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Functional Integration of a Portable Non-Enzymatic Electrochemical Glucose Sensor in Simulation-Based Medical Education Through a Teleconsultation Workflow

Leonel Vasquez-Cevallos [1,*], Darwin Castillo [2,*], Pedro A. Salazar-Carballo [3], Paul E.D. Soto-Rodriguez [4], Franklin Parrales-Bravo [5,6] and Roberto Tolozano-Benites [6]

[1] Facultad de Ingenierías, Arquitectura y Ciencias de la naturaleza, Universidad Ecotec, Km. 13.5 Samborondón, Samborondón, EC092302, Ecuador

[2] Departamento de Química, Facultad de Ciencias Exactas y Naturales, Universidad Técnica Particular de Loja, San Cayetano Alto s/n, Loja 11-01-608, Ecuador

[3] Instituto de estudios avanzados IUDEA, Departamento de Física, Universidad de La Laguna, C/Astrofísico Francisco Sánchez, s/n. E-38203, Tenerife, Spain

[4] Laboratory of Sensors, Biosensors and Advanced Materials, Institute of Materials and Nanotechnology, University of La Laguna, ULL, La Laguna, Spain

[5] Faculty of Computer Science, Complutense University of Madrid, 28040 Madrid, Spain

[6] Universidad Bolivariana del Ecuador, UBE, Km 5 ½ vía Durán—Yaguachi, Durán 092405, Ecuador; rtolozano@ube.edu.ec

* Correspondence: lvasquez@ecotec.edu.ec (L.V.-C.); dpcastillo@utpl.edu.ec (D.C.); Tel.: +593-993507013 (L.V.-C.)

Abstract

Introduction: Portable non-enzymatic electrochemical glucose sensors offer potential for decentralized healthcare and medical education; however, their integration into clinically meaningful teleconsultation workflows remains limited. This study presents the functional integration of a portable copper-modified electrochemical glucose sensor into a rural web- and Android-based telemedicine platform within a simulation-based medical education framework. **Materials and Methods**: Screen-printed carbon electrodes were electrochemically activated and modified via copper electrodeposition. Electrochemical characterization was performed using cyclic voltammetry to identify the glucose oxidation region and chronoamperometry for quantitative detection. Glucose solutions in PBS (pH 10) were measured using 70 µL samples, and the resulting signals were converted into glucose values (mg/dL) through a calibration model and incorporated into simulated gynecological teleconsultation workflows. **Results:** The sensor exhibited a stable amperometric response at +0.60 V, with a linear range of 3.125–50 mM ($R^2 = 0.9822$), an area-normalized sensitivity of 0.061 $\mu A \cdot mM^{-1} \cdot cm^{-2}$, and a limit of detection of 1.39 mM. Implementation within the simulation scenario (n = 26) demonstrated 69% high/very high perceived usability and 88% high/very high educational value. **Conclusion:** These results support the feasibility of integrating portable electrochemical sensing into teleconsultation-based training environments and establishing a practical framework for future validation and deployment in rural telemedicine applications.

Keywords: non-enzymatic glucose sensor; portable sensor; copper-modified electrode; electrochemical sensing; telemedicine; teleconsultation; simulation-based medical education

1. Introduction

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Diabetes is a major contributor to global mortality, with approximately 3.4 million deaths reported in 2024 [1,2]. This burden is particularly significant in developing countries, such as Ecuador, where limited healthcare resources and systemic constraints hinder effective disease management [3,4]. Meanwhile, undergraduate students require safe and structured training environments to develop practical skills and clinical decision-making in diabetes-related care [5]. Consequently, there is a growing need for accessible and cost-effective glucose monitoring solutions that can support both decentralized healthcare delivery and health science education settings [6].

In this context, electrochemical sensing platforms enable portable glucose detection through the integration of miniaturized electrodes and portable potentiostats [7–9]. A key advancement is the transition from enzymatic to non-enzymatic sensors, as enzymatic approaches are constrained by the instability of glucose oxidase [10]. Non-enzymatic sensors rely on the direct oxidation of glucose at electrocatalytic surfaces, including nanostructured transition metal oxides, noble metals, and carbon-based materials [11]. Among these, carbon electrodes can be electrochemically activated via cyclic voltammetry and subsequently modified through copper electrodeposition, generating redox-active sites that enhance glucose oxidation [12,13]. The resulting electrochemical response is commonly characterized using cyclic voltammetry and chronoamperometry, with glucose concentration quantified through linear calibration models [13,14].

