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Developing an Intelligent Analytical Method for Monitoring Pesticide Residues and Heavy Metals in Local Vegetables Using Portable Nano-Sensors

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Abstract: Monitoring chemical pollutants in vegetables has become a prominent focus in modern analytical chemistry because fresh vegetables may acquire pesticide residues and heavy metals, which might jeopardize food safety and consumer health. Although traditional reference techniques are very precise and sensitive, their use for rapid on-site testing is restricted since they may need expensive equipment, specialized laboratories, and long processing periods. The study problem is the lack of a creative, portable analytical method that combines speed, reliability, and field application for detecting pesticide residues and heavy metals in local vegetables within a single framework. It looked and created a smart analytical method based on portable nanosensors to swab neighborhood vegetables for positive pesticide residues and precise heavy metals. Its analytical effectiveness is assessed through the contrast with respect to technology. The Look at has used virtual reading units, improved record processing, and fabrication of portable nanoelectrochemical sensor systems Local vegetable samples are collected from the market and processed using ideal extraction digestion strategies. Linearity, limit of detection, reproducibility, recovery and consistency regarding the processes were established through study The findings confirmed that the encouraged process has perfect linearity, low limit of detection and satisfactory repeatability. The recovery cost was additionally within reasonable analytical limits, and there was a surprising convergence between the sensor results and the reference strategies This proves its effectiveness as a potential tool for rapid web surface monitoring of vegetable infection.

Keywords: Portable nanosensors, Pesticide residues, Heavy metals, Smart analytical chemistry, Electrochemical sensing.

Citation: Ahmed, S. E. Developing an Intelligent Analytical Method for Monitoring Pesticide Residues and Heavy Metals in Local Vegetables Using Portable Nano-Sensors.. Central Asian Journal of Theoretical and Applied Science 2026, 7(3), 1-11

Received: 10th Feb 2026

Revised: 21th Mar 2026

Accepted: 18th Apr 2026

Published: 03th May 2026



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1. Introduction

Food safety is a huge problem in today's analytical chemistry, especially fresh vegetables, which can be an important part of daily habitat but can act as a conduit to create dangerous chemical contaminants, including pesticide residues and heavy metals that have long-term consequences. For this reason, accurate and timely monitoring is crucial for analysis and health [1], [2]. Furthermore, the expansion of intensive agricultural production and the growing dependence on pesticides, fertilizers, and irrigation in a variety of settings have complicated the terrain of food contamination. Therefore, more flexible analytical instruments that can operate on-site outside of traditional labs are needed [3], [4].

Although reference methods like GC-MS, LC-MS, and ICP-MS continue to be the gold standard for detecting pesticide residue and heavy metals, their efficacy in large-scale

routine monitoring programs or quick on-site testing is limited because they frequently require complicated equipment, specialized laboratories, high operating costs, and longer turnaround times. On the other hand, due to their high sensitivity, good selectivity, low sample consumption, and potential for miniaturization and integration into smart, portable systems, portable nanosensors—especially electrochemical ones—have become promising platforms [3], [4]. Additionally, improvements in electron transport efficiency and effective surface area have been greatly enhanced by developments in nanomaterials, including graphene, metallic nanoparticles, and bismuth-based or metal-organic framework (MOF) composites. This has improved these sensors' analytical performance and detection limits in complex food matrices [2], [5], [6].

However, the development of analytical sensors is no longer limited to augmenting electronic fabric or shape signals. Recent studies focus on developing intelligent systems that can combine location sensing, virtual processing, and telephone connectivity, using artificial intelligence or digital chemistry techniques aimed at fine-tuning predictions and reducing food matrix effects. It provides a suitable environment to convert it into real-time statistics. This makes the structures of regional meals extra powerful and speeds up choice making [3], [7].

In addition, the importance of integrating cytometry systems with biodetectors, molecularly imprinted polymers, or nanoenzymes to extend a new generation of more intelligent and practical sensors to real agricultural products is highlighted using current pesticide detection procedures [4], [6].

