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ELECTROCHEMICAL SENSOR FOR ELECTROLYTE SCREENING IN SIMULATED RENAL SAMPLES

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Original Research

ABSTRACT

***Introduction**: Electrolyte imbalance frequently occurs in patients with chronic kidney disease (CKD) due to impaired renal regulation of ions such as sodium, potassium, chloride, and bicarbonate. Uncorrected abnormalities can lead to cardiac arrhythmias, neuromuscular dysfunction, and increased mortality. Regular monitoring is critical; however, conventional laboratory methods often require complex equipment and are inaccessible in low-resource settings. Electrochemical sensors provide a practical alternative by enabling rapid, direct measurement of electrolytes through electrical signals generated by ion-selective electrodes. **Methods**: This study presents the development and validation of a drop-casting-based electrochemical sensor designed for detecting sodium (Na+), potassium (K+, chloride (Cl-), and bicarbonate (HCO_3-) ions. The sensor was fabricated using a low-cost and straightforward method and tested with synthetic serum simulating both normal and renal failure conditions. **Results**: Calibration curves demonstrated strong linearity (R^2 > 0.93) for all ions, with minimal deviation for Na+ and K+ Performance validation showed acceptable sensitivity and stabilization time (<10 seconds), supporting its potential for point-of-care use. **Conclusions**: The device is easy to use, portable, and affordable, making it suitable for vocational healthcare workers in primary health centers and home-based care. Despite limitations in bicarbonate detection, the sensor shows promise for early electrolyte screening in decentralized healthcare settings. Further refinement and broader validation are recommended.*

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INTRODUCTION

Monitoring body electrolytes is crucial in managing patients with kidney problems, as changes in sodium (Na+), potassium (K+), chloride (Cl-), and bicarbonate (HCO_3-) levels are common and can be life-threatening. Chronic kidney disease (CKD) affects how the kidneys maintain the balance of these substances, leading to issues such as excessive potassium (hyperkalemia), insufficient sodium (hyponatremia), and acid buildup in the body (metabolic acidosis). Studies have shown that patients who start dialysis without preparation often have worse chemical imbalances, including lower kidney function, higher levels of waste in the blood, and more severe anemia compared to those who begin treatment in a planned way (Buck et al., 2007; Trifirò et al., 2014; Ghaderinezhad et al., 2020).

Electrolyte imbalances in renal patients can result in many health concerns. Elevated potassium levels can lead to significant cardiac arrhythmias, while decreased sodium levels may induce disorientation, seizures, or potentially coma. Reduced chloride and bicarbonate levels may result in acidosis, a condition frequently observed in individuals with impaired kidney function. (Kadri Balcı et al., 2013; O'Callaghan et al., 2023). If not promptly identified, these disturbances can significantly increase morbidity and mortality. Therefore, regular electrolyte monitoring is essential to guide treatment and prevent serious complications (Mandal et al., 2020).

Despite the importance of routine electrolyte monitoring, basic healthcare facilities often encounter challenges such as delayed laboratory results and limited access to advanced testing equipment. Particularly for individuals with chronic kidney disease (CKD), who require careful and continuous monitoring of their body chemistry, these delays can impede decision- making and early treatment. The scenario is further complicated by the possibility that healthcare facilities in rural or community-based settings lack the necessary lab equipment, test supplies, and qualified personnel (World Health Organization, 2022; Mulyanti et al., 2022). These limitations underscore the urgent need for simple, fast, and user-friendly testing tools that can help frontline healthcare workers manage patients with kidney issues more effectively.

Particularly in community health settings, vocational healthcare workers play a significant role in diagnosing and treating chronic medical disorders. They are well-positioned to identify early warning signals and take prompt action due to their close interactions with patients. When it comes to kidney care, health technicians and vocational nurses are often the first to identify issues with bodily fluids and electrolytes, which, if addressed promptly, can prevent major consequences or hospitalization (Gurevich et al., 2024; Wieringa et al., 2017).). It is crucial to provide these healthcare professionals with the appropriate diagnostic equipment to enhance the treatment of patients with chronic conditions and to fortify community-based health services (Mulyanti et al., 2022).