Despite these advancements, the practical adoption of portable electrochemical sensors within telemedicine platforms and simulation-based environments remains challenging because of the limited seamless integration of sensor outputs into clinical and educational workflows [17–19]. This challenge is compounded by the need for efficient conversion of raw electrochemical signals into clinically interpretable information [15], which often requires additional post-processing to obtain quantitative glucose values [8,16].

Building upon these identified gaps, this study aimed to evaluate the feasibility and practical integration of a portable copper-modified non-enzymatic electrochemical glucose sensor into a web- and Android-based telemedicine platform. Specifically, it investigated whether electrochemical signals could be reliably converted into clinically interpretable glucose values (mg/dL) and seamlessly incorporated into a teleconsultation workflow for use in simulated gynecological scenarios.

2. Materials and Methods

2.1. Portable Electrochemical Sensor Platform

Screen-printed carbon electrodes (ED-S1PE-C21, MicruX Technologies, Spain) were used for all electrochemical experiments. Each strip integrates a carbon working electrode (3 mm diameter; 7.1 mm^2 geometric area), a carbon auxiliary electrode, and a printed silver pseudo-reference electrode on a single substrate, providing a compact configuration suitable for portable measurements. The configurations of the working (WE), reference (RE), and auxiliary (AE) electrodes, along with their corresponding electrical contact pads, are illustrated in Figure 1a [20,21].

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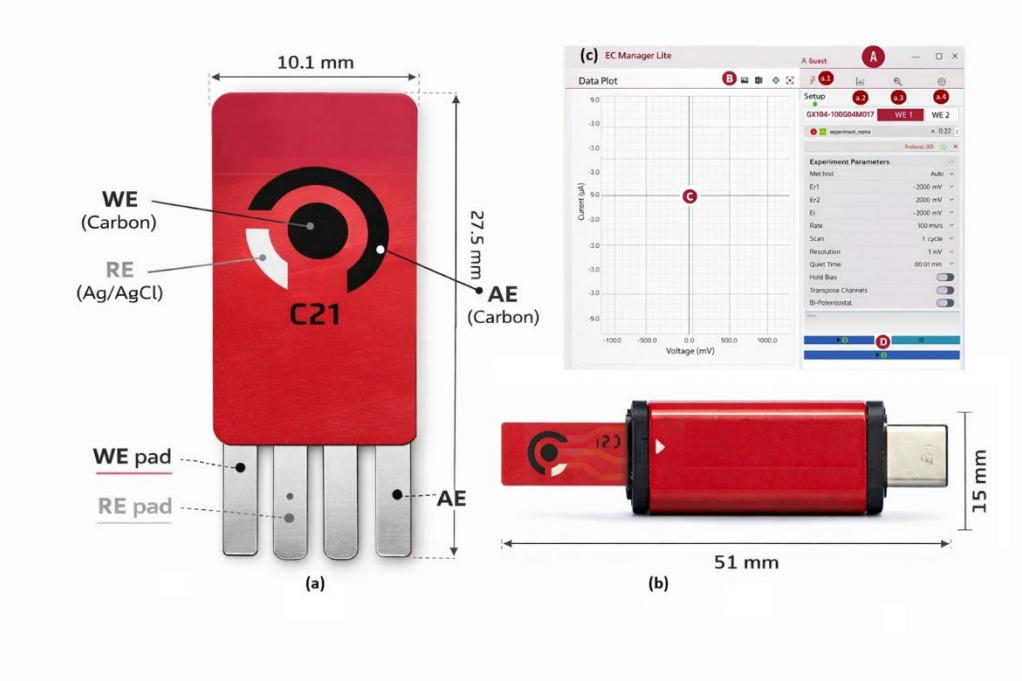

Figure 1. Electrochemical sensing platform: (a) Screen-printed carbon electrode (ED-S1PE-C21). (b) Portable ECSens bipotentiostat. (c) Graphical User Interface (GUI) of EC Manager Lite for Windows PC.