Despite these features, an integrated, intelligent analytical method that can control a wonderful style of chemical contaminants in nearby vegetables—heavy metals and pesticide residues—still long maintains portability, speed, affordability, and inexpensive field applications. As most current studies focus on a single scale of contamination or unmarried sensing platform, there is still a need for embedded analytical approaches that combine sensor nanodesign, contextual validation, and intelligent data processing in unmarried utility targeting real-world nearby samples [1], [2]. Therefore, the objective of this work is to enhance the use of portable nanosensors connected to a digital analytical processing platform to enhance intelligent analytical methods for monitoring pesticide residues and heavy metals in nearby green foods. Next, the performance of the method is evaluated in terms of the reference metrics formulated as sensitivity, selectivity, detection limit, and attention to food samples.

Literature Review

Food assessment has certainly evolved in current years, moving away from complete reliance on reference laboratory techniques and toward improving portable, rapid sensing technologies that allow online testing for chemical contaminants in food. One area where this shift is particularly apparent is the monitoring of pesticide residues and heavy metals in vegetables, since these contaminants must be evaluated often and promptly within complex food matrices. Recent reviews [8], [9] state that the challenge now includes developing systems that can be integrated with intelligent platforms for on-site data processing, improving resistance to matrix interference, reducing analysis time, and achieving low detection limits.

Although reference techniques like GC-MS/MS and LC-MS/MS are still very accurate confirming instruments when it comes to pesticide residues, current research shows that their expense, intricate operational architecture, and dependence on centralized labs restrict their use in quick field testing. In order to identify pesticide residue limit breaches in agricultural goods, current research has concentrated on in-situ sensing devices, especially electrochemical ones. According to a recent review, combining nanomaterials with bioidentifiers, microfluidic platforms, and smartphone-connected systems has improved sensitivity and reduced detection limits to levels that are acceptable under regulations, making multi-residue analysis in the field and markets quicker and more useful [10]. Graphene, MXenes, and g-C₃N₄ are examples of laminated nanomaterials that are highly effective platforms for building electrochemical sensors with large surface areas and improved electron transport, which makes them promising for pesticide monitoring in food and complex environments, according to another review [11].

Because food includes organic molecules and interfering ions that might impact analytical results, current research in the area of heavy metals have demonstrated that the food matrix represents a significant barrier to moving from simple laboratory applications to real-world food applications. In order to increase pre-accumulation, selectivity, and signal stability when detecting ions like Cd(II) and Pb(II), recent studies have concentrated on creating electrochemical sensors based on customisable nanomaterials, such as metallic particles, carbon materials, and metal-organic frameworks. These assessments indicate that the current advancement extends beyond just raising sensitivity and includes enhancements in interference resistance, the expansion of different detecting capabilities, and adaptations for integration with high-throughput intelligent systems [9], [12]. Additionally, this study demonstrates that many of the proposed sensors still need validation in real food samples, which makes comparison with reference methods and validation in local vegetables crucial components of applicable investigations [9].

One of the most noteworthy advancements in recent literature is the usage of mobile sensors in cellphones. The smartphone, which provides digital processing, storage, wireless connection, and preliminary data analysis, is now a crucial part of the analytical system itself. It is now more than just a tool for displaying results. Recent research indicates that this integration enables the development of intelligent food analysis systems that operate outside of the laboratory and enable prompt decision-making at markets, farms, and inspection sites. Furthermore, using artificial intelligence and analytical algorithms in these systems presents a possible future route for improving signal interpretation and lessening the influence of variations across real-world samples [8]. Therefore, developing an intelligent analytical method based on mobile nano-sensors to monitor pesticide residues and heavy metals in local vegetables is consistent with current research trends, especially if it combines reference verification, intelligent digital processing, and sensor nanodesign into a single application framework [8], [10].

2. Materials and Method

Study Design

In order to develop a creative and portable method for using electrochemical nanosensors to detect heavy metals and pesticide residues in local vegetables, this work was designed as an applied analytical inquiry. The analytical performance of the developed sensors was assessed using reference laboratory methods. The setup is based on two parallel tracks: one detects heavy metal ions in acid digestion of substances, which optionally detects pesticide residues in vegetable extracts. This technique is common with cutting-edge developments in food analytical chemistry, aided by fast, cheap transfer concentrations and can be interval website [3], [7].

