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Portable LSPR Sensing Platform with Cloud-Based Data Logging for Malathion Monitoring in Agricultural Food Samples

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Abstract

Excessive use of malathion in agriculture can result in food contamination, environmental pollution, and health risks to consumers. Conventional detection methods such as High-Performance Liquid Chromatography (HPLC) and Gas Chromatography-Mass Spectrometry (GC-MS) offer high accuracy but require expensive equipment and laboratory-based analysis. This work presents a portable Localised Surface Plasmon Resonance (LSPR) sensing platform with integrated cloud-based data logging for the monitoring of malathion in agricultural food samples. The developed system combines gold nanobipyramids (GNBPs), an AS7265x spectroscopy sensor, and ESP32-enabled wireless communication to support spectral acquisition, real-time monitoring, and centralised cloud data storage. Experimental evaluations were conducted using chilli, tomato, and cabbage extracts at a resonance wavelength of 860 nm. Chilli extract showed an increase in intensity from 20.172 to 69.056, with an R^2 value of 0.9963, while cabbage extract increased from 63.895 to 86.507, with an R^2 value of 0.993, following the addition of GNBPs and malathion. In contrast, tomato extract showed a decreasing intensity trend from 106.305 to 82.379, possibly due to nanoparticle aggregation influenced by the acidic properties of the sample matrix. The obtained results demonstrated distinguishable spectral variations between pesticide-free and malathion-treated samples, indicating the feasibility of the proposed sensing platform for preliminary pesticide screening. In addition, the implemented cloud logging framework enabled real-time wireless storage of spectral datasets, improving data accessibility, traceability, and long-term record management for future agricultural monitoring applications.

1. Introduction

Pesticides are widely used in modern agriculture to improve crop productivity and reduce losses caused by insects and plant diseases. Among commonly used pesticides, malathion is widely used for its effectiveness in controlling agricultural pests. However, excessive or uncontrolled use of malathion may result in chemical residues accumulating on food products such as vegetables and fruits. Continuous exposure to pesticide residues may introduce health risks to consumers, including neurological disorders, respiratory complications, and environmental contamination through soil and water pollution [1], [2]. Because of this, monitoring pesticide residues in agricultural food products has become increasingly important for food safety and environmental protection.

Conventional pesticide residue analysis is commonly performed using laboratory-based techniques such as High-Performance Liquid Chromatography (HPLC) and Gas Chromatography-Mass Spectrometry (GC-MS). These methods are highly sensitive and accurate. Nevertheless, the instruments are expensive, require trained personnel, and entail relatively long processing times before results are obtained [3]. In many agricultural environments, especially during field monitoring or preliminary screening, these approaches are less practical due to limited portability and the absence of real-time monitoring capability. The delay between sample collection and laboratory analysis may also reduce the efficiency of rapid food safety inspection processes.

Recent developments in nanomaterial-based sensing technologies have introduced alternative approaches for rapid pesticide monitoring. Gold nanoparticles (AuNPs), particularly gold nanobipyramids (GNBPs), have attracted significant attention because of their unique optical behaviour associated with Localised Surface Plasmon Resonance (LSPR). When malathion molecules interact with the surface of gold nanoparticles, the local dielectric environment surrounding the nanoparticles changes, producing measurable spectral and intensity variations [3], [4]. These changes can be observed using spectroscopic sensing devices, enabling rapid and relatively low-cost colourimetric detection without requiring a full laboratory setup.

Although significant progress has been reported in nanoparticle-assisted pesticide sensing, most existing studies focus primarily on sensing performance in laboratory-controlled environments. Comparatively less attention has been given to integrating portable plasmonic sensing platforms with wireless communication and centralised cloud-based data management for field-oriented agricultural monitoring. In many reported implementations, spectral measurements are either processed offline or displayed locally without systematic storage capability, limiting long-term data traceability and remote accessibility. Consequently, the development of a compact sensing platform capable of performing spectral acquisition, wireless transmission, and centralised cloud logging within a single integrated system remains an area requiring further investigation.

Several studies have explored nanoparticle-assisted sensing systems for pesticide detection. Martínez et al. [3] discussed recent advances in pesticide sensing technologies using nanomaterial-based approaches to improve sensitivity and selectivity. Du et al. [5] further highlighted the growing interest in nano-engineered sensing structures for environmental monitoring applications due to their fast response and portable implementation capability. In another related work, Halim [6] developed an IoT-based agricultural monitoring platform using ESP32 and wireless communication technologies for real-time acquisition of environmental data. Although the system demonstrated effective remote monitoring capability, the work did not involve plasmonic sensing mechanisms or cloud-based spectral data logging for pesticide analysis.

This work builds upon a previously developed prototype that employed gold nanoparticles and the AS7265x spectroscopy sensor for pesticide sensing applications [6]. In the earlier implementation, spectral measurements were acquired using an Arduino UNO microcontroller and the results were displayed locally through an LCD interface. While the prototype demonstrated the feasibility of plasmonic sensing for pesticide monitoring, the absence of wireless communication and centralised data storage limited its suitability for long-term monitoring, remote accessibility, and systematic data management. These limitations motivated the development of an enhanced sensing platform with integrated cloud-based logging capability.