Electrochemical measurements were performed using a MicruX ECSens BIPOT bipotentiostat (MicruX Technologies, Spain). The device applies controlled potential waveforms and records the resulting current response for voltammetric and amperometric measurements. It operates within a potential range of ±1.5 V, with current measurements spanning from µA to mA and a potential resolution of 250 µV, enabling sensitive detection using screen-printed electrodes. The physical configuration with the inserted electrode is shown in Figure 1b [22].

EC Manager Lite is a graphical user interface (GUI) used to control the MicruX ECSens BIPOT electrochemical sensing system. The software supports experiment setup, execution, visualization, and data management. As shown in Figure 1c, the interface includes modules for (A) protocol and parameter configuration, (B) data visualization and export, (C) real-time current–potential display, and (D) measurement control. Data can be exported in spreadsheet formats (e.g., XLSX) for further analysis, while graphical outputs can be saved as image files (e.g., PNG or JPEG) [22].

Direct copper electrodeposition on commercially available screen-printed carbon electrodes was selected as a simple and reproducible approach compatible with integration into telemedicine and simulation-based workflows, avoiding the complexity of nanostructured sensor fabrication.

2.2. Electrode Preparation and Electrochemical Characterization

All reagents were of analytical grade. D-glucose powder was used to prepare standard solutions in phosphate-buffered saline (PBS, pH 10) using an analytical balance and calibrated micropipettes to ensure accurate concentrations. Distilled water was used to rinse the electrodes during the preparation. Solutions were handled under standard laboratory conditions.

Electrode preparation began with the electrochemical activation of the carbon electrodes on the screen-printed three-electrode area (ED-S1PE-C21, comprising working, reference, and auxiliary electrodes). A 70 µL droplet of 1 mM NaOH solution was applied to the working electrode, and activation was performed using an ECSens BIPOT potentiostat. The potential was scanned from 0.0 V to −2.0 V, promoting the formation of oxygen-containing functional groups on the carbon surface, which increases the electroactive area and facilitates subsequent copper nucleation [23–25].

Following electrochemical activation, the screen-printed three-electrode area was rinsed with distilled water to remove residual species. Copper electrodeposition was subsequently performed by

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applying a 70 µL droplet of 0.1 M $CuSO_4$ onto the same area. A three-step chronoamperometric deposition protocol was then applied within the same droplet, with potentials sequentially shifted toward more negative values (−0.05 V for 100 s, −0.40 V for 350 s, and −0.60 V for 650 s). This sequence was initially defined based on prior copper-based electrodeposition approaches [26] and subsequently optimized empirically to achieve stable copper deposition on the carbon working electrode through Cu^{2+} ion reduction. The resulting copper-modified surface exhibited behavior consistent with the reported electrocatalytic behavior of copper-based electrodes for non-enzymatic glucose detection [26,27].

The glucose standard solutions were prepared based on the following molar relationship:

$$m=C\times V\times M, \quad (1)$$

where m is the glucose mass, C is the target concentration, V is the solution volume, and M is the molecular weight of D-glucose (180.16 $g\cdot mol^{-1}$). A 100 mM stock solution was prepared by dissolving 36.0 mg of D-glucose in 2 mL of solution. Additional standards (50, 25, 12.5, 6.25, and 3.125 mM) were obtained by serial dilution for electrochemical measurements, enabling the calibration of the sensor response across the studied concentration range [28,29].

Using the same electrochemical setup described above, electrochemical characterization and glucose calibration were performed by cyclic voltammetry to identify the glucose oxidation region, followed by chronoamperometry at a fixed potential. Initially, a 70 µL PBS droplet was placed on the electrode surface. The glucose concentrations were then adjusted by replacing 35 µL of PBS with 35 µL of glucose solution prepared in PBS, maintaining a constant final volume of 70 µL. Accordingly, the final concentration was $C_{(final)} = C_{(added)} \times (V_{(added)} / V_{(total)})$. The steady-state current was recorded at increasing glucose concentrations, and a calibration curve (current vs. glucose concentration) was obtained to evaluate electrode sensitivity.

