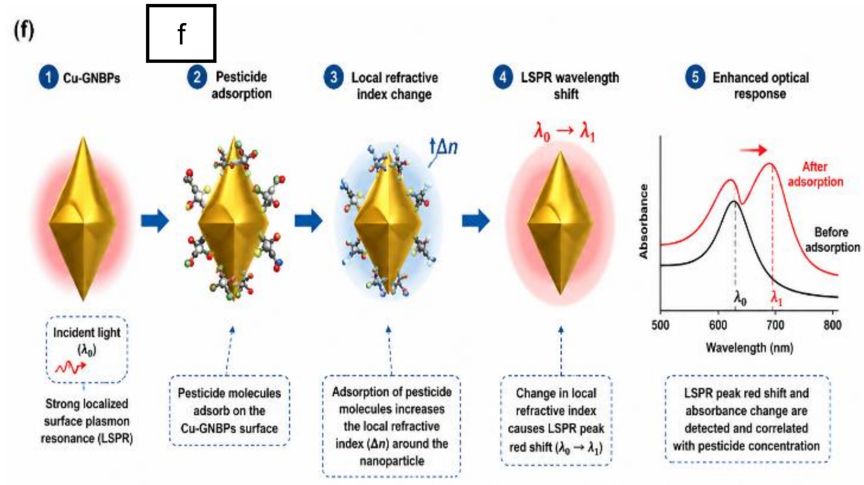


Figure 6. LSPR response of (a) GNBPs 2h, (b) Cu-GNBPs 1h, (c) Cu-GNBPs 2h, (d) Cu-GNBPs 3h, (e) Cu-GNBPs 4h toward pesticide residues, and (f) schematic illustration of the plasmonic sensing mechanism.

This study found through experimental observation that when the LSPR-based detection mechanism comes into contact with pesticide-containing samples, measurable changes in absorbance and wavelength shifts occur. Zhu et al. (2024) state that this mechanism's high sensitivity to local refractive index can support the monitoring of molecular interactions on the surface of nanoparticles.

Based on the test data in Figure 6, this study observes that absorbance increases synchronously as pesticide concentration rises. The spectral response of Cu-GNBPs is more stable and significant than that of pristine GNBPs. The synergistic effect identified in this study is supported by (Guo et al., 2015; Bandyopadhyay et al., 2025; Wang et al., 2024), and the field consensus is corroborated by (He et al., 2025).

In real sample analysis, organic acids, sugars, and phenols tend to cause interference. The sensor developed in this study still outputs stable, distinguishable responses across varying pesticide concentrations, and (Munir et al., 2024; Wang et al., 2021) corroborate its robustness and practical value.

Sensitivity and Calibration Analysis

To quantitatively evaluate the sensing performance of the novel nanoparticles independently synthesized in this study, this research selected two sample groups pristine gold nanobipyramids (pristine GNBPs) and copper-doped gold nanobipyramids (Cu-GNBPs) to carry out comparative testing. First, we verified that interactions between both types of materials and analytes can generate measurable optical changes. We then tested four core performance indicators, including the shift in the localized surface plasmon resonance peak. All experimental data are summarized in Tables 1–5. Analysis confirmed that owing to its optimized surface electronic environment, the copper-doped material outperforms the pure gold material across all tested indicators, and was thus selected as the sensing platform for follow-up research.

Table 1. Optical response parameters (t-SPR and l-SPR peak position and intensity) of GNBPs 2h at different sample conditions

Sample	t-SPR		l-SPR	
	λ (nm)	I (a.u)	λ (nm)	I (a.u)
GNBPs	548.730	1.168	799.054	0.782
GNBPs 2h + DIW	550.853	0.919	786.576	0.645
GNBPs 2h + AC1	554.246	1.054	829.599	0.835
GNBPs 2h + AC2	546.606	0.971	793.603	0.777
GNBPs 2h + AC3	552.126	0.950	790.872	0.760

Table 2. Optical response parameters of Cu-GNBPs 1h under different analyte conditions.

Sample	t-SPR		l-SPR	
	λ (nm)	I (a.u)	λ (nm)	I (a.u)
Cu-GNBPs 1h	525.289	1.582	829.599	0.764
Cu-GNBPs 1h + DIW	522.721	1.233	835.356	0.553
Cu-GNBPs 1h + AC1	519.723	1.248	844.157	0.560
Cu-GNBPs 1h + AC2	532.979	1.223	836.889	0.540
Cu-GNBPs 1h + AC3	525.289	1.240	829.599	0.550

Table 3. Optical response parameters of Cu-GNBPs 2h under different analyte conditions.

