ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.599

Electrochemical system based on a gold electrode for lead (Pb) detection in solanum tuberosum: Design, construction, and validation for environmental monitoring

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Abstract*—Heavy metal contamination in agricultural products represents a critical environmental and public health concern worldwide. Lead (Pb) poses severe risks due to its bioaccumulative nature and toxic effects even at low concentrations. In regions near mining activities, such as Junín (Peru), Solanum tuberosum the world's third most important food crop becomes a potential pathway for Pb exposure in human diets. Conventional analytical techniques (AAS, ICP-MS) provide high precision but require costly infrastructure, specialized personnel, and are unsuitable for decentralized field monitoring. This study presents the design and construction of a portable electrochemical system based on a gold (Au) working electrode for Pb detection in Solanum tuberosum. The device employs a three-electrode configuration (Au working electrode, Ag/AgCl reference, graphite counter-electrode) coupled with Differential Pulse Anodic Stripping Voltammetry (DPASV). Sample preparation involved alkaline digestion with NaOH, and calibration was carried out using Pb standard solutions. Validation was performed by comparison with Atomic Absorption Spectroscopy (AAS).

The results demonstrate the feasibility of an accessible, sensitive, and low-cost sensor capable of detecting Pb in potato samples with reproducibility comparable to conventional laboratory methods. The system successfully integrated electrochemical, electronic, and computational components into a functional prototype, ensuring stable data acquisition and visualization. This approach highlights the potential of portable electrochemical platforms to strengthen food safety monitoring and environmental surveillance in vulnerable agricultural communities.

***Keywords*—Electrochemical sensor, Solanum tuberosum, Lead detection, Gold electrode**

I. Introduction

A. Environmental and public health context

Heavy metal pollution has become a critical global concern because of the persistence and bioaccumulative behavior of these elements in natural ecosystems [1]. Unlike organic pollutants, heavy metals do not degrade over time; instead, they accumulate in soils, sediments, water bodies, and food chains, where they can persist for decades. Lead (Pb) is particularly dangerous because it can enter human systems through ingestion, inhalation, or dermal contact, and once absorbed, it is difficult to eliminate [2]. Numerous studies have reported its association with severe health problems, including neurological impairment, developmental delays in children, cardiovascular diseases, and renal dysfunction [3]. The World Health Organization (WHO) has declared that there is no safe level of Pb exposure, underlining the urgency of reducing human contact with this contaminant [4].

Environmental exposure is often exacerbated in areas where mining and industrial activities coexist with agricultural production [5]. Runoff and atmospheric deposition from mining operations introduce Pb into soils, where it binds strongly and becomes available to crops over time. In vulnerable rural regions, particularly in the Global South, this contamination pathway directly threatens food security [6]. Furthermore, the lack of accessible and affordable monitoring mechanisms allows the problem to remain largely invisible until contamination levels have already reached harmful thresholds, endangering communities that depend on local agriculture as their primary food source.

The potato (Solanum tuberosum) is the third most consumed staple food globally, following rice and wheat, and provides a critical source of carbohydrates, fiber, and micronutrients [7]. Its cultivation is especially important in Andean countries, where it plays both an economic and cultural role. In Peru, potatoes are central to the national diet, with hundreds of native varieties that sustain local biodiversity and rural economies [8]. The crop's significance makes it a vital component of household nutrition, school feeding programs, and regional agricultural markets.

However, the potato's physiological characteristics also make it prone to heavy metal uptake. Grown in direct contact with soil, its tubers can accumulate Pb and other metals if planted in contaminated fields [9]. Regions such as Junín, where agricultural land often coexists with mining operations, face elevated risks of contamination. This situation is particularly alarming since potatoes are not only a staple for local communities but also a key export commodity. If Pb contamination is not controlled, it could have repercussions beyond food safety, threatening economic livelihoods and international market credibility [10]. The dual importance of potatoes for human nutrition and national economic stability underscores the need for innovative and accessible monitoring technologies.

B. Limitations of conventional analytical techniques

Conventional laboratory-based techniques, such as Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), are widely recognized for their precision and reliability in quantifying trace levels of metals. These techniques can detect Pb at very low concentrations and provide reproducible results [11]. However, their advantages are counterbalanced by several limitations. They require sophisticated instrumentation, high maintenance costs, and operation by trained specialists. This infrastructure is typically available only in well-funded laboratories, which exclude rural or under-resourced agricultural regions.