2.3. Telemedicine Integration in Simulated Gynecology Workflows

The telemedicine platform used was based on a web- and Android-based telemedicine platform (WATP) [30], which evolved from earlier initiatives for rural healthcare and medical training in Ecuador. Previous work validated an initial web-based platform for clinical case discussion and medical education; however, it was limited to browser-based interactions [31]. An AWS-hosted telemedicine deployment was later introduced for rural Cayapas communities and showed limited adoption [32]. To address these limitations, a new WATP was introduced in 2022, incorporating an Android-based telemedicine app (ABTapp) for rural practitioners and medical students, with a web platform for specialists and faculty. This platform was developed using an iterative, user-centered design and included offline functionality for teleconsultation in low-connectivity environments [30,33,34].

To address the identified limitations in user engagement, a structured educational implementation strategy was adopted, integrating real and simulated clinical cases within rotating nursing internship programs and final-year undergraduate medical courses. Teleconsultation was implemented through an asynchronous workflow in which clinical cases were generated, submitted, and reviewed by students and supervising faculty as part of a formative assessment process [33,34].

To operationalize this integration, a gynecology simulation scenario was designed following a simulation-based medical education framework, including structured preparation and pre-briefing, and was implemented as a skills-based activity in Simulation Zone 1 at the SIMUEES Clinical Simulation Center [35]. The activity was conducted during the first academic term (April–August 2025) within the gynecology course. Simulated blood samples with five predefined glucose concentrations were prepared to reproduce clinical variability. The students handled the samples under standard precautions using gloves and a micropipette (70 µL), applied each sample to a previously modified working electrode, and acquired the electrochemical signal using the portable potentiostat described in the experimental section.

The measured current was converted into glucose concentration (mg/dL) using a spreadsheet-based calibration template derived from the experimental linear calibration model. The template was

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implemented as a standalone tool in which the steady-state current obtained from chronoamperometric measurements was manually entered, and the corresponding glucose value was automatically calculated. This value was then entered into the teleconsultation form within the telemedicine platform as part of a simulated gynecology clinical case. The activity was conducted as a supervised formative assessment, requiring students to interpret the obtained value in the clinical context and justify their diagnostic decisions during the teleconsultation process.

After the simulation activity, implementation was evaluated using a structured survey administered via the QuestionPro platform to assess perceived usability and formative value of the simulation scenario. Students and supervising faculty completed the questionnaire, providing feedback on the integration of electrochemical measurements within the teleconsultation workflow and its relevance for clinical learning. Participation was voluntary, and informed consent was obtained from all respondents prior to data collection. All procedures complied with the institutional ethical guidelines for educational research

3. Results

3.1. Electrochemical Performance of the Cu-Modified Electrode

Figure 2a compares the Cu-deposited electrode with the unchanged control, revealing a visible difference in the surface appearance after modification. The cyclic voltammetric response of the Cu-modified electrode in PBS (Figure 2b) exhibits an anodic peak at +0.60–+0.65 V and a cathodic peak at +0.38–+0.42 V during the reverse scan. Chronoamperometric responses recorded at +0.60 V, +0.65 V, and +0.70 V (Figure 2c) show higher current values at increasing potentials, accompanied by increased baseline variation. The amperometric response exhibited good repeatability, with a relative standard deviation below 4% under the tested conditions.