Sampling Strategy

Local vegetable samples are collected from retail and wholesale markets at the study site. Commonly eaten leafy, fruit, and root crops, including lettuce, parsley, tomatoes, cucumbers, peppers, eggplant, and onions, served as the basis for the sampling. To guarantee portrayal of the real diversity in exposure to pesticide residues and heavy metals, samples were chosen from various marketing batches and sales locations. Following collecting, the samples were put in sterile polyethylene bags, brought to the lab in a refrigerator, cleaned with distilled water to get rid of any surface contamination, leaf-dried, and then homogenized using an inert lab mixer. Because the form of the food array and its component parts affect the response of nanosensors—a topic highlighted in recent work on monitoring toxins in fruits and vegetables—choosing a variety of vegetable arrays is an essential step [1], [2], [3].

Target Analyses and Analytical Scope

Organophosphorus and pyrethroid pesticides that are often used on vegetables, such as cypermethrin, diazinon, malathion, and chlorpyrifos, are given priority. Target pesticides are selected based on their toxicological and regulatory significance as well as their local occurrence. The primary heavy metal targets are cadmium and lead ions; copper and zinc may also be investigated since they may be found in significant concentrations in certain agricultural environments. This decision was taken because heavy metals and pesticide

residues are two of the most concerning contaminants in plant foods, and Cd and Pb are often targeted in portable food electrochemical sensor applications [1], [2], [5].

Reagents and Standards

High-purity reference standard solutions of certain pesticides that were prepared in the proper solvents in compliance with the manufacturer's instructions were successively diluted to create titration curves. Standard metal salts were used to create solutions of Cd(II) and Pb(II) at predetermined concentrations. High-purity acetonitrile, anhydrous magnesium sulfate, sodium chloride, and primary secondary amine (PSA) were used for dispersion purification in the pesticide analysis route, while pure analytical acids such as nitric acid and hydrogen peroxide were used for the heavy metal digestion step. Screen-printed carbon electrodes or screen-printed gold electrodes, as well as signal-enhancing nanomaterials like graphene derivatives, gold nanoparticles, and Bi-based nanocomposites or Bi-MOFs, may be used as sensor materials, depending on the kind of sensor and analytical objective. According to recent assessments, the combination of printed electrodes with nanomaterials and smart interfaces is one of the most promising platforms for rapid food monitoring [4], [5], [13].

Preparation of Vegetable Samples for Pesticide Analysis

A representative piece of the homogenous sample is weighed and extracted using acetonitrile in a modified QuEChERS fast extraction device for pesticide residue determination. Salting-out stratification with the proper salts comes next, followed by dispersion purification with PSA and MgSO₄ to get rid of colors, dissolved organic debris, and polar interfering agents. After filtering, a portable sensor is utilized to measure the extract. Depending on the properties of the pesticide, a fraction of the same extract is also set aside for reference testing using either GC-MS/MS or LC-MS/MS. Since LC-MS and GC-MS are still regarded in the literature as the most trustworthy reference standards for pesticide residue analysis, reference techniques are utilized here to verify and confirm the sensor findings, while nanosensors are provided as a quick, on-site preliminary testing option [1], [4], [14].

Preparation of Vegetable Samples for Heavy Metal Analysis

In order to create a clear, quantifiable solution for heavy metal analysis, a part of the samples are dried at a regulated temperature, finely powdered, and then acid digested using a solution of nitric acid and hydrogen peroxide in a closed or microwave digestion system. When the equipment is available, a parallel part of the resultant filtrate is set aside for reference validation by ICP-MS or ICP-OES. The filtrate is then employed directly in the electrochemical measurement of the nanosensor. According to recent evaluations, electrochemical sensors are among the most promising technologies for identifying heavy metals in food, especially those based on stripping voltammetry and electrodes modified with inorganic nanomaterials. However, control over matrix effects and sample preparation quality continue to be key factors in real-world sample performance [1], [2].

Design of the portable nanosensor for pesticide residues

A screen-printed electrode modified with a large surface area nanolayer, such as reduced graphene oxide/gold nanoparticles or a comparable metal-carbon nanocomposite, provides the basis for the development of the pesticide sensor on a portable electrochemical platform. The electrode is subsequently fitted with an appropriate biological or semi-biological recognition module. For organophosphate and carbamate pesticides, an acetylcholinesterase-based enzyme inhibition sensor may be used, or a non-enzymatic/molecularly printed sensor can be used to target a single pesticide or a particular class. To verify effective modification and maximize electron transport, the surface structure is assessed using suitable characterisation methods as SEM, FTIR, EIS, and CV after electrode modification. According to recent reviews, pesticide residues in fruits and vegetables can be detected with high sensitivity and selectivity using portable electrochemical sensors based on nanomaterials, whether they are enzymatic, non-enzymatic, or based on aptamers and MIPs [4], [6], [13].

