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Research Article

Glucose Sensor Obtained by Recycling Copper from Li-Ion Batteries

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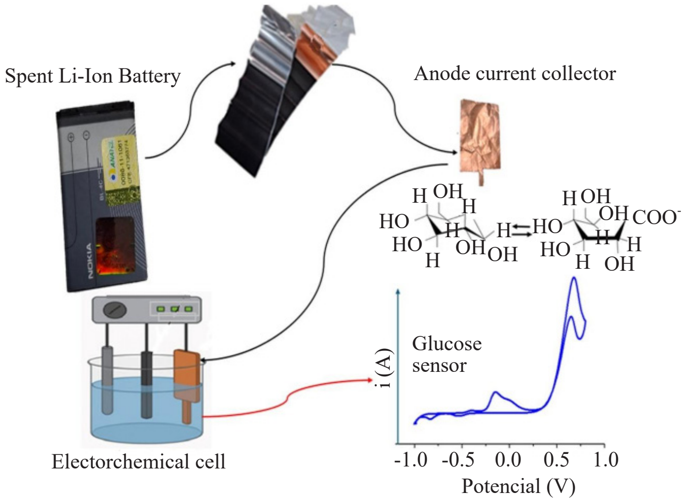
Received: 11 April 2025; **Revised:** 30 June 2025; **Accepted:** 8 July 2025

Graphical Abstract:



Abstract: The sustainable transformation of electronic waste into high-value functional materials represents a crucial challenge in modern science. In this work, we report the fabrication of a non-enzymatic glucose sensor using copper directly recovered from the anode current collectors of spent lithium-ion batteries—without any additional chemical treatment or surface modification. The recycled copper was characterized by X-Ray Diffraction and applied as a working electrode in alkaline media, where its electrochemical behavior was investigated by cyclic and linear sweep voltammetry. The sensor exhibited excellent analytical performance, including a wide linear range up to 400 ppm glucose ($R^2 = 0.99$), a low detection limit of 12.94 ppm (≈ 71.85 $\mu mol \cdot L^{-1}$), and a high specific sensitivity of 1,960 $\mu A \cdot mM^{-1} \cdot cm^{-2}$. Notably, common interferents such as fructose, uric acid, and ascorbic acid had negligible impact

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DOI: https://doi.org/10.37256/fce.6220256979

on the response, demonstrating strong selectivity. This study pioneers a cost-effective and environmentally friendly approach for electrochemical sensing, combining waste valorization with robust glucose detection, and advancing the circular economy through innovative material reuse.

Keywords**:** electrochemical glucose sensor, recycled copper, Lithium-Ion Battery

1. Introduction

The glucose detection plays a central role in the food industry, as glucose affects flavor, nutritional quality, preservation, and fermentation processes in products such as beverages, dairy, and processed foods. Non-enzymatic electrochemical sensors have emerged as effective tools for this application, offering advantages such as low cost, stability, fast response, and robust performance in complex matrices.[1] In the literature, copper electrodes modified by surface oxidation or chemical bath deposition are reported to form copper oxides (CuO or Cu_2O) with high electrocatalytic activity, enabling sensitive glucose detection suitable for food and biomedical applications. It has been demonstrated in the literature that CuO electrodes synthesized at pH 10 exhibit a sensitivity of 21.5 $mA \cdot mM^{-1} \cdot cm^{-2}$ and a detection limit of 1.1 mM, outperforming similar electrodes prepared at higher pH values.[2] The electrochemical detection of glucose using CuO-based electrodes in alkaline media follows a well-established redox mechanism. Initially, the surface CuO is electrochemically oxidized to CuOOH as shown in equation (1):[3]

$$CuO + OH^- \rightarrow CuOOH + e^- \quad (1)$$

The CuOOH species then serves as an active redox mediator, oxidizing glucose to gluconolactone and regenerating CuO in the process, as described in equation (2):[3]

$$2CuOOH + \text{glucose} \rightarrow 2CuO + \text{gluconolactone} + 2H_2O \quad (2)$$

This catalytic cycle results in the generation of an anodic current proportional to the glucose concentration. The non-enzymatic strategy is advantageous due to its low cost, chemical stability, and reproducibility. In recent studies, CuO-decorated laser-induced graphene electrodes have demonstrated detection limits as low as 9.7 µM with high sensitivity in real matrices such as artificial urine.[3]