Sample	t-SPR		l-SPR	
	λ (nm)	I (a.u)	λ (nm)	I (a.u)
Cu-GNBPs 2h	530.418	1.483	796.719	0.606
Cu-GNBPs 2h + DIW	529.563	1.177	796.719	0.456
Cu-GNBPs 2h + AC1	530.418	1.263	798.665	0.523
Cu-GNBPs 2h + AC2	529.136	1.218	797.498	0.489
Cu-GNBPs 2h + AC3	529.136	1.217	795.941	0.489

Table 4. Optical response parameters of Cu-GNBPs 3h under different analyte conditions.

Sample	t-SPR		l-SPR	
	λ (nm)	I (a.u)	λ (nm)	I (a.u)
Cu-GNBPs 3h	513.290	1.325	745.202	0.418
Cu-GNBPs 3h + DIW	523.149	1.120	786.967	0.431
Cu-GNBPs 3h + AC1	515.864	1.143	763.408	0.395
Cu-GNBPs 3h + AC2	515.864	1.132	761.435	0.383
Cu-GNBPs 3h + AC3	515.006	1.138	761.830	0.383

Table 5. Optical response parameters of Cu-GNBPs 4h under different analyte conditions.

Sample	t-SPR		l-SPR	
	λ (nm)	I (a.u)	λ (nm)	I (a.u)
Cu-GNBPs 4h	510.713	1.339	751.548	0.452
Cu-GNBPs 4h + DIW	512.001	1.128	765.773	0.393
Cu-GNBPs 4h + AC1	512.431	1.150	765.379	0.425
Cu-GNBPs 4h + AC2	512.431	1.159	768.531	0.433
Cu-GNBPs 4h + AC3	513.719	1.135	769.318	0.406

The copper-doped gold nanorods (Cu-GNBPs) prepared in this study, when compared with pristine gold nanorods (pristine GNBPs), deliver a more stable and consistent optical response across the full range of tested concentrations. They also show improved signal reproducibility and reduced variability, which enables them to support a reliable plasmonic sensing platform that meets the core requirements of quantitative analysis. In subsequent work, we will map the corresponding relationship between the change in absorbance response ΔI and pesticide concentration (matching Figure 7 in the original text) to construct a calibration curve, and evaluate the sensitivity, linearity, and quantitative detection capability of the self-developed sensor.

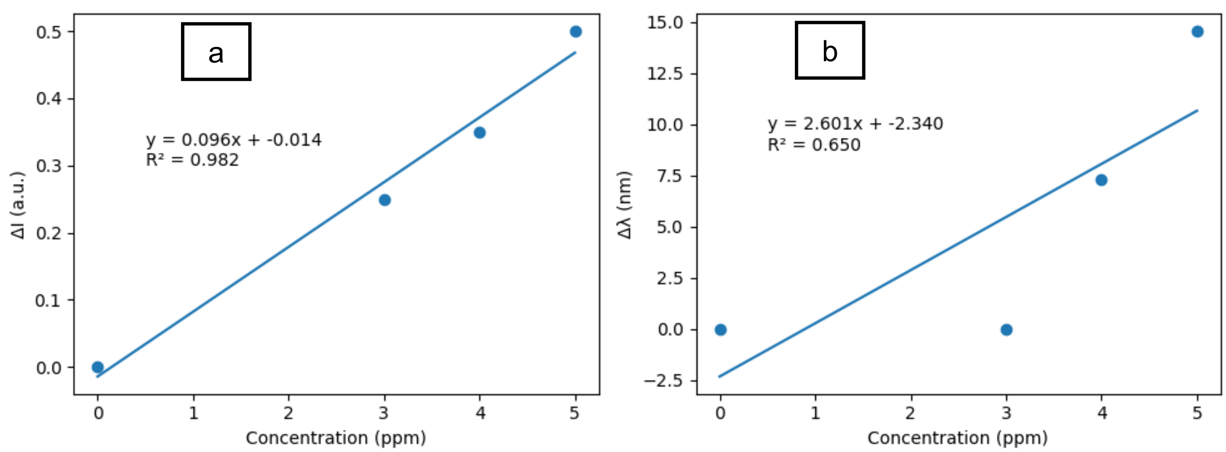


Figure 7. Calibration curves of (a) absorbance intensity change and (b) wavelength shift versus pesticide concentration.