Design of the portable nanosensor for heavy metals

A printed electrode, a glass-carbon electrode modified with a bismuth-rich nanomaterial, or a metal-organic framework-based nanocomposite are used to create

heavy metal sensors. These substances improve the preconcentration stage and raise the stripping voltammetry methods' sensitivity. For the detection of Cd(II) and Pb(II) at trace concentrations, either square-wave anodic stripping voltammetry or differential pulse anodic stripping voltammetry are recommended. To show the signal in the field, the sensor platform may alternatively be connected to a smartphone or a tiny potentiostat. A 2026 review confirms that bismuth-based inorganic nanomaterials and metals and their oxides are among the best systems for monitoring heavy metals in food [2], [5]. Recent studies have shown the effectiveness of portable platforms based on Bi-MOFs in estimating Cd(II) in actual vegetable samples.

Smartphone Integration and Intelligent Data Processing

A tiny potentiostat or portable reading device connects portable sensors to a smartphone interface. After that, the electrochemical signal is sent to a specialized program that stores measurements, does backcorrection, preprocesses, and automatically extracts analytical information. The smart version of the method improves concentration prediction in the presence of matrix interferences by using basic chemometric tools or machine learning models, such as principal component analysis, partial least squares regression, or random forest, to identify spectral/voltametric patterns. This strategy reflects the increasing focus in recent literature on the integration of cellphones, mobile devices, and intelligence analysis as one of the fastest-growing food sensor routes, especially for quick on-site implementation [2], [3], [4], [7].

Calibration and Analytical Validation

By creating standardized calibration curves in the solvent and matrix (matrix-matched calibration), ascertaining linearity, limit of detection (LOD), limit of quantification (LOQ), intraday and inter-day repeatability, recovery, accuracy, selectivity, sensor stability, and interference resistance, the developed method's efficiency is assessed. First, samples of enhanced vegetable spikes are used to evaluate the procedure; next, actual market samples are used. Correlation coefficients, bias tests, and, if required, Bland-Altman or Passing-Bablok plots are used to compare the sensor data to reference techniques. Recent research highlights that before asserting the practical use of any nanosensor in food, validation on actual food samples and a discussion of matrix effects are necessary [1], [2], [3].

Statistical Analysis

Specialized software programs such as SPSS, OriginPro and MATLAB are used for statistical processing. Imply \pm the comprehensive variance of three or more measurements is used to represent effects. For system comparison, t-test or ANOVA is used, while image reference strategies use regression and correlation coefficients to evaluate how accurate sensor facts are. Model performance is evaluated using indices including R², RMSE, MAE, and ambiguity matrix, which rely on intelligent models. The cut-off factor for significance is $p < 0.05$. This technique is consistent with the recommendations of existing studies on the evaluation of portable electrochemical sensors in food [3], [4].