Therefore, this study presents a compact LSPR-based sensing platform integrated with wireless cloud data logging for malathion monitoring in agricultural food samples. The proposed system combines GNBPs, an AS7265x spectroscopy sensor, and an ESP32 microcontroller to support spectral acquisition, local visualisation, wireless communication, and centralised data storage within a single platform. Unlike the previous implementation, the developed prototype automatically transmits spectral measurements to Google Sheets via Wi-Fi, enabling systematic record management and improved data accessibility. Experimental evaluations were conducted using chilli, tomato, and cabbage extracts to investigate the spectral response of the sensing platform under different food sample conditions and to assess its feasibility for preliminary agricultural food safety monitoring.

2. System Architecture and Methodology

2.1 Overall System Architecture

The proposed portable sensing platform was developed by integrating an LSPR-based sensing mechanism with wireless cloud data logging capability for agricultural food sample monitoring. The system architecture consists of four main modules, namely the sensing module, spectral acquisition module, processing and communication module, and cloud data logging module. Fig. 1 illustrates the overall workflow of the developed prototype.

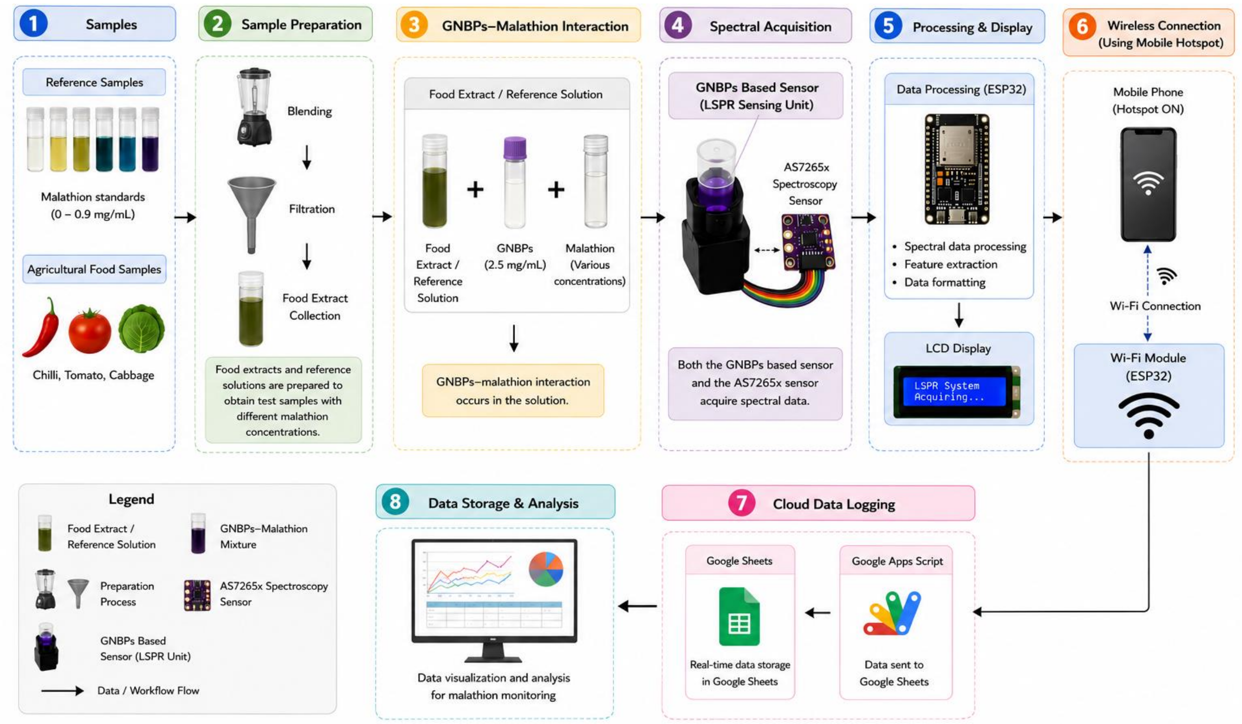


Fig. 1 *Overall workflow of the proposed portable LSPR sensing platform with cloud-based data logging for malathion monitoring in agricultural food samples*

The sensing module utilises GNBPs as the plasmonic sensing medium for malathion detection. When malathion molecules interact with the GNBPs' surfaces, the local dielectric environment around the nanoparticles changes. This interaction modifies the nanoparticles' optical response, leading to changes in light absorption and scattering intensity via the LSPR effect. The generated optical response is then measured using the AS7265x spectroscopy sensor.

The spectral acquisition module is centred on the AS7265x spectroscopy sensor, which can simultaneously capture multiple wavelength channels. In this work, the sensor was used to acquire spectral intensity readings from the prepared food samples and malathion mixtures. The sensor measurements were performed continuously during the sampling process to observe the spectral behaviour associated with the interaction between malathion and GNBPs.

The processing and communication module is controlled using the ESP32 microcontroller. The ESP32 acts as the main controller responsible for sensor interfacing, spectral data acquisition, LCD display control, wireless communication, and cloud data transmission. Compared to the previous implementation developed using an Arduino UNO [13], the ESP32 provides built-in Wi-Fi, simplifying wireless data communication while improving system portability and deployment flexibility.

For cloud data logging, the acquired spectral readings are transmitted wirelessly through Wi-Fi and automatically stored in Google Sheets using Google Apps Script integration. The cloud logging mechanism enables long-term data storage, centralised monitoring, and future offline analysis without requiring manual data transfer procedures. At the same time, the measured data are displayed locally on the LCD module for immediate monitoring feedback during sample acquisition.