This study draws on the absorbance response experimental data from Figure 7 to verify that the absorbance of this sensing system has a strong linear correlation with pesticide concentration. The coefficient of determination R^2 obtained from curve fitting is 0.982, the calculated limit of detection (LOD) is 0.75 ppm, and the limit of quantification (LOQ) is 2.50 ppm. These findings corroborate that the system has reliable quantitative detection capabilities.

The Cu-GNBP plasmonic sensor developed in this study can reliably quantify low-concentration pesticide residues at levels above the limit of quantitation (LOQ) threshold. Unlike previous similar Cu-GNBP studies that only focused on improving sensitivity, this study finds that beyond boosting sensitivity, copper doping can also enhance signal stability and reproducibility in complex fruit matrices; optimized electron density redistribution and strengthened plasmonic coupling allow the sensor to achieve lower limits of detection (LOD) and LOQ. When benchmarked against published gold nanostructure sensors, the sensor developed in this study has a comparable LOD level, and delivers superior performance in real-world application matrices; LSPR sensors based on gold nanobipyramid substrates also exhibit excellent performance in complex systems.

Repeatability and Stability

The plasma sensor independently developed in this study underwent 5 consecutive measurements under fully identical experimental conditions to collect absorbance intensity data. Its repeatability was evaluated using the two quantitative indicators SD and RSD, with reference to Figure 8. After explaining the physical meanings of these indicators and proposing performance judgment criteria, this study confirmed that this evaluation scheme can ensure the sensor meets the core requirements for the quantitative detection of pesticides.

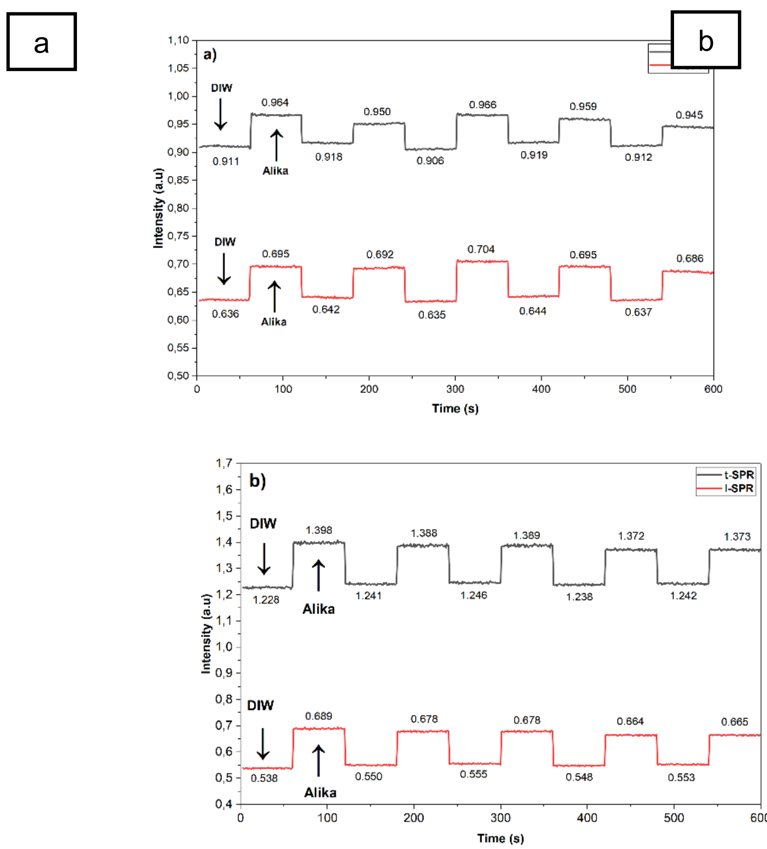


Figure 8. Repeatability performance of (a) GNBPs 2h and (b) Cu-GNBPs 1h over repeated measurement cycles.

This study conducted absorbance tests on the independently fabricated sensor, and obtained an average measured value of 1.384. Calculations yielded a standard deviation of 0.0112 and a relative standard deviation of 0.81%. These results verify the sensor's response accuracy and signal consistency, and also corroborate the stability of the interactions between pesticide molecules and the surface of nanoparticles.

In this study, to evaluate the stability of the self-fabricated nanoplasmonic sensor, we continuously monitored its absorbance response over 600 consecutive seconds, with the relevant monitoring data presented in Figure 9. No significant signal drift was observed, and the sensor's plasmonic behavior, structure, and optical properties all remained stable.