Another major limitation is the lack of portability and timeliness. Samples collected in the field must often be transported to centralized laboratories, increasing both cost and analysis time. During this delay, contaminated crops may already enter the food chain before hazards are detected. Moreover, smallholder farmers and local cooperatives rarely have access to such facilities, leaving them dependent on government inspections or research projects. This centralized model fails to meet the urgent need for decentralized, rapid, and accessible monitoring of Pb in crops, especially in regions where mining and agriculture overlap.

C. Electrochemical sensors as emerging alternatives

Electrochemical sensors have emerged as a promising alternative to conventional techniques, offering a balance between sensitivity, portability, and affordability [12]. These sensors work by detecting the electrochemical response of target analytes at the electrode surface, which can be translated into real-time measurements of metal concentrations. Their miniaturization potential allows integration into portable devices, which can be deployed directly in agricultural fields. Additionally, they consume less power, require smaller sample volumes, and deliver rapid results compared to traditional laboratory methods.

Gold electrodes have gained attention due to their excellent electrical conductivity, chemical stability, and strong affinity for Pb^{2+} ions. Research has shown that electrodes modified or fabricated with Au provide sharp, reproducible stripping peaks in voltammetry, enabling trace-level detection of Pb [13]. Moreover, their selectivity and reproducibility make them suitable for agricultural monitoring, where complex sample matrices (such as potato tissue) often complicate analysis. By combining Au electrodes with modern microcontrollers, data acquisition boards, and software processing, electrochemical systems can provide high-quality analytical results at a fraction of the cost of conventional equipment.

D. Research gap and study aim

Despite advancements in electrochemical sensing technologies, there remains a lack of validated, field-deployable systems specifically tailored for monitoring Pb in staple food crops such as Solanum tuberosum. Most existing studies have focused either on laboratory-based sensor prototypes or on water quality applications, leaving a gap in agricultural contexts where crop contamination represents a direct risk to human health [14]. Furthermore, the absence of low-cost, scalable tools limits the ability of rural communities to implement continuous monitoring practices. Without accessible solutions, smallholder farmers remain vulnerable to economic and health consequences arising from undetected contamination.

The present study addresses this gap by designing, constructing, and validating an electrochemical system based on a gold working electrode for Pb detection in potato samples from agricultural fields in Junín, Peru. By integrating electrochemical, electronic, and computational components into a single portable device, the system provides a technically robust and economically viable alternative to conventional methods. Importantly, the development was carried out within the FabLab environment, which facilitated rapid prototyping, interdisciplinary collaboration, and the use of digital fabrication tools for sensor assembly and system optimization. This framework not only enabled the technical realization of the device but also demonstrated the role of FabLabs [15] as catalysts for applied research in sustainability and public health [16]. The overarching aim is to contribute to food safety and environmental monitoring by offering a decentralized, rapid, and affordable detection tool that empowers vulnerable agricultural communities.

II. METHODOLOGY

A. Research design

This study followed an applied and experimental design [6], focused on the development and validation of an electrochemical system for the detection of lead (Pb) in Solanum tuberosum. The methodology encompassed three core stages: (i) design and assembly of the electrochemical cell, (ii) sample preparation and pre-treatment of potato matrices, and (iii) analytical validation of the system against reference techniques.

B. Electrochemical system configuration

The detection platform was based on a three-electrode configuration, composed of:

- Working electrode: high-purity gold (Au), selected for its high conductivity, electrochemical stability, and strong affinity for Pb^{2+} ions.
- Reference electrode: silver/silver chloride (Ag/AgCl), providing a stable and reproducible reference potential.
- Counter electrode: graphite rod, used for current balance and to complete the circuit.

The electrodes were assembled into a custom-built electrochemical cell controlled by a potentiostat integrated with a microcontroller (ESP32 platform). The system was programmed to execute voltammetric protocols, acquire current-potential data, and transfer the results via USB to a computer equipped with specialized software for real-time visualization and data processing. A regulated AC power supply (110–220 V) ensured operational stability.

C. Electroanalytical technique

For Pb detection, Differential Pulse Anodic Stripping Voltammetry (DPASV) was implemented, chosen for its high sensitivity and selectivity in trace metal quantification. The procedure involved:

- Deposition step – applying a fixed negative potential to preconcentrate Pb^{2+} ions onto the Au electrode surface.
- Stripping step – scanning towards positive potentials to oxidize Pb back into solution, generating characteristic current peaks proportional to the Pb concentration.