To improve portability and suitability for agricultural monitoring applications, all sensing and processing components were integrated into a compact 3D-printed enclosure. The portable structure simplifies handling during experimental measurements and reduces alignment disturbances between the optical components and the sensing chamber.

2.2 LSPR-based Sensing Principle

Localised Surface Plasmon Resonance (LSPR) is an optical phenomenon in which conduction electrons on the surface of metallic nanoparticles collectively oscillate in response to incident light at specific wavelengths. In this work, gold nanobipyramids (GNBPs) were used as the plasmonic sensing material due to their strong optical sensitivity and stable spectral response characteristics [4].

When malathion molecules are introduced into the GNBP solution, they adsorb onto the nanoparticle surface. This interaction alters the refractive index and dielectric properties surrounding the nanoparticles, leading to measurable changes in the optical intensity captured by the spectroscopy sensor. As the concentration of malathion increases, the spectral response also changes due to variations in plasmonic absorption behaviour.

The sensing mechanism implemented in this work does not rely on complex laboratory instrumentation. Instead, the plasmonic response is measured using the AS7265x spectroscopy sensor integrated with the portable sensing platform. This approach allows rapid spectral acquisition while maintaining low system cost and improved portability for agricultural monitoring applications.

2.3 Hardware Design

The hardware architecture of the proposed prototype comprises the AS7265x spectroscopy sensor, ESP32 microcontroller, LCD display module, RGB LED illumination source, rechargeable power supply, and a supporting optical enclosure. Fig. 2 illustrates the hardware connectivity and component arrangement of the proposed sensing platform.

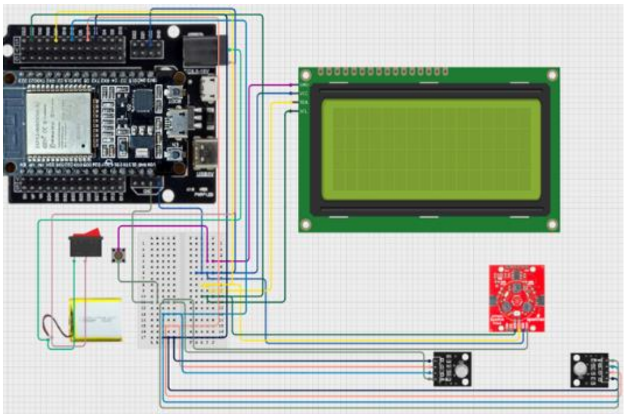


Fig. 2 *Hardware connectivity and component arrangement of the proposed sensing platform*

The ESP32 microcontroller serves as the primary control unit of the system. It performs sensor initialisation, spectral data acquisition, LCD communication, Wi-Fi connection management, and cloud data transmission. The microcontroller continuously acquires spectral intensity values from the AS7265x sensor during the measurement process, then processes the data for local display and cloud storage.

The AS7265x spectroscopy sensor was selected due to its multi-channel spectral sensing capability. The sensor captures intensity readings across multiple wavelength bands simultaneously, allowing spectral behaviour changes associated with malathion interaction to be observed more effectively. In this implementation, the sensor readings were collected repeatedly for each sample to improve measurement consistency.

To ensure stable optical acquisition, the RGB LED module, sample cuvette, and spectroscopy sensor were carefully aligned inside the 3D-printed enclosure. The LED source was positioned approximately 0.2 mm from the cuvette to provide consistent illumination, while the AS7265x sensor was placed at approximately 0.6 mm from the sensing chamber to optimise light reception. This arrangement helped reduce external light interference and minimise optical misalignment during measurements.

A rechargeable portable power source was integrated into the prototype to improve mobility during experimental testing. The overall hardware structure was designed to reduce cable dependency while maintaining stable operation throughout the measurement process.

2.4 Cloud Data Logging Framework

The wireless communication framework was developed using the built-in Wi-Fi capabilities of the ESP32 microcontroller. After acquiring spectral data from the sensor, the ESP32 transmits the measured values over an existing Wi-Fi connection to a Google Sheets database for long-term storage and monitoring.

Google Apps Script was used as middleware between the ESP32 and Google Sheets. The Apps Script receives incoming HTTP requests from the ESP32 and automatically inserts the transmitted data into predefined spreadsheet columns. Each measurement entry includes the acquisition date, timestamp, and spectral intensity values obtained from all sensor channels.

The database structure was organised systematically to simplify future data analysis and comparison activities. The first column stores the date and time, while the remaining columns contain the spectral intensity readings for each sensing channel. During each measurement cycle, multiple readings were collected and averaged before being stored in the spreadsheet.

In addition to cloud storage, the transmitted data were displayed in real time via the Arduino IDE serial monitor for communication verification and debugging. This dual-monitoring approach improves data reliability while simplifying troubleshooting during system development and experimental testing. The integration of cloud-based data logging enables the developed prototype to support centralised record management without requiring manual file transfer. Compared to conventional standalone sensing systems, the proposed implementation improves accessibility of experimental data while supporting future expansion towards web-based or mobile monitoring applications.

2.5 Software Workflow

The firmware implementation was developed using Arduino IDE for ESP32 programming. Several software modules were integrated into the system, including sensor initialisation, spectral acquisition, LCD display handling, Wi-Fi communication, and cloud database transmission.