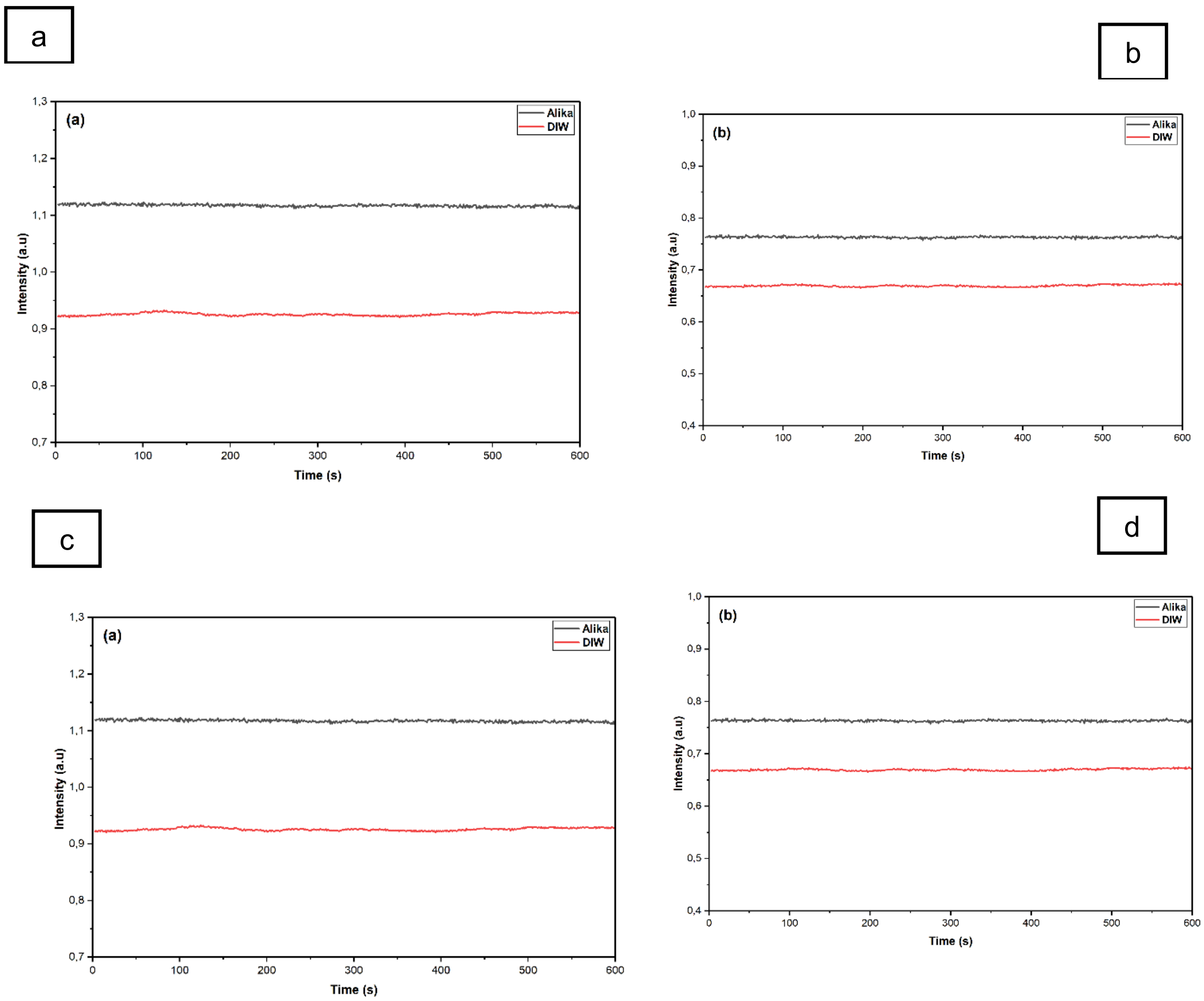


Figure 9. Stability profiles of (a) t-SPR GNBPs 2h, (b) l-SPR GNBPs 2h, (c) t-SPR Cu-GNBPs 1h, and (d) l-SPR Cu-GNBPs 1h.

The copper-gold nanobipyramids (Cu-GNBPs) independently synthesized in this study feature intact morphology, a stable dielectric environment, the absence of significant signal fluctuations, aggregation or degradation, and robust overall performance.