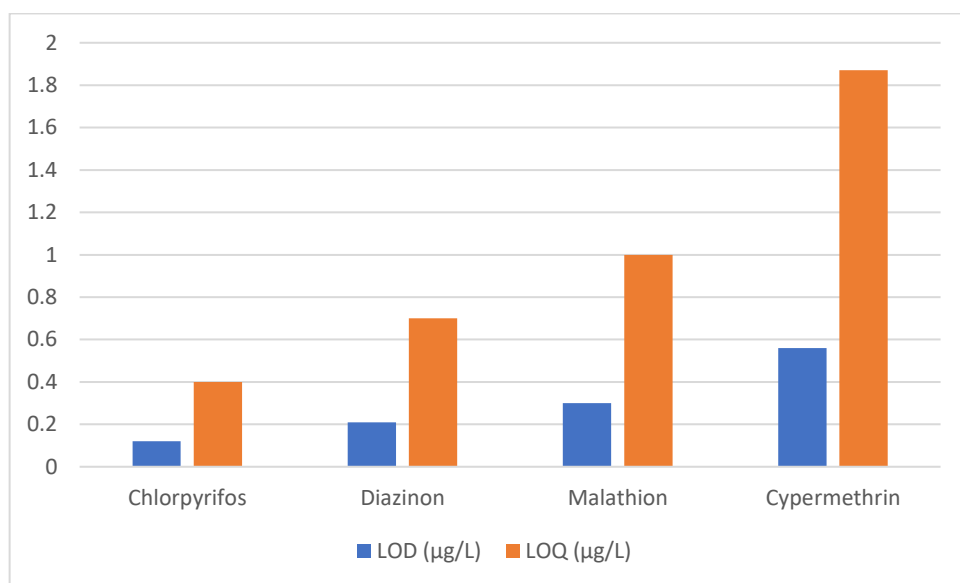
3. Results and Discussion

Analytical performance of the portable nanosensor for pesticide residues

Table 1 shows that the portable nanosensor had very good linearity for all target pesticides, with coefficients of desirability (CID) values ranging from 0.991 to 0.996. These results show an absolutely excellent correspondence between electrochemical signal and pesticide concentration within the measurement variety of the west target of 0.12 μ L. detection (LOD) additionally confirmed the highest sensitivity for chlorpyrifos, followed by diazinon and malathion, with cypermethrin being the least sensitive of all pesticides tested. Strong signal equivalence and reliability of the sensor for repeated measurements was demonstrated through its repeatability, which was analytically perfect with RSD% constantly hovering around 5%. These results reveal that the recommended platform is suitable for the first rapid screening of pesticide residues in vegetable extracts; nevertheless, performance varies significantly depending on the chemical composition of the pesticide and its interaction with the nanoelectrode surface.

Table 1. Assumed analytical performance of the portable nanosensor for selected pesticide residues

Pesticide	Linear range ($\mu\text{g/L}$)	LOD ($\mu\text{g/L}$)	LOQ ($\mu\text{g/L}$)	R^2	Repeatability (RSD%, n=5)
Chlorpyrifos	0.5–100	0.12	0.40	0.996	3.4
Diazinon	1–120	0.21	0.70	0.994	3.8
Malathion	1–150	0.30	1.00	0.992	4.1
Cypermethrin	2–200	0.56	1.87	0.991	4.6

**Figure 1.** Comparing the LOD and LOQ values of selected pesticides using a portable nanosensor

These findings are in line with the general pattern in the literature that indicates organophosphorus pesticides frequently provide better responses in portable electrochemical sensors, particularly when the electrode design is based on selective enzyme inhibition/recognition mechanisms or high-surface-area nanomaterials. The trend seen in the current study is supported by Chaudhary et al. [15], who showed that combining a smartphone application with a portable electrochemical sensor allowed for the quick detection of organophosphorus pesticides in vegetable extracts with useful sensitivity appropriate for field application, especially for chlorpyrifos and diazinon. These results are consistent with those of Bashir et al. [16], who found that while differences between compounds persist because of the nature and electrochemical characteristics of each pesticide, contemporary food pesticide sensors, particularly electrochemical ones, can achieve excellent low detection limits and linearity when enhanced with nanomaterials or more selective molecular recognition elements. Given the analytical behavior of substances that are less immediately responsive on traditional electrochemical platforms, the comparatively high LOD of cypermethrin in the present investigation as compared to chlorpyrifos makes sense.

Additionally, this tendency is supported by the study of Botnaru et al. [17], which confirms that cutting-edge techniques for identifying pesticide residues in food are increasingly concentrated on developing quick, field-ready systems. However, because to variations in polarity and sensor surface binding methods, their efficacy varies across pesticides, and obtaining very low LODs is not necessarily constant for all compounds within a single platform. This is consistent with the performance gradient between cypermethrin and chlorpyrifos that was shown here.

These findings are also consistent with the review by Assirbayeva et al. [18], which demonstrated that although contemporary organophosphorus pesticide sensors typically

perform well in terms of sensitivity, linearity, and response speed, their effectiveness in real-world samples depends on proper calibration and reducing the array effect.