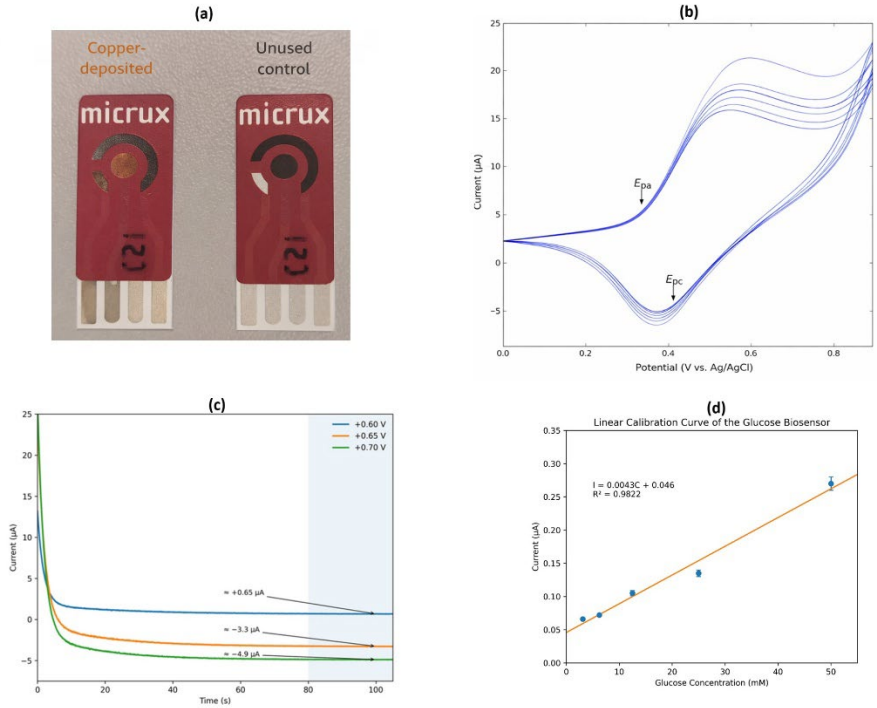

Figure 2. Electrochemical characterization and calibration of the glucose sensor. (a) Cu-modified vs. control electrode. (b) Cyclic voltammetry. (c) Chronoamperometric response. (d) Calibration curve.

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The calibration curve obtained from amperometric measurements is shown in Figure 2d. A proportional relationship between glucose concentration and the steady-state current was observed in the range of 3.125–50 mM, with a linear fit of $R^2 = 0.9822$. At 100 mM, a deviation from linearity was observed. The calibration slope was 0.00433 $\mu A \cdot mM^{-1}$, corresponding to an area-normalized sensitivity of 0.061 $\mu A \cdot mM^{-1} \cdot cm^{-2}$ for an electrode area of 0.071 cm^2. The limits of detection (LOD) and quantification (LOQ) were 1.39 mM and 4.62 mM, respectively.

3.2. Results of Telemedicine Integration in Simulated Gynecology Workflows

Figure 3 summarizes the simulation-based workflow for integrating electrochemical glucose measurement into teleconsultation and evaluating its perceived usability and educational value. Prepared glucose sample solutions were used, and each participant completed the measurement process, documented the results, and submitted a teleconsultation through the Cayapas platform. Among the 26 participants (n = 26), the evaluation showed high acceptance of the workflow, with 69% reporting high or very high perceived usability and 88% reporting high or very high educational value. These results support the feasibility of this integration as a simulation-based telemedicine approach with strong perceived learning benefits.

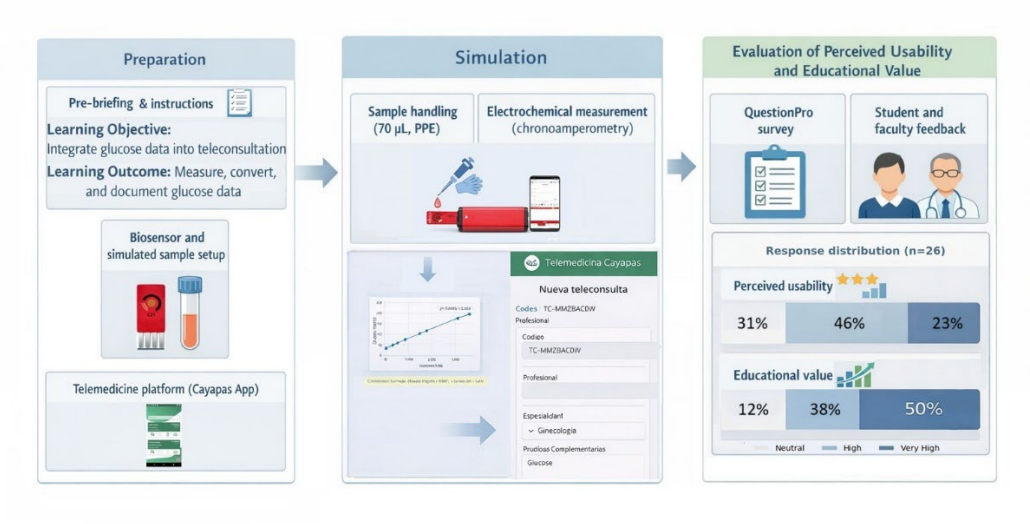

Figure 3. Implemented workflow for electrochemical glucose data integration into a simulated gynecological teleconsultation.