During operation, the system first initialises the AS7265x sensor and attempts to establish a Wi-Fi connection. If the Wi-Fi connection or sensor initialisation fails, warning messages are displayed on the LCD module to notify the user regarding the system status. Once initialisation is successful, the system proceeds to spectral data acquisition. For each food sample, multiple spectral readings are collected continuously to improve measurement consistency and reduce fluctuation effects. The measured values are displayed on the LCD during acquisition before being wirelessly transmitted to the Google Sheets platform. The complete operational workflow of the developed system is illustrated in the system flowchart shown in Fig. 3. This implementation enables semi-automated monitoring and systematic storage of spectral measurement data for future analysis.

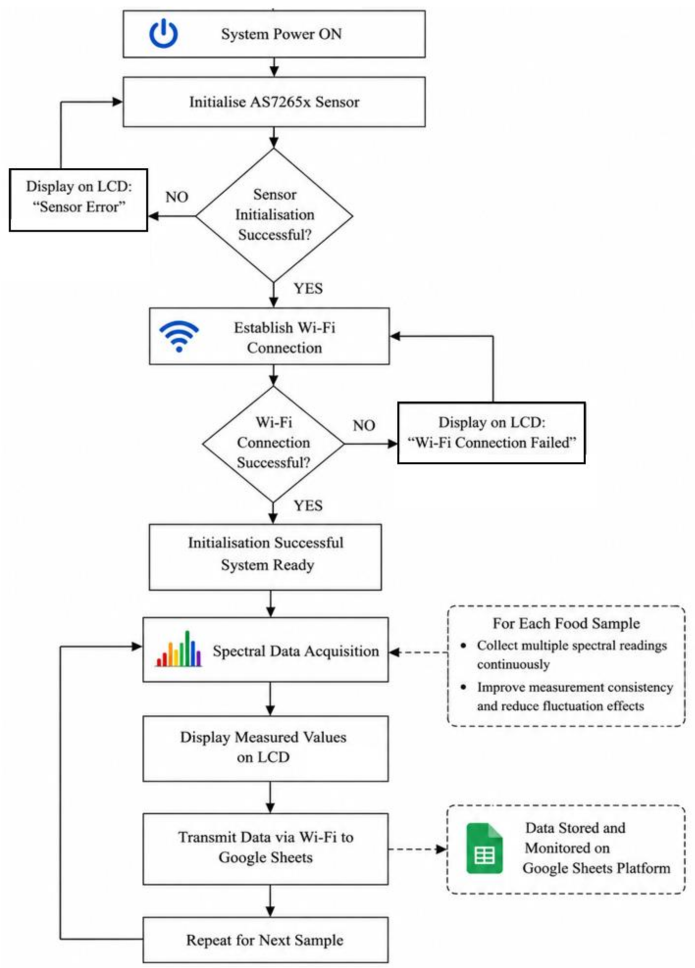


Fig. 3 *Operational workflow of the proposed sensing platform*

3. Results and Discussion

3.1 Prototype Development and System Implementation

Fig. 4 shows the complete prototype arrangement consisting of the AS7265x spectroscopy sensor, RGB LED illumination source, ESP32 microcontroller, LCD display module, rechargeable power supply, and 3D-printed enclosure. The prototype is powered by a rechargeable 3.7 V, 5000 mAh battery, enabling portable, autonomous operation without a continuous external power source.

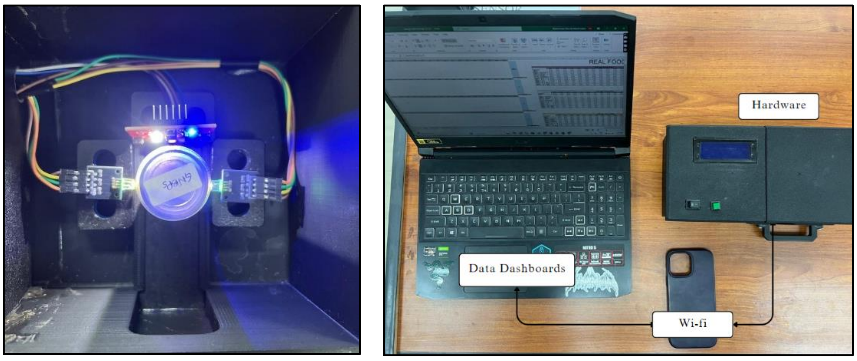


Fig 4. *(Left) Optical arrangement of the RGB LED, AS7265x sensor, and GNBPs sensing chamber; (right) Complete prototype of the developed sensing platform*

The optical arrangement inside the enclosure was designed carefully to maintain stable light transmission during spectral acquisition. The RGB LED module was positioned approximately 0.2 mm from the sample cuvette to provide consistent illumination across the sensing chamber. Meanwhile, the AS7265x spectroscopy sensor was positioned approximately 0.6 mm from the cuvette to improve optical reception and reduce interference from unwanted light. This configuration helped improve measurement consistency throughout the experimental acquisition process.

The integration of the 3D-printed enclosure also improved system portability and simplified the alignment between the optical components and the sensing chamber. Compared to conventional laboratory-based instrumentation, the developed prototype offers a more compact, portable sensing structure suitable for preliminary agricultural monitoring applications.

In addition, the ESP32 microcontroller operated successfully as the main processing and communication unit throughout the experimental evaluations. The controller continuously acquired spectral readings, displayed the measured values locally on the LCD module, and transmitted the data wirelessly to the cloud database without requiring external computer interfacing during the measurement process.