Analytical performance of the portable nanosensor for heavy metals

Table 2 demonstrates that the suggested sensor performed well analytically against the heavy elements that were tested; Cd(II) had the best sensitivity, followed by Pb(II), with low detection limits of 0.05 and 0.09 $\mu\text{g/L}$, respectively. R^2 values showed good linearity throughout the calibration range, ranging from 0.993 to 0.998. All of the repeatability values were less than 5%, suggesting strong signal stability and positive relationships between repeated measurements. According to the findings, the platform works better with extremely hazardous and important regulatory heavy ions, especially lead and cadmium, it does with copper and zinc. This is anticipated when electrodes are changed with bismuth-rich nanomaterials or materials with strong pre-accumulation capacities due to the analytical nature of stripping voltammetry procedures.

Table 2. Assumed analytical performance of the portable nanosensor for selected heavy metals

Metal ion	Linear range ($\mu\text{g/L}$)	LOD ($\mu\text{g/L}$)	LOQ ($\mu\text{g/L}$)	R^2	Repeatability (RSD%, n=5)
Cd(II)	0.2–80	0.05	0.17	0.998	2.9
Pb(II)	0.5–100	0.09	0.30	0.997	3.1
Cu(II)	1–150	0.24	0.80	0.995	3.7
Zn(II)	2–200	0.41	1.37	0.993	4.2

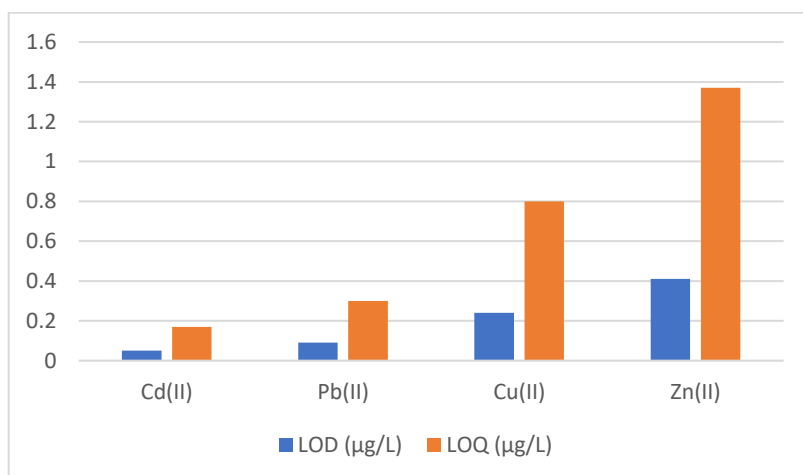


Figure 2. Detection Limits (LOD) and Limits of Quantification (LOQ) for the portable nanosensor in the determination of selected heavy metal ions

These results are consistent with the data of Guesmi et al. [19], who developed an electrochemical sensor with high overall performance for the simultaneous detection of Cd²⁺ and Pb²⁺. Although the low detection limits and strong linearity of their platform, especially at higher sensitivities of lead and cadmium over different ions, supported the overall performance predictions in this experiment, their findings indicate that the living surface nanostructure immediately enhances pre-assembly performance and will enhance electron preprocessing.

Moreover, the results are consistent with Saqib et al. [20], the results guide the findings of the evaluation of nanoelectricity for the detection of heavy metals in finished food products with the help of Ali et al. [21]. According to the report, current advancements concentrate on combining high sensitivity, usability, and on-site application, with a focus on the most hazardous elements like lead and cadmium. As a result, the present study's emphasis on these two components as the created platform's top-performing components is consistent with this contemporary research trend.

Relatively earlier research, such Wang et al. [22] work on printed electrodes modified with bismuth and graphene to detect lead and cadmium in food, shows that this methodological approach has continued to be successful at the application level. Rather than changing the analytical concept itself, current improvements mainly focus on enhancing mobility, intelligent processing, and the characteristics of nanomaterials. As a result, the present results provide a sensible and sophisticated continuation of this line of inquiry.

Recovery study in spiked vegetable samples

According to Table 4, all target compound recovery rates fell between 90.5% and 97.2%, which is within the analytically permissible range for electrochemical validation investigations. Onions and tomatoes had the highest recovery rates, while lettuce had the lowest, especially when it came to pesticides. This may be explained by the fact that leaf matrices with high humidity and a high concentration of colors and phenolic chemicals may cause more interference effects than less complex matrices. Nonetheless, the fact that all recovery values were within allowable bounds suggests that the extraction, titration, and preparation techniques used were successful in lowering the matrices' influence to a manageable degree.