The fabrication of nanocolumnar copper electrodes via Direct-Current Magnetron Sputtering (DC-MS) has also been reported, resulting in a highly porous and electrochemically active surface.[4] When tested in alkaline medium (50 mM NaOH), these nanostructured Cu electrodes exhibited a well-defined glucose oxidation peak at approximately + 0.68 V vs Ag/AgCl. This response is attributed to the electrochemical conversion of glucose into gluconolactone, possibly mediated by transient Cu(III) species, as illustrated in equations (1) and (2). The electrodes achieved a low detection limit of 5.2 µM and exhibited excellent selectivity, with minimal interference from common physiological species. This study highlights the potential of DC-MS-fabricated Cu nanostructures as scalable, low-cost, and robust platforms for non-enzymatic glucose sensing.

Moreover, recent studies have demonstrated that metallic copper itself can serve as an effective platform for non-enzymatic glucose sensors. In the work by Eissa et al.,[5] unoxidized Cu electrodes were employed as the conductive base for metal oxide coatings, with the copper core contributing to structural stability and efficient electron transfer. These findings support the strategy of using copper metal directly, as proposed in the present study, highlighting its potential as a sustainable and scalable sensing material. In addition to being a promising alternative for sensor construction, copper offers a major advantage: it can be efficiently sourced from Lithium-Ion Battery (LIB) recycling, contributing to both economic value and environmental sustainability. In LIBs, copper serves as the current collector of the graphite anode. While the scientific literature reports various strategies for recycling LIB components with applications in electrocatalysis, energy storage, water treatment, adsorption, and sensors,[6-11] most efforts have focused on cobalt, widely reused in electrochemical devices, including non-enzymatic glucose sensors. In contrast, the reuse of copper—despite its abundance, excellent electrical conductivity, and role in the anode current collector—remains underexplored. Given its ability to form electrocatalytically active species in alkaline media, favorable economic profile (mean ≈ US$ 4,418/ton from 1991-2020),[12] and potential to reduce reliance on virgin resources, copper stands out as an attractive and sustainable material for low-cost sensor platforms.

Thus, the use of copper as a sensor material to address two major challenges simultaneously: the demand for more efficient glucose sensors and the environmental impact of Lithium-Ion Battery (LIB) waste. This approach is timely, as the global expansion of portable electronics and electric vehicles has sharply increased LIB consumption and disposal. While essential to modern technologies, these batteries pose serious environmental risks when discarded improperly. Forecasts estimate over 11 million tons of LIB waste by 2030, potentially rising to 900 million tons by 2048 due to growing industrial and consumer demand.[6,7] This scenario has driven interest in recovering valuable metals from LIBs—such as lithium, cobalt, manganese, and copper—although copper remains comparatively underexplored for such applications.[6,12]

In this work, we propose the fabrication of a non-enzymatic glucose sensor using copper recovered from the anode current collectors of spent lithium-ion batteries. The recycled copper was employed directly—without any additional surface modification or oxidation treatment—and characterized via X-Ray Diffraction (XRD) prior to its use as the working electrode in alkaline solution. Electrochemical techniques, including cyclic voltammetry and linear sweep voltammetry, were used to evaluate the redox behavior of the electrode and its analytical performance in glucose detection. This approach demonstrates the potential of combining electronic waste recycling with the development of functional electrochemical sensors for practical applications in both food analysis and medical diagnostics.

2. Experimental

2.1 *Sample preparation and characterization*

Spent Lithium-Ion Batteries (LIBs) were manually disassembled to separate the anode, cathode, steel casing, separators, and current collectors. The carbon layer on the copper current collector (anode) was mechanically removed, and the collector was washed with distilled water until the rinse water appeared clear. The crystalline phase of the recovered anode material was analyzed by X-Ray Diffraction (XRD) using a Rotaflex-Rigaku 200 B diffractometer equipped with Cu Kα radiation, a Co filter, and a scan rate of 0.02° min^{-1}.