4. Discussion

The copper-modified carbon electrode exhibited a concentration-dependent amperometric response in PBS (pH 10), with linearity observed between 3.125 and 50 mM ($R^2 = 0.9822$). A slight deviation from linearity was observed at 100 mM glucose, which may be attributed to diffusion limitations or partial surface saturation at higher glucose concentrations. Cyclic voltammetry and chronoamperometry confirmed the electrochemical activity of the copper-modified surface at the selected operating potential of +0.60 V. The low relative standard deviation (< 4% RSD) further indicated good repeatability under the tested conditions. These findings support the use of direct copper modification of carbon-based electrodes for non-enzymatic glucose sensing under buffered conditions [26,27].

Rather than maximizing analytical performance through complex nanostructured architectures [36,37,39], the present study adopted direct copper electrodeposition on commercially available screen-printed carbon electrodes [26,27] as a practical strategy compatible with the intended simulation-based workflow. In this context, the value of the proposed sensor lies not only in glucose detection but also in its straightforward preparation, reproducible implementation, and compatibility

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with educational and teleconsultation-oriented settings, where operational simplicity is essential for system integration [40–42].

Furthermore, the usability and educational evaluation results (n = 26) showed favorable acceptance of the proposed workflow, with 69.23% of the participants reporting positive usability ratings and 88.47% indicating strong educational value. Neutral usability responses (26.92%) highlighted opportunities to refine the usage protocol and further improve the user experience and learning outcomes in this and other medical training courses. One potential improvement involves standardizing the interaction steps and providing brief user guidance prior to the simulation to enhance consistency and ease of use [40].

One study limitation, which represents the next step toward expanded validation of the proposed approach, is the need for validation under real biological conditions to address potential interferences and variability in clinical samples, as well as the inclusion of advanced electrochemical and physicochemical characterization of the sensor surface in future work. Nevertheless, the current approach using simulated samples provides a safe, reproducible, and low-cost framework for training, avoiding invasive procedures and reducing resource use. Additionally, educational validation was limited to a single academic period with a small sample of participants (n=26). This initial scope was chosen to enable the controlled implementation of the workflow and to assess its feasibility within the available training context. Future studies should extend validation to additional academic periods and larger cohorts, incorporating more realistic simulation scenarios and structured assessments to improve generalizability. This would enable the evaluation of knowledge retention, skill acquisition, and cognitive load, supporting the educational validity of the proposed approach. Overall, the proposed approach demonstrates the feasibility of integrating electrochemical glucose sensing into a teleconsultation-based training environment, providing a practical foundation for future clinical and educational applications.

5. Conclusions

This study demonstrated the integration of a portable copper-modified non-enzymatic glucose sensor into a rural telemedicine platform within a simulation-based medical education framework. The proposed workflow encompasses sensor preparation, electrochemical measurement, and the transformation of signals into clinically interpretable glucose values for teleconsultation. Therefore, the use of a portable electrochemical glucose sensor, simulated samples, and a gynecological teleconsultation simulation workflow provided a controlled and safe environment, enabling reproducible implementation within structured training scenarios.

In this context, the positive usability and educational perceptions observed among participants support the practical feasibility of this approach in simulation-based learning. The proposed workflow can be adapted to similar gynecological scenarios and extended to other medical training contexts where glucose monitoring is clinically relevant, supporting its replication across simulation centers.

In summary, this approach provides a practical framework for integrating electrochemical sensing into telemedicine-oriented medical education and establishes a foundation for further validation and transfer toward real-world healthcare applications.

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Data Availability Statement: Raw electrochemical data supporting the findings of this study, including cyclic voltammetry and chronoamperometric measurements, are available from the corresponding author upon reasonable request. No publicly archived datasets were generated in this study.

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Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the study design, data collection, analyses, or interpretation; manuscript writing; or the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

Ag	Silver
Ag/AgCl	Silver/Silver Chloride
AE	Auxiliary Electrode
CNTs	Carbon Nanotubes
CuO	Copper(II) Oxide
CV	Cyclic Voltammetry
LOD	Limit of Detection
LOQ	Limit of Quantification
MOF	Metal–Organic Framework
NaOH	Sodium Hydroxide
PBS	Phosphate-Buffered Saline
RE	Reference Electrode
RSD	Relative Standard Deviation
WE	Working Electrode
CA	Chronoamperometry
SPCE	Screen-Printed Carbon Electrode
GUI	Graphical User Interface
R^2	Coefficient of Determination
mg/dL	Milligrams per Deciliter

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