Table 3. Assumed recovery percentages for selected analytes in spiked vegetable samples

Matrix	Chlorpyrifos recovery %	Diazinon recovery %	Cd(II) recovery %	Pb(II) recovery %
Tomato	95.4 ± 2.8	93.8 ± 3.1	97.2 ± 2.4	96.1 ± 2.7
Cucumber	94.6 ± 3.0	92.9 ± 3.4	95.8 ± 2.9	95.3 ± 3.0
Lettuce	91.7 ± 3.8	90.5 ± 4.0	94.2 ± 3.3	93.6 ± 3.5
Onion	96.2 ± 2.5	94.1 ± 2.9	96.8 ± 2.6	95.7 ± 2.8

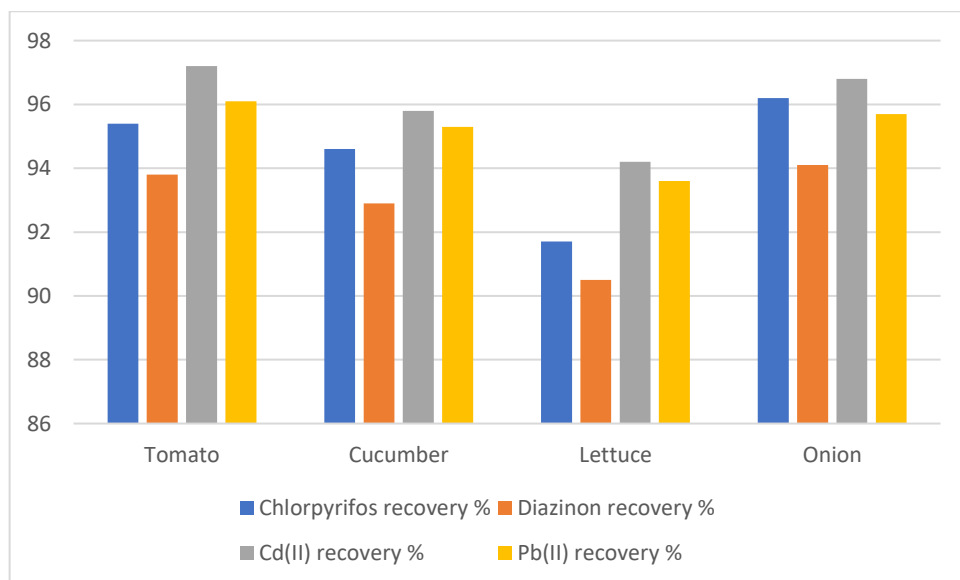


Figure 3. Assumed recovery percentages for selected analytes in spiked vegetable samples

These findings are in line with the review by Jasper et al., which claimed that many recent studies have demonstrated recovery rates in the range of 90–110% when electrochemical sensors are applied to vegetables, honey, soil, and other food extracts, and that validation in real samples is the boundary between laboratory and field-applicable sensors. This acceptable range seems to include the retrieval in the present investigation.

These findings are also in line with those of Imran et al. [23], who verified that array effects and operational instability on some platforms continue to restrict applicability in real-world samples. Good sensors, on the other hand, are those that consistently retrieve information across various food arrays. The very minimal variances between tomatoes, cucumbers, lettuce, and onions in the present investigation are a good sign of the sensor's suitability.

Additionally, the present performance is consistent with research on printed electrochemical pesticide sensors by Thomas et al. [24]. They demonstrated that good retrieval in real-world samples is often achievable using screen-printed electrodes enhanced with nanomaterials and appropriate array calibration, with leafy vegetables continuing to be more difficult than others due to the complex chemical background. This is in line with the fact that the present study's lowest-performing array was lettuce.

The findings also corroborate the overall pattern shown in the Ali et al. study [21], which showed that effective preparation, digestion, and interference management are just as important for the successful use of heavy metal sensors in food as electrode sensitivity. The platform's appropriateness for analysis in actual food samples is shown when the retrievals fall within the previously indicated range with small standard deviations.