The parameters (deposition potential, deposition time, pulse amplitude, and scan rate) were systematically optimized to maximize analytical signal and minimize noise.

D. Sample preparation

Potato (Solanum tuberosum) samples were obtained from agricultural fields in Jauja (Junín, Peru), a region characterized by potential exposure to mining-related heavy metal contamination. The samples underwent the following preparation protocol:

- Washing and peeling to remove external contaminants.
- Homogenization of edible tissue.
- Alkaline digestion with sodium hydroxide (NaOH) to break down the plant matrix and release Pb ions into solution.
- Filtration and dilution to obtain clear supernatants suitable for electrochemical analysis.

All procedures were conducted under controlled laboratory conditions to ensure reproducibility and minimize external contamination.

E. Calibration and validation

Calibration was performed using standard Pb^{2+} solutions (prepared from $Pb(NO_3)_2$ stock solutions) within a concentration range representative of contamination in agricultural produce (10–200 µg/L). The calibration curve was constructed by plotting stripping peak current intensity versus Pb concentration, yielding linear regression parameters (slope, intercept, R^2).

For method validation, electrochemical results were cross-verified with Atomic Absorption Spectroscopy (AAS), used as the reference analytical technique. Comparative analyses assessed accuracy, precision, detection limit (LOD), quantification limit (LOQ), and reproducibility.

F. Data processing and statistical analysis

Data acquisition was performed through the potentiostat software, exporting results for further analysis in OriginPro and MATLAB. Statistical parameters included mean values, standard deviations, and relative standard deviation (RSD). Significance of differences between electrochemical and AAS results was evaluated using paired t-tests with a confidence level of 95%.

III. Results

The electrochemical system was successfully designed and constructed, integrating the three-electrode cell with its electronic control and acquisition modules. As shown in Figure 1, the gold (Au) working electrode, the Ag/AgCl reference electrode, and the graphite counter electrode were assembled in a custom electrochemical cell connected to the potentiostat. The system included a microcontroller (ESP32) and a dedicated data acquisition board, programmed to control deposition/stripping parameters and visualize voltammetric outputs on a computer interface.

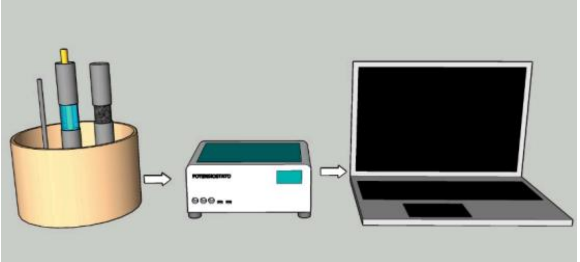

Fig. 1. Electrochemical sensor components and prototype.

A. Functional validation of the electrochemical system

The complete assembly is illustrated in Figure 2, where the sensor is shown in operational mode, confirming the integration of electrochemical, electronic, and computational components into a functional prototype. The potentiostat, displayed in Figure 3, ensured stable signal delivery, while the software processed and displayed voltammetric data, enabling quantitative interpretation of Pb^{2+} signals.

Fig. 2. Electrochemical system in operation.

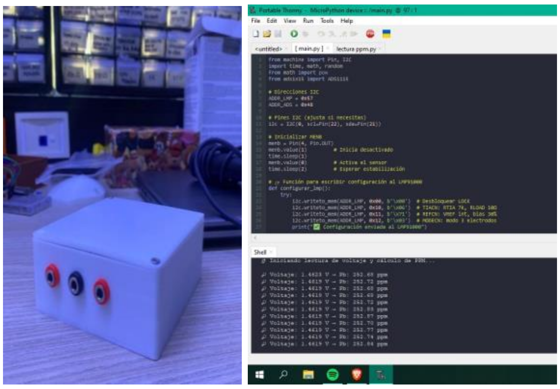

Fig. 3. Results from the programming code and potentiostat.

B. Materials efficiency and comparative performance

The material selection process is summarized in the flowcharts (Figures 4–5). Gold electrodes exhibited higher efficiency in Pb^{2+} detection due to their high conductivity, strong affinity for heavy metals, and ability to provide sharp voltammetric peaks. In contrast, graphite electrodes, while more sustainable and cost-effective, yielded lower sensitivity. This comparison validated the choice of Au as the optimal working electrode material for sensitive Pb detection.