2.2 *Electrode preparation and electrochemical measurements*

Electrochemical experiments were performed in a conventional three-electrode cell at 25 °C using an Autolab PGSTAT 101 potentiostat. The working electrode consisted of copper recovered from the current collector, with an exposed surface area of 0.01 cm^2, while the remaining surface was insulated with electrical tape. A platinum plate (2 cm^2) served as the counter electrode, and a saturated Ag/AgCl electrode as the reference. Measurements were carried out in 0.1 mol·L^{-1} NaOH solution under quiescent conditions. A stock glucose solution (10 g·L^{-1}) was prepared, and aliquots were incrementally added to the cell (final volume: 10 mL) to achieve the desired concentrations. Cyclic voltammetry and linear sweep voltammetry were conducted after each addition to evaluate the electrochemical response. Tests were also performed with the addition of fructose (7.2 mg·L^{-1}), uric acid (50 mg·L^{-1}), and ascorbic acid (8.8 mg·L^{-1}) to assess the influence of potential interferents. A schematic representation of the copper recovery and application process was prepared to summarize the experimental workflow, as shown in Figure 1.

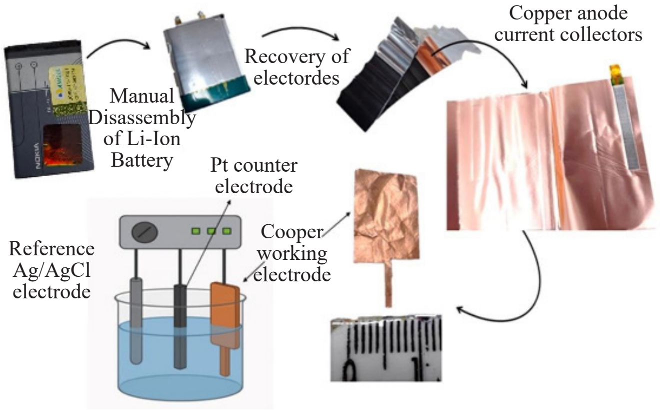

Figure 1. Schematic representation of copper recovery from the anode current collector of lithium-ion batteries and its application in the electrochemical detection of glucose in aqueous solution

3. Results and discussion

Figure 2 shows the X-Ray Diffraction (XRD) pattern of the complete anode from Li-Ion Batteries, which includes both the copper current collector and the carbon layer. The diffraction peaks confirm the presence of both carbon and metallic copper. The carbon layer was easily removed, allowing the copper collector to be reused in the fabrication of the electrodes.

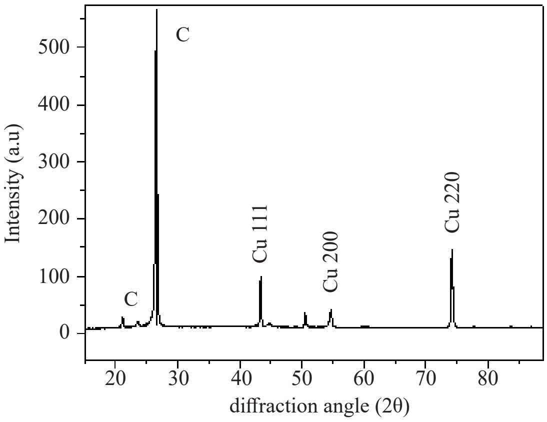

Figure 2. X-Ray Diffraction (XRD) pattern of the recycled anode from Li-ion batteries used in this study

Figure 3 shows the cyclic voltammetry profile of a copper electrode in 0.1 mol·L^{-1} NaOH solution. The voltammogram reveals a series of well-defined redox processes associated with the copper surface in alkaline media. During the anodic sweep, copper (Cu) is first oxidized to Cu_2O, followed by further oxidation to $Cu(OH)_2$ and eventually to CuOOH at more positive potentials.

In the cathodic scan, these species are reduced sequentially, confirming the reversible formation of copper oxides and hydroxides. These redox transitions indicate the formation of an active surface layer that can participate in electron transfer reactions, which is critical for electrocatalysis. Given this redox behavior and the formation of CuOOH—an electrocatalytically active species—the modified copper electrode is a promising candidate for the electrochemical detection of glucose in alkaline medium.

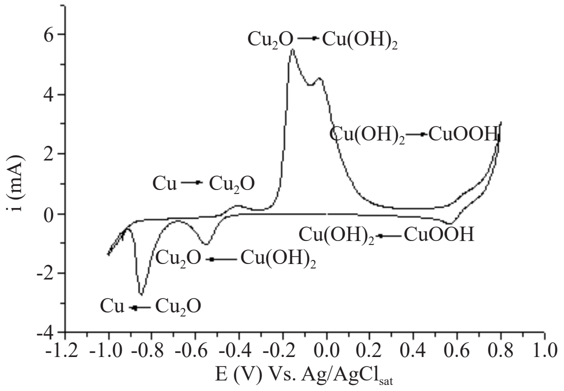

Figure 3. The cyclic voltammetry profile of a recycled copper electrode in 0.1 $mol \cdot L^{-1}$ NaOH solution