3.2 Real-Time LCD Monitoring and User Interface

The LCD module provided real-time feedback regarding sensor initialisation, Wi-Fi connection status, and spectral acquisition progress. Examples of the displayed system status messages are shown in Fig. 5. Error messages were displayed whenever communication or sensor initialisation failures occurred. During measurement, the display continuously updated spectral intensity values, allowing users to monitor system operation directly without requiring external software interfaces.

3.3 Cloud Data Logging

One of the main contributions of this work is the implementation of wireless cloud-based spectral data logging using the ESP32 microcontroller and Google Sheets platform. The wireless communication framework operated successfully throughout the experimental evaluations and allowed continuous transmission of sensor readings without requiring physical cable connections between the prototype and external computing devices. The ESP32 established a Wi-Fi connection and transmitted the measured spectral intensity values to Google Sheets via HTTP, using Google Apps Script. The Apps Script handled the incoming data requests and automatically mapped the received sensor values into the corresponding spreadsheet columns.

Fig. 6 shows the cloud database structure, consisting of multiple columns representing the spectral sensing channels, along with timestamp information for each acquisition cycle. The first column stored the date and time, while the remaining columns stored the spectral intensities obtained from the AS7265x sensor. Multiple readings were collected for each sample before the average values were calculated and recorded for further analysis.

In addition to cloud storage, the transmitted data were also monitored in the Arduino IDE serial monitor for debugging and verification. The dual-monitoring approach enabled real-time validation of locally transmitted data against remotely stored cloud records. The wireless cloud logging implementation significantly improves the sensing platform's flexibility compared to the previous prototype developed using an Arduino UNO [13], which only supported a local LCD display without centralised storage.

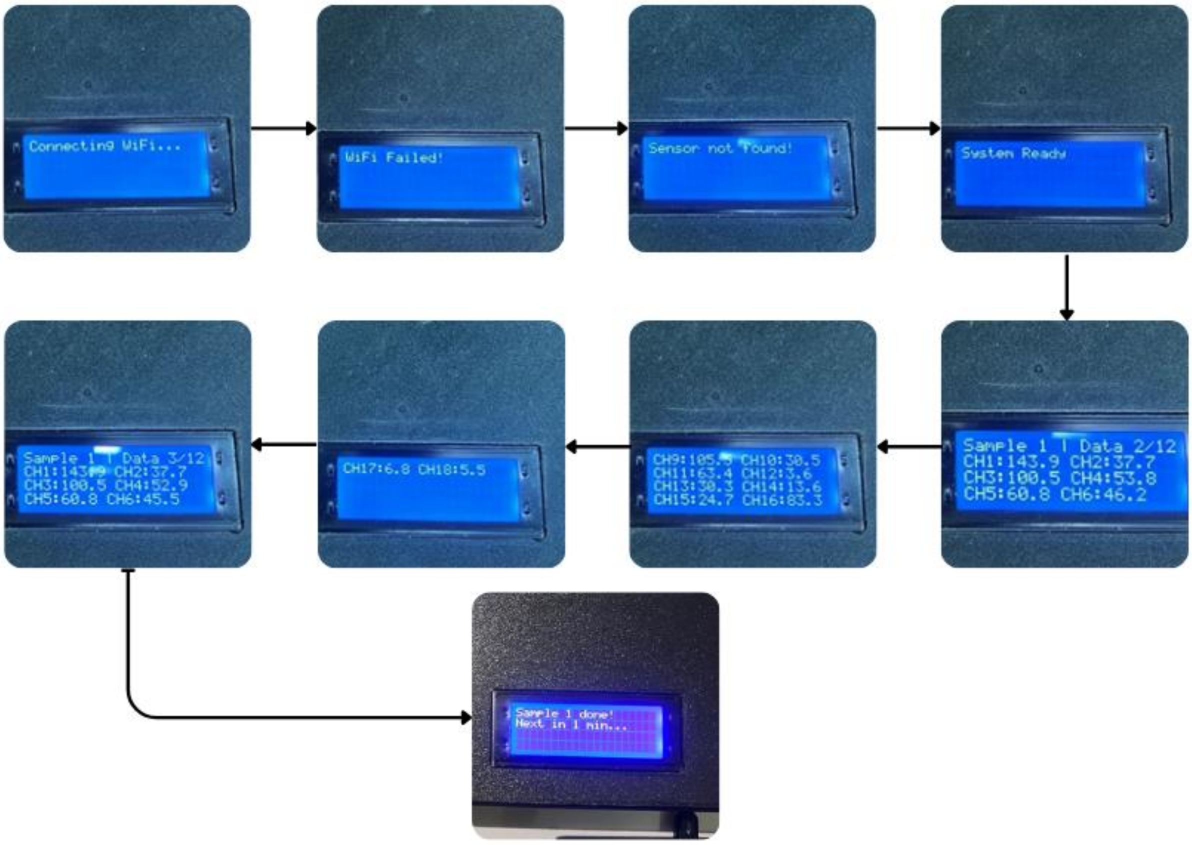
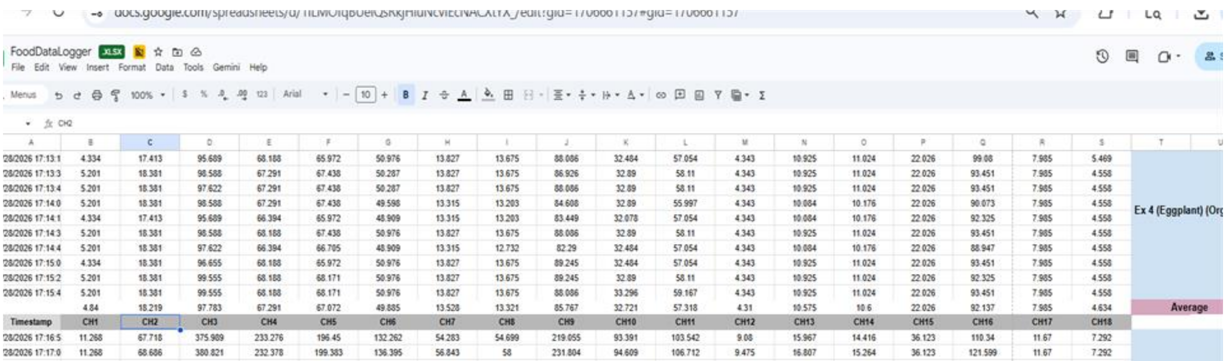