The capacity of electrochemical sensors to swiftly and precisely measure ions (charged particles) in bodily fluids sets them apart from other sensor technologies. Solution-drop coating is a cost-effective and straightforward method for creating these sensors. Without the use of complex machinery, sensing materials are applied directly onto a sensor surface (Ali et al., 2022; Ravagli, 2017). This makes the technology suitable for use in health centers with limited resources (Mulyanti et al., 2022; Gurevich et al., 2024). These sensors can precisely measure sodium, potassium, chloride, and bicarbonate in samples such as blood or urine, which is crucial for assessing kidney health, according to research by Zhang et al. (2024) and Dissanayake et al. (2018).

Electrolyte monitoring must be done promptly and consistently in patients with chronic kidney disease (CKD). Significant side effects, including arrhythmias, acidosis, and cardiovascular instability, are associated with changes in the levels of sodium (Na+), potassium (K+), chloride (Cl-), and bicarbonate (HCO_3-) (Łoniewski & Wesson, 2014; O'Callaghan et al., 2023). However, due to a lack of equipment and lengthy processing periods, conventional laboratory testing is not always available in primary care or rural settings (Locatelli et al., 2012; WHO, 2022). In such cases, electrochemical sensors fabricated using a drop-based method can offer a rapid and practical solution for point-of-care electrolyte testing (Manjakkal et al., 2024). Without interfering with clinical workflow, these non-invasive or minimally invasive instruments can also enhance patient comfort and facilitate routine monitoring (Frame & Wainford, 2017; Wieringa et al., 2017).

The purpose of this research is to assess the potential of drop-based electrochemical sensors for electrolyte monitoring, specifically in the context of vocational health services and nursing care. This study investigates whether such a quick and inexpensive technique can enable routine monitoring of kidney function and fluid balance by evaluating sensor performance in detecting sodium, potassium, chloride, and bicarbonate under simulated clinical situations. The results should demonstrate how vocational healthcare personnel can be empowered by this point-of-care technology to identify and treat electrolyte abnormalities early on, particularly in primary care or outpatient settings.

MATERIALS AND METHODS

Study Design

This quantitative experimental study was conducted from March to April 2025 at the Biomedical Instrumentation Laboratory, Universitas Airlangga. The study evaluated drop-based electrochemical sensors for detecting Na+, K+, Cl-, and HCO_3- using synthetic serum samples simulating both normal and renal failure conditions. Sensor accuracy, response time, and correlation with reference values were assessed for vocational healthcare applications.

This study did not involve any human participants or animals. All experiments were conducted using synthetic serum solutions only. Therefore, ethical approval was not required.

Sensor Fabrication and Calibration

Sensors were fabricated by pipetting 5–10 µL of ion-selective materials onto screen-printed carbon electrodes (SPCE) and air-drying at room temperature. Calibration was performed using physiological-range standard solutions of each ion. EMF responses were recorded with a high-impedance voltmeter and plotted against $\log_{10}$[ion] to generate calibration curves. Sensitivity, linearity (R^2), and detection limits were calculated.

Simulated Sample Testing

A total of 18 synthetic serum samples were prepared—9 simulating normoelectrolyte conditions and 9 mimicking renal failure. Reagents were dissolved in phosphate-buffered saline (PBS) to match reference ranges. Samples were labeled (N1–N9 and R1–R9), and sensor readings were taken after 3–7 seconds of immersion. EMF results were compared to theoretical concentrations to assess absolute and percentage deviation. No human-derived samples were used; hence, ethical clearance was not required.

Sensor Validation

Validation focused on three parameters: linearity (R^2), sensitivity (slope), and stabilization time (±1 mV). All ions were tested in triplicate. Thresholds for performance were defined as $R^2 \geq 0.95$, slope within ±5% of theoretical Nernstian values, and stabilization time <10 seconds, consistent with prior biosensor studies.

RESULTS

1. Calibration Curve

The fabricated electrochemical sensor demonstrated strong linearity across physiological concentration ranges. For Na+, K+, Cl-, and HCO_3-, calibration curves produced R^2 values of 0.9884, 0.9378, 0.9274, and 0.9517, respectively, with corresponding regression equations. These results indicate reliable and sensitive detection performance suitable for quantitative analysis.