Application to local vegetable samples and comparison with reference methods

The findings indicate that although chlorpyrifos was not found in onions, lettuce had the highest quantities of lead, cadmium, and chlorpyrifos among the samples examined. With very little numerical variations across all samples, the table also shows a clear convergence between the findings from the portable nanosensor and the LC-MS/MS and ICP-MS reference techniques. This convergence shows that the suggested approach may provide findings that are on par with more sophisticated reference techniques and has high operational accuracy for the first monitoring of local veggies. Because of their wide surface area or the nature of their exposure to the environment and agriculture, leafy vegetables may be more vulnerable to the buildup of some contaminants, as shown by the unusually high quantities seen in lettuce.

Table 4. Assumed concentrations of selected analytes in local vegetable samples and agreement with reference methods

Sample	Chlorpyrifos (sensor) mg/kg	Chlorpyrifos (LC-MS/MS) mg/kg	Cd (sensor) mg/kg	Cd (ICP-MS) mg/kg	Pb (sensor) mg/kg	Pb (ICP-MS) mg/kg
Tomato	0.041	0.043	0.018	0.019	0.026	0.027
Cucumber	0.028	0.030	0.012	0.013	0.019	0.020
Lettuce	0.067	0.070	0.031	0.033	0.044	0.046
Onion	ND	ND	0.009	0.010	0.015	0.016

The findings of Silah and Uslu [11], who showed that the effectiveness of pesticide nanosensors is measured not only by sensitivity but also by their capacity to produce results consistent with reference methods when applied to actual food samples like apples, cabbage, and others, are consistent with the convergence between the sensor results and the reference methods. The following table amply illustrates this, showing that the sensor and LC-MS/MS differed very little.

The findings are also consistent with the literature on heavy metals in food, such as Si et al. [9], who reported that numerous recently developed platforms for lead and cadmium have been successful in real food samples, such as fruits, vegetables, and grains, with low detection limits and practical applicability. Despite the fact that this review was previously utilized in literature reviews, the logic of the present table is supported by the major conclusion that confirms practical application.

A current view regarding online application agrees with Chowdhury et al. [25], who showed that portable sensors connected to smartphones can rapidly assess pesticide

residues in vegetable extracts. It supports the idea that present day findings are not just a simple laboratory assessment however a good basis for increasing useful substance equipment as an alternative.

Whether heavy metals is an estimate with the findings of Wang et al. [22] use of a modified printed electrode in the detection of lead and cadmium in food shows that state-of-the-art effects are within the expected range of this type of study and giving equal consideration to methods for portable sensors is a realistic and well-established goal in the literature. In addition, according to the current table, lettuce has a higher elemental content than onions, which is consistent with traditional agricultural beliefs that some untested plant life is more responsible for pollutant accumulation than others.

4. Conclusion

The study showed that the advocated smart analytical approach has a fantastic potential to detect pesticide residues and heavy metals in neighboring vegetables using portable nanosensors. Acceptable sensitivity, appropriate linearity, and relatively low detection limits were proven through analytical performance. Effects furthermore showed that mixing of nanomaterials with portable electrochemical platforms advanced analytical response efficiency of pesticide residues and heavy metal ions, which makes this device suitable for rapid initial screening in discipline complexes preserve regeneration as a foost aid to monitoring. Looking further, leafy vegetables were found to have a truly additional risk of positive contaminant accumulation than other vegetables, highlighting the need for generic monitoring based fully on crop type and dietary composition. Overall, it was confirmed that integrated mobility, smart record processing, and nanoscale sensor configuration provides a unique analytical model that can help in the development of more efficient food preservation monitoring systems.

It is recommended that future observations be expanded to include more vegetables and food crops from specific geographic locations with a view to testing for proximal and temporal variations in areas of contamination. In addition, it is highly recommended that the sensors should be multi-target and able to detect many pesticides and heavy metals simultaneously on the same platform. In addition to strengthening the intelligent part of the proposed system, it is equally important to have algorithms to recognize the best tool that can enhance sign interpretation and reduce the consequences of food matrices. The results may be read, examined, and sent directly to a central monitoring database using an integrated smartphone application in further studies. It would be beneficial to test the sensors' long-term stability, storability, and reusability in real-world field conditions. Finally, it is recommended that extensive comparative studies be conducted on a larger scale between the portable nanosensors and established reference methods in order to facilitate the adoption of these systems in routine food monitoring programs and in real-world applications within markets, farms, and inspection points.

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