Fig. 5 *Examples of system status messages displayed on the LCD module*



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
28/2026 17:13:1	4.334	17.413	95.689	68.188	65.972	50.976	13.827	13.675	88.086	32.484	57.054	4.343	10.925	11.024	22.026	99.08	7.985	5.469	
28/2026 17:13:3	5.201	18.381	98.588	67.291	67.438	50.287	13.827	13.675	86.926	32.89	58.11	4.343	10.925	11.024	22.026	93.451	7.985	4.558	
28/2026 17:13:4	5.201	18.381	97.622	67.291	67.438	50.287	13.827	13.675	88.086	32.89	58.11	4.343	10.925	11.024	22.026	93.451	7.985	4.558	
28/2026 17:14:0	5.201	18.381	98.588	67.291	67.438	49.598	13.315	13.203	84.608	32.89	55.997	4.343	10.084	10.176	22.026	90.073	7.985	4.558	
28/2026 17:14:1	4.334	17.413	95.689	66.394	65.972	48.909	13.315	13.203	83.449	32.078	57.054	4.343	10.084	10.176	22.026	92.325	7.985	4.558	Ex 4 (Eggplant) (Org
28/2026 17:14:3	5.201	18.381	98.588	68.188	67.438	50.976	13.827	13.675	88.086	32.89	58.11	4.343	10.925	11.024	22.026	93.451	7.985	4.558	
28/2026 17:14:4	5.201	18.381	97.622	66.394	66.705	48.909	13.315	12.732	82.29	32.484	57.054	4.343	10.084	10.176	22.026	88.947	7.985	4.558	
28/2026 17:15:0	4.334	18.381	96.655	68.188	65.972	50.976	13.827	13.675	89.245	32.484	57.054	4.343	10.925	11.024	22.026	93.451	7.985	4.558	
28/2026 17:15:2	5.201	18.381	99.555	68.188	68.171	50.976	13.827	13.675	89.245	32.89	58.11	4.343	10.925	11.024	22.026	92.325	7.985	4.558	
28/2026 17:15:4	5.201	18.381	99.555	68.188	68.171	50.976	13.827	13.675	88.086	33.296	59.167	4.343	10.925	11.024	22.026	93.451	7.985	4.558	
	4.84	18.219	97.783	67.291	67.072	49.885	13.528	13.321	85.767	32.721	57.318	4.31	10.575	10.6	22.026	92.137	7.985	4.634	Average
Timestamp	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14	CH15	CH16	CH17	CH18	
28/2026 17:16:5	11.268	67.718	375.989	233.276	196.45	132.262	54.283	54.699	219.055	93.391	103.542	9.08	15.967	14.416	36.123	110.34	11.67	7.292	
28/2026 17:17:0	11.268	68.686	380.821	232.378	199.383	136.395	56.843	58	231.804	94.609	106.712	9.475	16.807	15.264	36.123	121.599	11.67	7.292	

Fig. 6 *Example of cloud-stored spectral measurement data in Google Sheets*

3.4 Spectral Response of Pure Malathion and Malathion-GNBP Samples

The spectral response of the developed sensing platform was first evaluated using pure malathion samples and malathion mixed with gold nanobipyramids (GNBPs). The analysis focused on observing the intensity variations at the resonance wavelength of 860 nm to investigate the optical interaction between malathion molecules and the plasmonic sensing medium.

For pure malathion samples without GNBPs, the measured intensities generally increased throughout the acquisition. The observed response mainly originated from the optical absorption and scattering properties of the malathion solution itself, without plasmonic interaction. Since no gold nanoparticles were present in the solution, the LSPR mechanism was not activated, resulting in a relatively direct spectral intensity response.

The spectral graphs presented in Figures 7 and 8 were generated from datasets stored in Google Sheets after the measurement process was completed. This demonstrates the practicality of the integrated cloud logging framework for organising, storing, and retrieving experimental spectral datasets during agricultural sensing experiments.

Fig. 7(a) demonstrates increasing intensity behaviour at 860 nm. In contrast, samples containing both malathion and GNBPs produced a noticeable reduction in spectral intensity at the same wavelength, as illustrated in Fig. 7(b). The decrease in intensity was due to the interaction between malathion molecules and the gold nanobipyramid surfaces. When malathion binds to the nanoparticle surface, the dielectric environment around the nanoparticles changes, thereby activating the LSPR. This interaction increases light absorption by the plasmonic structure and reduces the transmitted optical intensity measured by the AS7265x spectroscopy sensor.