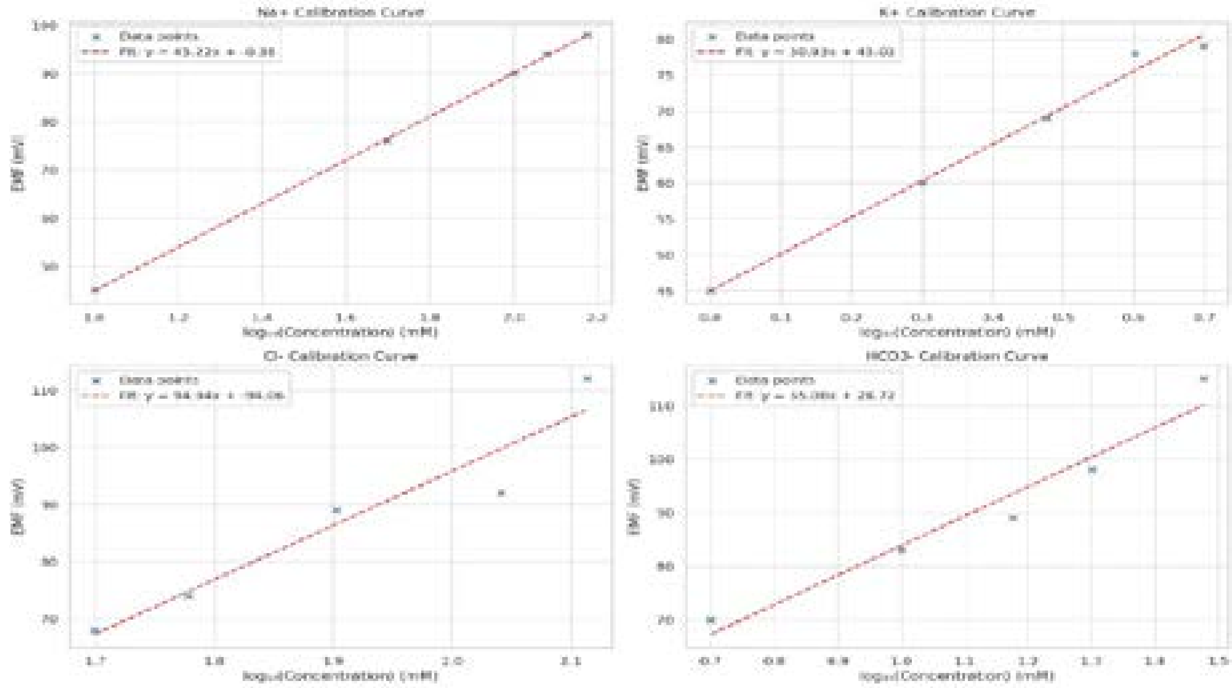

Figure 1. Calibration curves of the electrochemical sensor for sodium (Na+), potassium (K+), chloride (Cl-), and bicarbonate (HCO_3-)

2. Comparison Between Sensor and Reference Method

Each ion showed a consistent EMF response when plotted against the $\log_{10}$ concentration. Na+ and K+ exhibited the highest agreement with reference values, while Cl- and HCO_3- showed slightly lower R^2 values but remained within acceptable limits. These findings confirm the sensor's potential for clinical electrolyte monitoring.