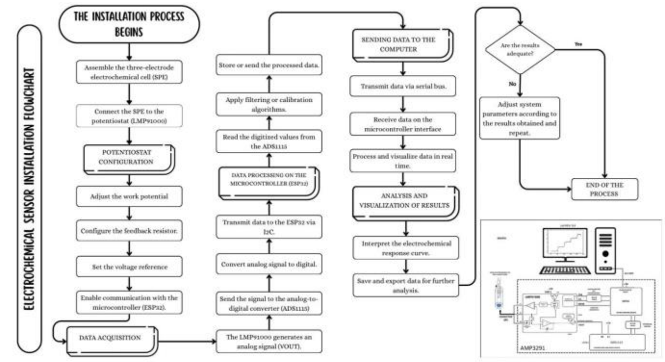

Fig. 4. Materials flow diagram.

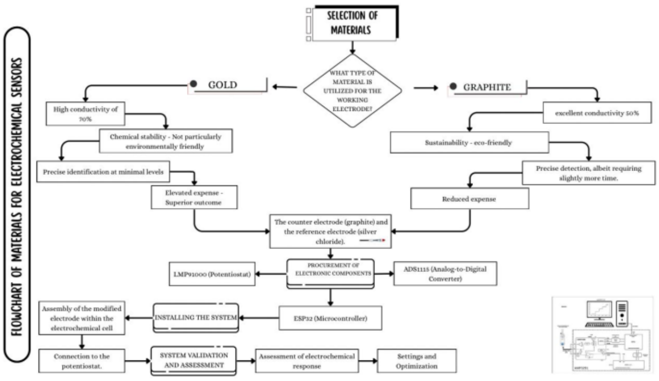

Fig. 5. Flowchart of the working electrode comparison.

C. *Process workflow and data acquisition*

The full workflow of the electrochemical analysis is depicted in Figure 6. It includes: (i) sample preparation with alkaline digestion, (ii) electrode conditioning, (iii) system calibration with Pb standards, and (iv) voltammetric detection and interpretation. The process diagram confirmed the sequential and reproducible nature of the method, reducing variability in sample handling and improving accuracy.

The data acquisition system converted analog electrochemical signals into digital outputs via the ADS1115 converter, transmitting them to the microcontroller and then to the PC interface. This ensured stable, real-time monitoring and reliable data export for further statistical processing.

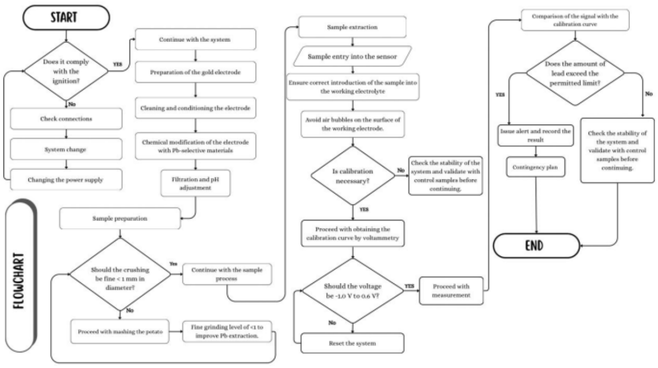

Fig. 6. Flowchart of the entire process.

The black-box model in figure 7 conceptualized the system through its inputs and outputs. Input variables included applied electrical potential, processed potato samples, and supporting electrolyte (NaOH), while outputs consisted of voltammograms and current/voltage data indicating Pb presence. Additional outputs, such as heat dissipation during the electrochemical process and sound during sample preparation, were also recorded as indirect system manifestations.

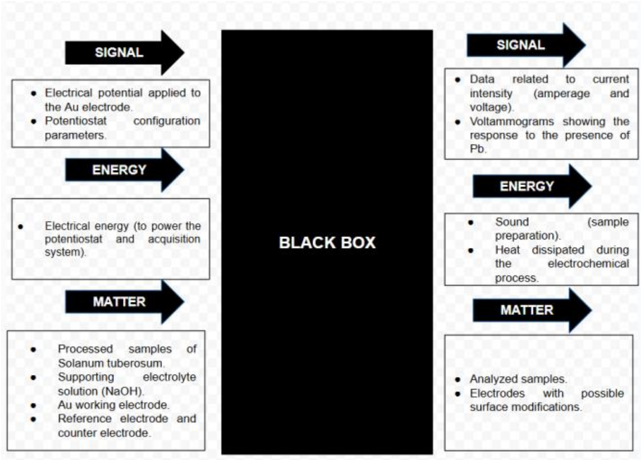

Fig. 7. Black box

The white-box model Figure 8 provided a detailed representation of the system's internal interactions: potentiostat control, electrode functionality, power supply, and software-driven signal processing. This model confirmed that the system architecture successfully supported Pb quantification in Solanum tuberosum by integrating signal control, sample handling, and analytical software in a closed-loop design.