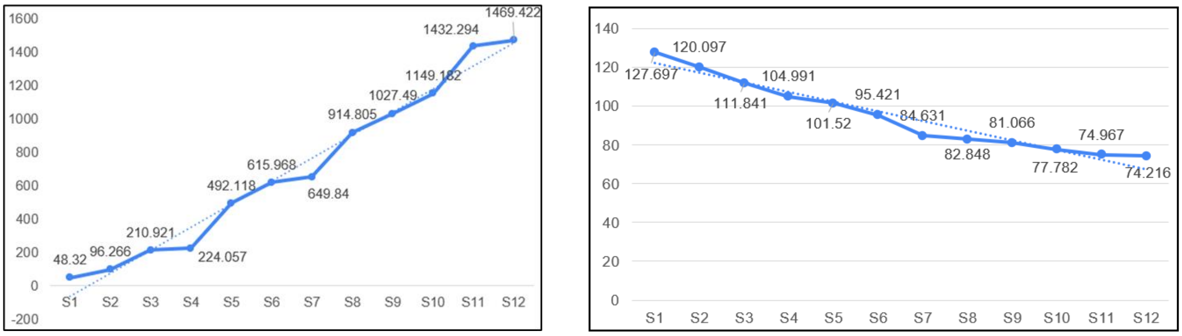


Fig. 7 *Graph of (a) pure Malathion, and (b) pure Malathion with GNBPs*

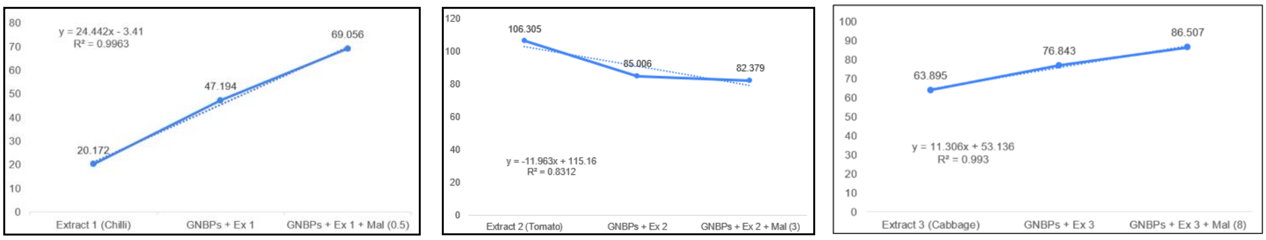
3.5 Spectral Evaluation Using Agricultural Food Samples

To further evaluate the applicability of the developed sensing platform for agricultural food monitoring, experiments were conducted using extracts of chilli, tomato, and cabbage. These food samples were selected because they represent commonly consumed agricultural produce with different chemical and optical characteristics. For each sample, spectral measurements were performed using pure extract, extract mixed with GNBPs, and extract mixed with both GNBPs and malathion. The spectral response analysis focused primarily on the resonance wavelength of 860 nm.

For chilli extract, the measured intensity increased consistently following the addition of GNBPs and malathion. The recorded intensity values at 860 nm increased from 20.172 for pure chilli extract to 47.194 after the addition of GNBPs, and then further increased to 69.056 upon the addition of malathion to the sensing solution. As shown in Fig. 8(a), the progressive increase in intensity indicates that the interaction between malathion molecules and the gold nanobipyramids modifies the local optical environment around the nanoparticles, resulting in a measurable enhancement of the spectral response. The observed trend indicates that the developed sensing platform was capable of distinguishing between the different sample conditions. Furthermore, the high R^2 value of 0.9963 indicates a highly consistent spectral trend across the tested sample states, supporting the feasibility of using the proposed platform for preliminary pesticide screening applications.

A different spectral behaviour was observed for the tomato extract samples. The measured intensity decreased from 106.305 for pure tomato extract to 85.006 following the addition of GNBPs, and further decreased to 82.379 after malathion was introduced. Unlike the chilli and cabbage samples, which exhibited increasing intensity responses, the tomato extract demonstrated an inverse spectral trend, as illustrated in Fig. 8(b). This behaviour may be attributed to the acidic composition of tomato extract, which can influence nanoparticle surface stability and promote partial aggregation of the gold nanobipyramids. Such aggregation may alter plasmonic absorption characteristics and reduce the amount of transmitted light detected by the spectroscopy sensor. Despite the differing response patterns, the sensing platform still produced distinguishable spectral variations across the tested sample conditions. The resulting R^2 value of 0.8312 indicates a reasonably consistent response trend, although greater variability was observed compared to the chilli and cabbage samples.

For cabbage extract, the measured intensity values again showed a positive response upon addition of GNBPs and malathion. The recorded intensities increased from 63.895 for pure cabbage extract to 76.843 after the introduction of GNBPs, and further increased to 86.507 when malathion was added to the sensing mixture. As illustrated in Fig. 8(c), the increasing trend suggests that the plasmonic interaction between malathion molecules and the nanoparticle surface enhanced the optical response detected at the resonance wavelength. Similar to the chilli extract measurements, the strong R^2 value of 0.993 indicates a highly consistent spectral trend across the tested sample conditions. The observed behaviour further supports the developed sensing platform's ability to differentiate between uncontaminated and malathion-treated agricultural food samples under the experimental conditions of this study.