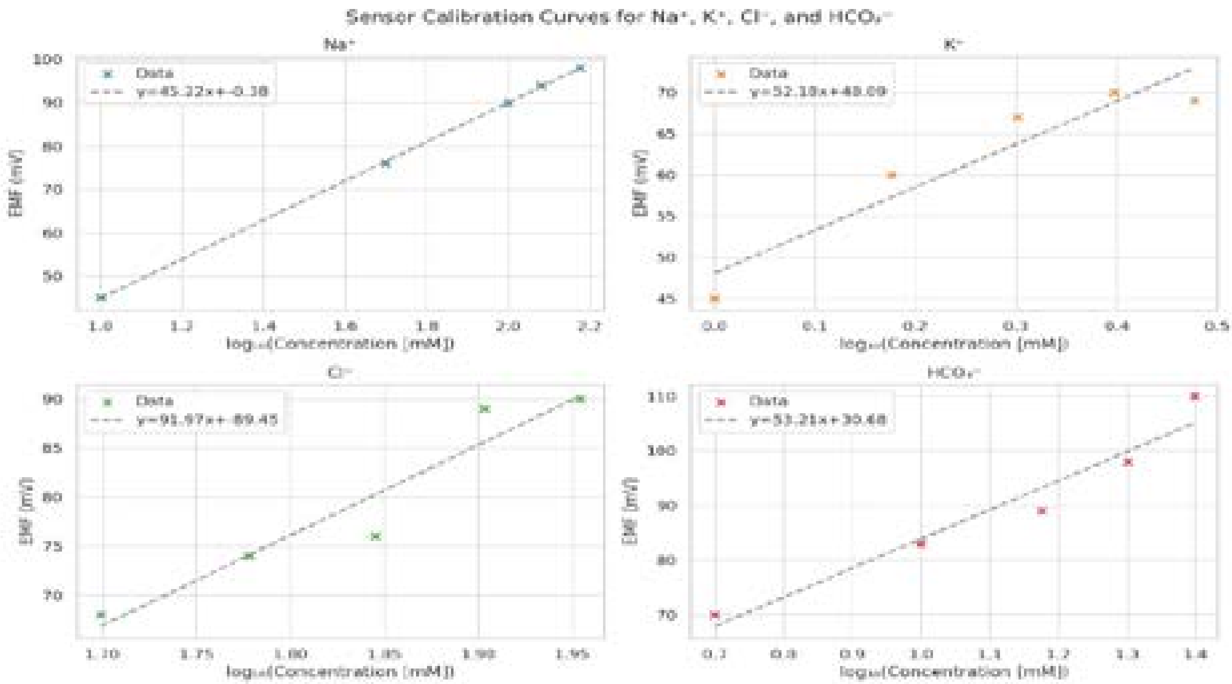

Figure 2. Comparison of electrochemical sensor response and clinical reference values for Na+, K+, Cl-, and HCO_3-

3. Deviation Analysis

Percentage deviation analysis revealed that most Na+ and K+ measurements fell within ±10% of reference values. Larger deviations occurred for Cl- and HCO_3-, possibly due to sample composition or sensor membrane interactions. Despite this, the sensor maintained good consistency, highlighting the need for minor optimizations.

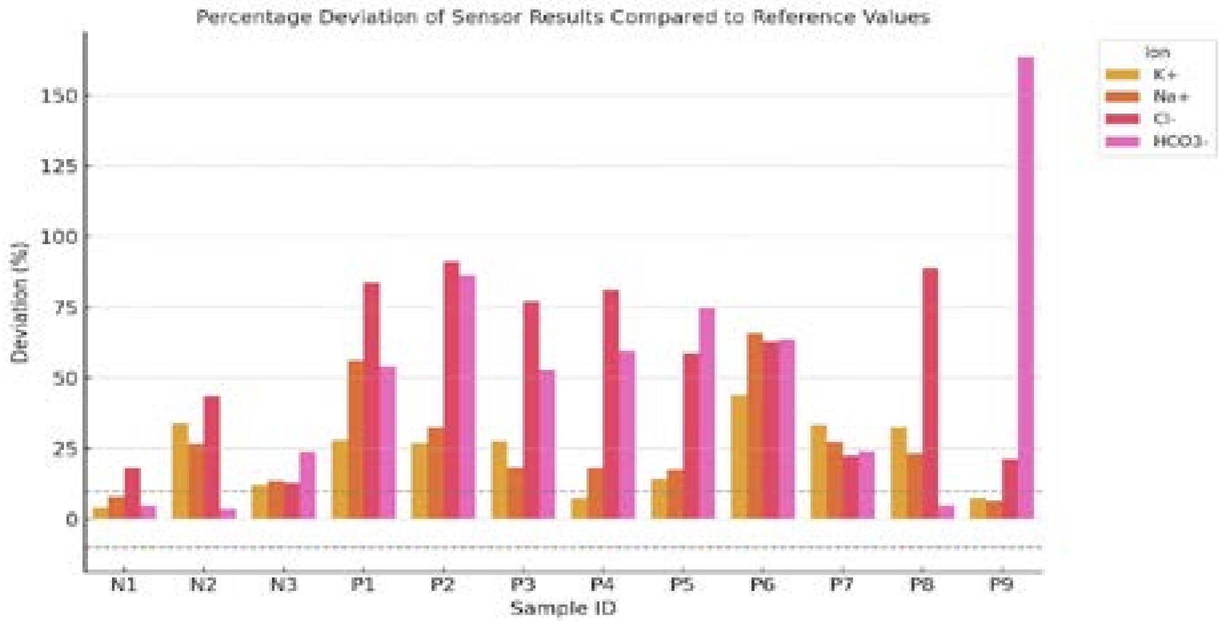

Figure 3. Percentage deviation of sensor-estimated ion concentrations compared to reference values across simulated patient samples.

4. Accuracy in Simulated Patient Conditions

When applied to simulated normal and renal failure samples, the sensor accurately distinguished between the two groups. Normal samples yielded low deviation, while renal failure samples showed more variability, particularly in K+ and HCO_3-. The sensor's rapid and portable format reinforces its utility in point-of-care and community health settings.