Figure 4 shows the linear sweep voltammograms obtained with the successive addition of glucose. In this case, it is observed that upon increasing glucose concentration, a significant enhancement of the anodic peak current at approximately 0.6 V occurs. This peak corresponds initially to the oxidation of copper(II) to copper(III). The generated copper(III) species subsequently oxidize glucose to gluconate, being simultaneously reduced back to copper(II). This electrocatalytic cycle enhances the overall anodic peak current, evidencing effective electrocatalytic activity due to the interaction between glucose molecules and copper-based catalytic sites present on the electrode surface. This redox activity is consistent with literature reports, such as the work by Li et al.,[13] where CuO nanowires grown on porous copper foam exhibited clear anodic peaks related to the Cu(II)/Cu(III) transition in alkaline media, a key step in glucose electrocatalysis. The study demonstrated that Cu(III) species act as electron mediators, oxidizing glucose to gluconolactone and yielding a strong anodic current response at potentials around + 0.35 V vs Ag/AgCl. The presence of CuO nanostructures was shown to enhance surface area and facilitate direct electron transfer, resulting in high sensitivity and a low detection limit. Although the present study uses metallic copper without anodization, the observed electrochemical behavior follows the same mechanistic pathway involving Cu(III) species as active oxidants in glucose detection.[13]

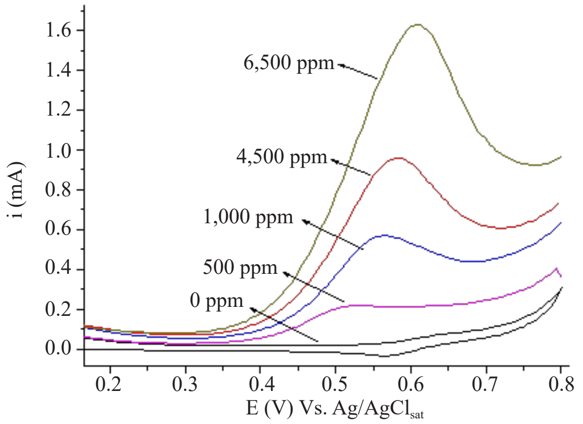

Figure 4. Cyclic voltammetry profile of the recycled copper electrode in 0.1 $mol \cdot L^{-1}$ NaOH solution. Successive additions of glucose were performed

Figure 5 shows the peak current (i) as a function of glucose concentration. A fully linear response ($R^2 = 0.99$) was obtained for glucose concentrations up to 400 ppm. Based on the calibration curve obtained from linear sweep voltammetry, the sensor exhibited an absolute sensitivity of 0.123 $\mu A \cdot (\mu mol \cdot L^{-1})^{-1}$ for glucose detection. Considering the geometry of the electrode—a cylindrical copper wire with a radius of 0.01 cm and a length of 1.00 cm—the electroactive surface area was estimated as 0.0628 cm^2. Normalizing the sensitivity by the electrode area yields a specific sensitivity of approximately 1.96 μA·(μmol·L^{-1}·cm^{-2})$^{-1}$, or 1,960 μA·(mmol·L^{-1}·cm^{-2})$^{-1}$. The method also showed a Limit of Detection (LOD) of 12.94 mg/L (≈ 71.85 μmol/L) and a Limit of Quantification (LOQ) of 39.21 mg/L (≈ 217.66 μmol/L). Although the LOD is not yet low enough for some biomedical applications, it is suitable for food analysis contexts and can be further improved by surface modification or nanostructuring. Importantly, the electrode was fabricated from copper recovered from Lithium-Ion Battery waste, offering a low-cost and environmentally friendly sensing platform aligned with circular economy principles.