(a) **(b)** **(c)**

Fig. 8 *Spectral responses from the extraction of (a) chilli, (b) tomato, and (c) cabbage*

Overall, the experimental results demonstrate that the sensing platform's spectral response is influenced not only by the presence of malathion but also by the intrinsic chemical composition of the tested food matrix. Chilli and cabbage extracts produced increasing intensity responses following the addition of GNBPs and malathion, whereas tomato extract exhibited a decreasing trend. These observations suggest that sample-dependent factors, such as acidity, pigmentation, and naturally occurring organic compounds, may affect the plasmonic interaction mechanism and, in turn, influence the measured spectral response. Nevertheless, all three food samples showed measurable intensity variations after exposure to malathion, indicating the proposed sensing platform's ability to detect changes associated with pesticide contamination across different agricultural products.

3.6 Discussion on Agricultural Monitoring Capability

The developed sensing platform demonstrates the feasibility of integrating plasmonic sensing, wireless communication, and cloud-based data management into a single, compact system for preliminary agricultural food-monitoring applications. The experimental results obtained from chilli, tomato, and cabbage extracts confirmed that measurable spectral variations could be observed following the introduction of GNBPs and malathion. Although the magnitude and direction of the spectral responses varied across the tested food samples, consistent intensity changes were observed, indicating that the sensing platform could detect alterations in sample composition associated with pesticide exposure.

Compared with conventional laboratory-based techniques such as HPLC and GC-MS, the proposed prototype offers several practical advantages for preliminary screening applications. The sensing process can be performed using a compact standalone device without requiring complex laboratory infrastructure, highly trained operators, or lengthy sample preparation procedures. Furthermore, the integration of ESP32 wireless communication enables automatic transmission of spectral measurements to a centralised cloud database, reducing the need for manual data recording and improving long-term data traceability. This capability may be particularly beneficial in agricultural environments where periodic monitoring and historical record management are required.

The cloud-based logging framework also provides a foundation for future smart agriculture applications. By storing spectral measurements together with timestamp information, the collected datasets can be accessed remotely and analysed over extended monitoring periods. Such a framework creates opportunities for future integration with web dashboards, mobile applications, machine learning algorithms, and decision-support systems to improve the efficiency of agricultural monitoring.

Despite these promising results, several limitations should be acknowledged. The present study primarily demonstrated the feasibility of the sensing platform and did not establish analytical performance parameters, such as limit of detection (LOD), limit of quantification (LOQ), sensitivity, repeatability, or selectivity against other pesticide compounds. In addition, only three agricultural food samples were evaluated under controlled laboratory conditions. Consequently, the current findings should be regarded as a preliminary proof-of-concept rather than a fully validated pesticide quantification system.

Overall, the results indicate that the proposed platform has potential as a low-cost, portable screening tool for agricultural monitoring applications. Future work should focus on expanding the range of tested food samples, performing comprehensive analytical validation, and enhancing the cloud infrastructure to support real-time visualisation and intelligent interpretation of spectral data for large-scale agricultural deployment.

4. Conclusion

This work successfully developed a compact LSPR-based sensing platform integrated with wireless cloud data logging for malathion monitoring in agricultural food samples. The proposed system combines gold nanobipyramids (GNBPs), an AS7265x spectroscopy sensor, and an ESP32 microcontroller to perform spectral acquisition, local monitoring, wireless communication, and centralised cloud-based data storage within a single portable platform.

Experimental evaluations conducted using chilli, tomato, and cabbage extracts demonstrated measurable spectral variations following the introduction of GNBPs and malathion. At the resonance wavelength of 860 nm, chilli extract exhibited an intensity increase from 20.172 to 69.056 with an R^2 value of 0.9963, while cabbage extract increased from 63.895 to 86.507 with an R^2 value of 0.993. In contrast, tomato extract showed a decreasing intensity trend from 106.305 to 82.379, which may be associated with changes in nanoparticle stability caused by the acidic characteristics of the sample matrix. Despite differing response patterns, all tested samples showed distinguishable spectral differences between pesticide-free and malathion-treated conditions, demonstrating the sensing platform's ability to detect changes associated with pesticide contamination.

In addition to the sensing functionality, the implemented Google Sheets framework successfully enabled real-time wireless storage of spectral datasets, improving data accessibility, traceability, and long-term record management. The integration of plasmonic sensing with cloud-based data logging provides a practical foundation for future agricultural monitoring systems that require both onsite measurement capability and centralised data management.

Nevertheless, the present work represents a preliminary feasibility study and does not establish analytical performance parameters such as limit of detection (LOD), limit of quantification (LOQ), sensitivity, repeatability, or selectivity against other pesticide compounds. Furthermore, the experimental evaluation was limited to three agricultural food samples under controlled laboratory conditions. Future work should focus on comprehensive analytical validation, evaluation using a wider range of food matrices, and the integration of real-time visualisation and intelligent data interpretation tools. Overall, the findings demonstrate the feasibility of combining portable plasmonic sensing and cloud-based monitoring within a single platform, providing an initial step towards field-deployable agricultural food safety monitoring systems.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Afiq, Zarina, Marlia;* ***data collection:*** *Muhammad Afiq;* ***experiment preparation:*** *Muhammad Afiq, Nur Liyana, Nur Anis Intan Aqiah, Farhanahani,* ***analysis and interpretation of results:*** *Muhammad Afiq, Nur Liyana, Zarina, Marlia;* ***draft manuscript preparation:*** *Muhammad Afiq and Zarina. All authors reviewed the results and approved the final version of the manuscript.*

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