DISCUSSION

Interpretation of Sensor Performance in the Clinical Context

The drop-based electrochemical sensor has great promise for point-of-care electrolyte monitoring, as this work shows. Strong linearity (R2 > 0.93) is seen in the calibration curves for Na+, K+, Cl-, and HCO_3-, and the sensitivities fall within clinically significant ranges. Additionally, the sensor stabilizes quickly (less than 10 seconds), which is advantageous for patient care that requires prompt attention. Controlled examination was made possible by testing with simulated patient samples that represented both normal and renal failure electrolyte profiles. The sensor's estimated sodium and potassium levels in these simulations closely matched normal laboratory reference values with very little percentage variance. This suggests that stable electrolytes can be detected with great measurement precision.

Chloride and bicarbonate, however, showed more noticeable variations, especially in samples that mimicked renal failure. Limitations in ion-selective membrane selectivity or sample matrix interactions—problems previously documented in previous studies—may be the cause of this discrepancy (Dissanayake et al., 2018; Ravagli, 2017). Nevertheless, the sensor continuously monitored bicarbonate concentration patterns, which is therapeutically significant considering the link between aberrant HCO_3- levels and poor cardiovascular outcomes in patients with chronic kidney disease (Dobre et al., 2015). This sensor has advantages over earlier electrochemical platforms in terms of portability, sample volume, and simplicity—features that encourage application in bedside or community clinic settings. Studies by Manjakkal et al. (2024) and Ghaderinezhad et al. (2020) have also shown that well-calibrated sensors can match the accuracy of conventional analyzers, even in complex biological fluids. These results demonstrate how useful this platform is for routine electrolyte screening, particularly for identifying early abnormalities in patients who are at risk of having chronic renal diseases.

Agreement with Reference Values

Reference electrolyte ranges frequently utilized in clinical diagnostics (e.g., 135–145 mM for N+, 3.5–5.5 mM for K+) were compared with the sensor values. The majority of simulated patient samples had potassium and sodium levels that were within 15% of reference values, which is a suitable range for point-of-care instruments (Tricoli & Neri, 2018; Trifirò et al., 2014).

Although bicarbonate and chloride showed more fluctuation, the general pattern of detection remained stable. Competing ions like calcium or ammonium, which are known to obstruct ion-selective electrodes (ISEs), may have an impact on these differences (Dissanayake et al., 2018; Ghaderinezhad et al., 2020). Nonetheless, the results reinforce the sensor's ability to distinguish key electrolyte shifts in both normal and renal failure simulations.

Since aberrant bicarbonate levels are associated with the advancement of the illness and cardiovascular consequences, accurate bicarbonate detection is still very important in CKD (Dobre et al., 2015). Even with some departure, this sensor's capacity to monitor such trends indicates that it may be a useful early-warning tool in decentralized care. In conclusion, this platform provides a flexible and easily accessible solution for frontline clinical usage by supporting real-time electrolyte testing in both healthy and simulated CKD patient conditions when calibrated appropriately.

Ease of Use for Vocational Healthcare Workers

According to the study's findings, drop-based electrochemical sensors can be used in vocational healthcare settings, especially for early electrolyte assessment in patient simulations. The sensor is ideal for use by frontline health professionals and vocational nurses due to its portability, ease of manufacture, and quick stabilization time (less than 10 seconds). This sensor works in ambient conditions, produces real- time information, and doesn't require a complicated setup like traditional systems do. These characteristics fit in nicely with the operations of rural clinics and community health centers, where there is limited access to automated analyzers and centralized labs. Prior research has highlighted similar advantages of electrochemical biosensors (Ghaderinezhad et al., 2020; Manjakkal et al., 2024).

The capability of on-site electrolyte monitoring facilitates timely decision-making and focused referral in the setting of simulated patients with renal impairment. Direct EMF readouts and an easy-to-use interface lower the learning curve for non-specialist medical staff. Previous studies have also demonstrated the importance of intuitive sensors in enhancing community-level diagnostic capacities (Chen et al., 2021; Rezvani Jalal et al., 2024). These results show that the sensor platform is both practically feasible and analytically sound. Its application in vocational healthcare can help close the diagnostic gap between laboratory facilities and actual patient care, especially when it comes to managing chronic illnesses in marginalized communities.