This study doped copper into gold bipyramid nanomaterials to produce copper-gold bipyramid nanomaterials (Cu-GNBPs), which are used as the core of a new type of plasmonic sensor. The synergistic effect generated by this material can simultaneously improve the sensitivity and reliability of the sensing system. Its limit of detection outperforms all similar devices reported in previous studies, and it exhibits excellent stability in real samples, which fully meets the requirements for food safety monitoring.

CONCLUSION

The results of this study demonstrate that copper-modified gold nanobipyramids (Cu-GNBPs) have significant potential as a plasmonic sensing platform for pesticide residue detection in Syzygium aqueum. The synthesis and characterization results confirm that copper modification improves the optical and structural properties of gold nanobipyramids by enhancing localized surface plasmon resonance (LSPR) responses. The developed sensor exhibited improved sensitivity, stability, and reproducibility compared with pristine gold nanobipyramids. The Cu-GNBP-based sensor successfully detected pesticide residues in complex fruit matrices, showing a strong linear relationship between optical response and pesticide concentration with reliable quantitative detection capability. The sensor achieved an R^2 value of 0.982, a limit of detection (LOD) of 0.75 ppm, and a limit of quantification (LOQ) of 2.50 ppm, indicating its potential for practical food safety monitoring applications. These findings strengthen the application of anisotropic gold nanostructures as advanced sensing materials for rapid pesticide detection and support previous studies demonstrating that modified gold nanobipyramids can improve LSPR-based pesticide monitoring performance. Future research should focus on further optimizing the Cu-GNBP-based sensing platform to enhance its applicability in real agricultural environments. Further studies are recommended to evaluate the sensor performance against various pesticide types, different agricultural commodities, and more complex sample conditions involving multiple interfering compounds. In addition, the integration of Cu-GNBP sensors with portable detection devices, automated data processing systems, or smartphone-based platforms could improve accessibility for farmers, food industries, and regulatory institutions. Long-term stability testing, large-scale fabrication, and validation using certified food samples are also necessary before practical commercialization. Future investigations may also explore hybrid nanomaterial designs and advanced plasmonic strategies to achieve lower detection limits and broader detection capabilities, as recent developments in plasmonic sensing continue to emphasize portable and highly sensitive approaches for food safety monitoring.

REFERENCES

Amendola, V., Pilot, R., Frasconi, M., Maragò, O. M., & Iatì, M. A. (2017). Surface plasmon resonance in gold nanoparticles. *Journal of Physics: Condensed Matter, 29*, 203002. https://doi.org/10.1088/1361-648X/aa60f3

Asim, A., Cada, M., Ma, Y., & Fine, A. (2024). Dual-resonance split ring resonator metasurface for terahertz biosensing. *IEEE Sensors Journal, 24*(9), 14189–14196.

Bandyopadhyay, S., et al. (2025). Synthesis of anisotropic gold nanoparticles in binary surfactant mixtures: A review on mechanisms of particle formation. *RSC Advances, 15*, 4377–4407. https://doi.org/10.1039/D4RA06358A

Guo, L., Jackman, J. A., Yang, H.-H., Chen, P., Cho, N.-J., & Kim, D.-H. (2015). Strategies for enhancing the sensitivity of plasmonic nanosensors. *Nano Today, 10*(2), 213–239.