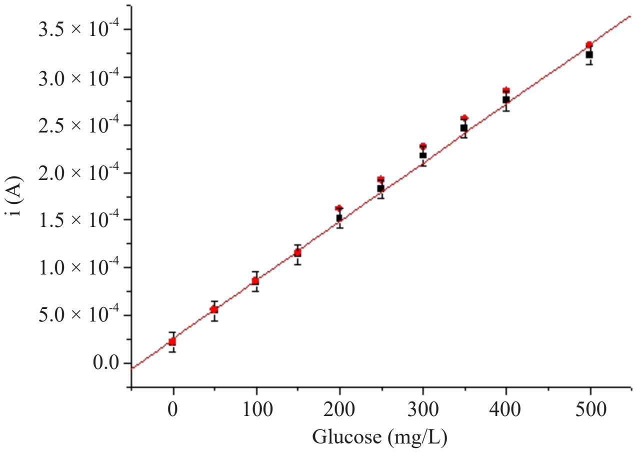

Figure 5. Peak current as a function of glucose concentration obtained by linear sweep voltammetry. Black points represent measurements with glucose only. Red points represent measurements in the presence of common interfering species (fructose at 7.2 mg/L, uric acid at 50 mg/L, and ascorbic acid at 8.8 mg/L), corresponding to their average concentrations in human blood

To evaluate the selectivity of the sensor, common electroactive species that may coexist with glucose in food and biological samples—namely fructose, uric acid, and ascorbic acid—were individually added at their typical physiological concentrations (Figure 5). These potential interferents were chosen because they share structural or redox characteristics with glucose and are often present in real matrices such as beverages or blood. However, their presence did not cause any significant change in the anodic peak current, remaining within the experimental error range. This result indicates good selectivity of the electrode toward glucose oxidation under the tested conditions, reinforcing its applicability in complex sample environments.

When compared to other copper-based non-enzymatic glucose sensors reported in the literature,[13-19] the sensor developed in this study exhibits a well-balanced performance between sensitivity, detection limit, and fabrication simplicity. Nanostructured systems such as CuO nanowires on copper foam[13] and CuO/ITO electrodes[14] present excellent analytical metrics, including low detection limits and high sensitivities, but typically require complex synthesis procedures and high-purity reagents. Likewise, composite electrodes involving carbon nanotubes[15-17] or noble metal doping such as Cu-Pd[19] enhance catalytic activity, yet increase the cost and technical demands of sensor fabrication. This information is summarized in Table 1.

In contrast, the copper electrode proposed in this work—fabricated directly from spent Lithium-Ion Battery waste—achieves a sensitivity of 1,960 μA·mM^{-1}·cm^{-2} and a detection limit of 0.078 mM. While not the most sensitive among the compared systems, its performance is well within the effective range for applications in food quality control and point-of-need glucose monitoring. The simplicity of preparation, combined with the use of recycled raw material, supports a sustainable and low-cost sensing platform. This positions the sensor as a practical and environmentally responsible alternative, aligned with the goals of circular economy and green chemistry.

Table 1. Comparison of non-enzymatic glucose sensors based on copper

Sensor	Potential (V)	Sensitivity ($\mu A \cdot mM^{-1} \cdot cm^{-2}$)	LOD (mM)	Linear range (mM)	Reference
CuO/ITO	0.35	2,272.64	1.0	0.002-0.6	14
CuO NWs/Cu foam	0.35	2,217.4	0.0003	0.001-18.8	13
CuO	0.4	3,150	0.098	0.003-5.3	15
Cu-CNTs-GCE	0.65	-	0.21	0.0007-3.5	16
CuO-SWCNT	0.45	1,610	0.05	0.00005-1.8	17
Cu NPs	0.65	460	5.0	< 3.0	18
Cu-Pd/GC	0.45	298	0.32	0.01-9.6	19
Recycled Cu	0.6	1,960	0.078	0.0718-2.22	This work

4. Conclusion

This study presents a novel and sustainable route for the fabrication of non-enzymatic glucose sensors through the direct reuse of copper recovered from the anode current collectors of spent lithium-ion batteries. Without requiring surface modification, oxidation steps, or complex nanostructuring, the resulting sensor demonstrated excellent linearity ($R^2 = 0.99$), a low detection limit (12.94 ppm), high sensitivity (1,960 $\mu A \cdot mM^{-1} \cdot cm^{-2}$), and remarkable selectivity against common interferents such as fructose, uric acid, and ascorbic acid. By repurposing battery waste into a functional electrochemical platform, this work not only simplifies sensor fabrication and reduces production costs, but also advances circular economy principles. The proposed strategy highlights the powerful synergy between waste valorization and analytical innovation, offering a scalable, low-cost, and environmentally responsible solution for glucose monitoring in food, medical, and environmental contexts.

Acknowledgements

We are grateful to CNPq for financial support. This work is a collaboration research project of Rede Mineira de Química (RQ-MG).

Conflict of interest

Authors declare that there is no conflict of interest.

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