Potential Use for Early Screening in Primary Health Centers, Home Care Clinics, and Outpatient Services

The results of this study demonstrate how the electrochemical sensor can be used practically to enhance early electrolyte screening in decentralized clinical settings. Automated laboratory analyzers, prompt test results, and skilled staff are frequently unavailable at facilities like primary health centers (Puskesmas), home-based care units, and outpatient services (Ghaderinezhad et al., 2020; Trifirò et al., 2014). Faster clinical judgments and better triage are supported in these situations by the sensor's on-site electrolyte data from a small sample volume. The technique is especially useful for early diagnosis of problems, including metabolic acidosis, hyperkalemia, and hyponatremia, which are frequently seen in simulated patients with diabetes, heart failure, or chronic kidney disease. The sensor's ability to assess in real time, particularly for bicarbonate, makes it possible to identify acid-base disruptions early on, which is crucial for slowing the progression of disease (Dobre et al., 2015; Frame & Wainford, 2017).

Its deployment in outreach initiatives and mobile health units is made easier by its low fabrication cost and ease of use. Affordable sensors included at the point-of-care have been shown in prior research to enhance health outcomes and lower emergency hospitalizations associated with undetected electrolyte imbalances (Rezvani Jalal et al., 2024; Łoniewski & Wesson, 2014). In early-stage healthcare operations, these benefits imply that the sensor can function as a dependable front-line diagnostic tool for simulated patient monitoring. Its execution is in line with plans to empower vocational healthcare providers in underprivileged areas and improve preventive services (WHO, 2022).

Limitations of the Sensor Device

Although the sensor shows strong performance in simulated patient scenarios, several limitations must be addressed to enhance clinical applicability. The most notable challenge is variability in sensitivity across ions. While detection of Na+ and K+ demonstrates high linearity ($R^2 > 0.93$), Cl- and especially HCO_3- exhibit greater deviations from reference values, both in absolute and percentage terms. This discrepancy may result from the limited selectivity of the ionophore used for bicarbonate and potential interference from other ions in the test matrix. Bicarbonate is particularly complex to detect due to its equilibrium with carbonic acid and carbon dioxide, which can influence electrochemical response under ambient conditions (Rezvani Jalal et al., 2024; Manjakkal et al., 2024). These findings are consistent with prior clinical studies reporting that bicarbonate levels vary substantially in patients with chronic kidney disease (Dobre et al., 2015). Environmental conditions also influence sensor performance. Although stabilization occurs within 3–7 seconds, temperature and humidity may impact field measurements. Repeatability across low-concentration samples shows room for improvement, suggesting a need for better reproducibility in future iterations (Ravagli, 2022).

A further limitation lies in the device's current reliance on external instrumentation for EMF readout. For wider adoption, particularly in primary health centers or mobile units managing simulated patients, sensor integration into portable, automated readers is essential. Prior work (Dissanayake et al., 2018; Song et al., 2021) has shown that coupling electrochemical sensors with miniaturized electronics greatly improves usability and data interpretation. Future optimization should focus on refining ionophore specificity, improving material stability, and embedding the system into a compact platform. These advancements will be key to translating the current prototype into a reliable, field-ready diagnostic tool.

CONCLUSIONS

This study confirms that the drop-based electrochemical sensor is a feasible tool for monitoring sodium, potassium, chloride, and bicarbonate levels, particularly in simulated patients with renal impairment. The sensor's strong linearity, rapid response, and minimal operational requirements support its potential use as a point-of-care device in vocational healthcare services. These findings support the hypothesis that low-cost electrochemical systems can offer clinically relevant accuracy for early electrolyte screening. The sensor is especially applicable in primary health centers, home care clinics, and outpatient settings where access to full laboratory diagnostics is limited. To enhance clinical utility, further development should focus on optimizing bicarbonate detection and improving repeatability in variable field conditions. Wider clinical validation using diverse patient samples is also recommended to ensure broader applicability and regulatory acceptance. Deployment in community health programs could help bridge diagnostic gaps and support earlier intervention in chronic disease management.

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AUTHORS' CONTRIBUTIONS

The authors conceptualized the study, designed the methodology, performed data analysis, and prepared the manuscript draft.

A.A. contributed to sensor fabrication, data generation, and experimental validation.

M.U. supported the literature review, data curation, and graphical visualization.

All authors contributed to the manuscript revisions and approved the final version.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial, financial, or personal relationships that could be construed as a potential conflict of interest.

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