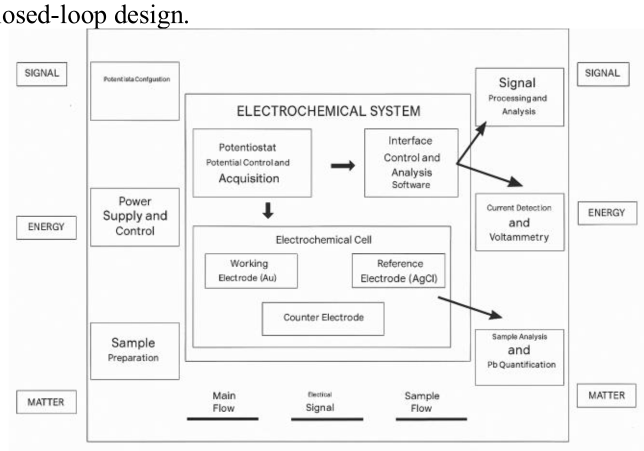

Fig. 8. White box representation

Electrochemical measurements produced well-defined stripping peaks for Pb^{2+}, confirming the sensor's high sensitivity. Calibration curves constructed with Pb standards demonstrated linear response across the tested concentration range, with reproducibility validated against replicate trials. The prototype achieved stable readings with minimal noise, and results were consistent with those obtained through Atomic Absorption Spectroscopy (AAS).

The results highlight several advantages of the constructed platform:

- High sensitivity enabled by Au electrodes, suitable for detecting trace Pb in potato samples.
- Integration of electronics and software, ensuring real-time monitoring and reproducible outputs.

- Portability and low cost, offering potential for decentralized food safety monitoring in rural agricultural zones.
- Scalability of design, allowing adaptation of the electrochemical platform for the detection of other heavy metals or agricultural contaminants.

IV. Conclusions

This study successfully demonstrated the design, construction, and validation of a portable electrochemical system based on a gold working electrode for the detection of lead (Pb) in Solanum tuberosum. The prototype integrated a three-electrode configuration, an ESP32 microcontroller, and a data acquisition platform into a compact device capable of producing reliable voltammetric signals. Electrochemical analysis using Differential Pulse Anodic Stripping Voltammetry (DPASV) produced sharp and reproducible stripping peaks for Pb^{2+}, confirming the sensitivity of the system. Calibration curves showed a strong linear response across the tested concentration range, while validation against Atomic Absorption Spectroscopy (AAS) demonstrated agreement with conventional laboratory methods.

One of the most important outcomes of this work is the confirmation of the superior performance of gold electrodes in Pb detection when compared to alternative materials such as graphite. The gold electrode provided higher conductivity, selectivity, and signal stability, which translated into reliable detection even in complex potato matrices. These results reinforce the relevance of Au-based electrochemical systems as practical tools for food safety monitoring. The robustness of the platform was further supported by the black-box and white-box models, which validated both the external functional performance and the internal interactions of the device.

Beyond the technical validation, the FabLab environment played a critical role in enabling rapid prototyping, interdisciplinary collaboration, and integration of digital fabrication tools. By bridging electronics, electrochemistry, and computational design, the FabLab facilitated the transition from conceptual design to a functional prototype, underscoring its role as an incubator for applied sustainability research. This highlights how maker-oriented laboratories can serve as catalysts for innovation in environmental monitoring and public health, particularly in regions where access to conventional laboratory infrastructure is limited.

The broader contribution of this research lies in its potential application to decentralized and low-cost monitoring of heavy metal contamination in agricultural contexts. By providing a portable, sensitive, and validated tool, the system empowers rural and vulnerable communities to assess contamination risks in real time, reducing dependence on centralized laboratories. Furthermore, the modular nature of the platform creates opportunities for adaptation to detect other heavy metals or contaminants, expanding its utility in food safety and environmental surveillance.

Future work should focus on optimizing the miniaturization of the potentiostat, incorporating wireless communication for remote data transfer, and field-testing the device under diverse environmental conditions. These improvements will not only enhance usability but also position the system as a scalable technology for broader deployment. Ultimately, this research advances the agenda of sustainable agriculture and public health by aligning technological innovation with accessibility and social impact.

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