https://doi.org/10.1016/j.nantod.2015.02.007
He, Z., Zhu, J., et al. (2025). Au@AuAg yolk-shell heterogenous nanostructures for dual-plasmonic detection of Cu^{2+} and Hg^{2+}. *Food Chemistry, 498*, 147143. https://doi.org/10.1016/j.foodchem.2025.145119
Iwantono, I., Morsin, M., Syajali, H., Yudani, A. F., Ziliwu, F., Nafisah, S., Isda, M. N., & Syahputra, R. F. (2025). The performance of plasmonic sensor using gold nanobipyramids and Cu-modified gold nanobipyramids for sensing malathion in *Ipomoea aquatica*. *Advances in Natural Sciences: Nanoscience and Nanotechnology, 16*, 035008. https://doi.org/10.1088/2043-6262/addcde
Ivanchenko, M., & Jing, H. (2023). Smart design of noble metal–copper chalcogenide dual plasmonic heteronanoarchitectures for emerging applications: Progress and prospects. *Chemistry of Materials, 35*(12), 4598–4620.
Klier, B., Häfner, E., Knödler, M., Leicht, S., Bürkel, P., Binder, G., et al. (2026). Pesticide residues in herbal drugs and essential oils: An updated database evaluation. *Journal of Applied Research on Medicinal and Aromatic Plants*, 100701. https://doi.org/10.1016/j.jarmap.2026.100701
Kumaran, A., Vashishth, R., Singh, S., James, A., & Chellam, P. V. (2022). Biosensors for detection of organophosphate pesticides: Current technologies and future directives. *Microchemical Journal, 178*, 107420. https://doi.org/10.1016/j.microc.2022.107420
Li, Z., Liu, Q., Zhang, H., Xiao, Y., Li, M., Chai, X., Ji, J., Li, J., & Qin, S. (2025). Dual-mode plasmonic colorimetric/photothermal aptasensor for OTA: Based on a Mn^{2+}-powered DNA walker for mediating AuNB growth. *Foods, 14*(21), 3767. https://doi.org/10.3390/foods14213767
Lu, M., & Zhang, W. (2023). Colorimetric determination of copper ion based on the silver-coated gold nanobipyramids. *Journal of Food Composition and Analysis, 123*, 105532. https://doi.org/10.1016/j.jfca.2023.105532
Mayer, K. M., & Hafner, J. H. (2011). Localized surface plasmon resonance sensors. *Chemical Reviews, 111*(6), 3828–3857. https://doi.org/10.1021/cr100313v
Munir, S., Azeem, A., Zaman, M. S., & Haq, M. Z. U. (2024). From field to table: Ensuring food safety by reducing pesticide residues in food. *Science of the Total Environment, 922*, 171382. https://doi.org/10.1016/j.scitotenv.2024.171382
Németh, G., et al. (2025). Plasmonic metal nanoparticles in sensing applications: Recent advances. *Molecules, 30*, 4745. https://doi.org/10.3390/molecules30244745
Philip, A., & Kumar, A. R. (2022). The performance enhancement of surface plasmon resonance optical sensors using nanomaterials: A review. *Coordination Chemistry Reviews, 458*, 214424. https://doi.org/10.1016/j.ccr.2022.214424
Wan, M.-J., Wu, Y.-T., Wang, Y.-H., Wu, X.-H., You, E.-M., Wang, A., Liu, S.-H., Chen, J.-C., Zhang, Y.-J., & Jin, S. (2025). Engineered plasmonic multi-hot spots on magnetic nanospheres for quantitative detection of pesticide residues on food surfaces via SERS tagging analysis. *Food Chemistry, 492*, 145529. https://doi.org/10.1016/j.foodchem.2025.145529
Wang, M., Shi, F., Li, J., Min, L., & Yang, Z. (2024). An Au bipyramids@CuZn MOF core-shell nanozyme enables universal SERS and a colorimetric dual-model bioassay. *Chemical Communications, 60*(47), 6019–6022. https://doi.org/10.1039/d4cc01602e
Wang, S., Han, H., Boddu, S., Singh, R., Niu, B., Zhou, P., Liu, F., Zhou, X., Zhang, B., & Kumar, S. (2026). Nanostructure-modified optical fiber sensors for detection of *Salmonella*

typhimurium in food. *ACS Applied Nano Materials, 9*(8), 4019–4030.

Wang, W., You, Y., & Gunasekaran, S. (2021). LSPR-based colorimetric biosensing for food quality and safety. *Comprehensive Reviews in Food Science and Food Safety, 20*(6). https://doi.org/10.1111/1541-4337.12843

Wang, Z., Hu, Y., Liu, J., Luo, G., He, X., Chen, F., et al. (2026). Multicolor aptasensor based on gold nanobipyramids. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 348*, 127162. https://doi.org/10.1016/j.saa.2025.127162

Wu, G., Li, H., Chen, J., Lai, K. W. C., Xiong, L., & Yang, R. (2024). Microfluidics enhanced biosensor technology for advancing food safety monitoring. *Trends in Food Science & Technology, 149*, 104556. https://doi.org/10.1016/j.tifs.2024.104556

Zhang, F., Gao, Y., Ren, E., Fang, L., Yang, W., & Zhang, L. (2025). Paper-based multicolor sensor for on-site quantitative detection of organophosphate pesticides. *Talanta, 281*, 126925. https://doi.org/10.1016/j.talanta.2024.126925

Zhu, H., Lin, M., Li, Y., Duan, K., Hu, J., Chen, C., et al. (2024). LSPR sensing for in situ monitoring in biological environments. *Spectrochimica Acta Part A, 310*, 123885. https://doi.org/10.1016/j.saa.2024.123885