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MATLAB-Driven Electrochemical CV Analysis of Sweat Electrolyte

Uzair Soomro[1], Nurmiza Othman[1]*, Intan Sue Liana Abdul Hamid[1]

[1] *Advanced Sensing Device and Technology Focus Group, Department of Electronic Engineering,Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, MALAYSIA*

*Corresponding Author: nurmiza@uthm.edu.my
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Abstract

Sweat-based biosensing is emerging as a transformative method for non-invasive health diagnostics, particularly in the monitoring of hydration and electrolyte imbalances. This study aims to investigate the electrochemical behavior of key sweat electrolytes—sodium (Na^+), chloride (Cl^-), and potassium (K^+)—through the use of cyclic voltammetry (CV) and simulations conducted with MATLAB. The primary objective is to characterize and validate a biosensor designed to detect these ions by analyzing parameters such as peak current, Nernst response, logarithmic current, and diffusion coefficients under varying concentrations (0.1 M, 1.0 M, and 5.0 M) and scan rates (1–100 mV/s). By employing a modified CV simulation model based on the Butler-Volmer equation, this study offers detailed electrochemical profiles and evaluates deviations from theoretical predictions. The results demonstrate that the current response increases with higher concentrations and scan rates, while larger peak separations indicate quasi-reversible kinetics and capacitive interference at elevated scan rates. Logarithmic transformations confirmed diffusion-dominated kinetics, with slope values closely aligning with the theoretical ideal of 0.5. Nernstian validation further corroborated the electrochemical reversibility of the biosensor, and an analysis of diffusion coefficients revealed limits to efficiency due to analyte saturation. The integration of simulation and electrochemical analysis showcased strong sensor sensitivity and stability, emphasizing its potential for continuous electrolyte monitoring in scenarios such as dehydration, exercise, or clinical diagnostics. These findings lay a robust foundation for the development of wearable biosensors intended for real-time health monitoring applications.

1. Introduction

Sweat is a remarkable fluid that plays a crucial role in maintaining the balance of our bodies. It helps to rid the body of waste, excess nutrients, and toxins, acting as a natural detoxifier [1]. This unique characteristic allows for the collection of sweat in a non-invasive manner, providing valuable health information without causing harm. As a result, sweat analysis has become an essential tool for diagnosing diseases, monitoring medication dosages, and tracking fitness levels in individuals [2]. The composition of sweat closely mirrors that of blood, containing a

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myriad of substances including salts, chloride, potassium, calcium, magnesium, iron, zinc, copper, and essential vitamins [3]. However, despite its richness in important chemicals, studying sweat poses unique challenges due to its generally low volume and concentration. To successfully gather a sufficient amount, researchers often employ specialized patches or devices that stimulate the sweat glands to enhance secretion [4].

Analyzing sweat can reveal critical insights into various health conditions, such as exposure to harmful chemicals, indicators of physical stress, organ function anomalies, and even nerve responses. Notably, variations in sweating patterns can signal underlying health issues like cystic fibrosis, hyperhidrosis (excessive sweating), and hematohidrosis (sweating blood) [5]. In the realm of biosensors, significant advancements have been made that positively impact a wide array of applications, including drug monitoring, environmental assessments, and medical diagnostics [6]. These sophisticated devices meticulously detect specific biomarkers relevant to their intended use. The efficiency of these biosensors is greatly influenced by their sensing area, which incorporates recognition elements specifically designed to identify targeted biomarkers.

Recent developments in biosensor technology for non-invasive health monitoring have placed a strong emphasis on sweat analysis, highlighting its vital connection to overall human health [7]. To support this innovation, electrochemical methods are often employed in sweat analysis, leading to the creation of wearable devices that combine functionality with comfort and flexibility [8, 9]. To ensure the reliability of biosensor data, thorough characterization tests are essential. These tests yield key values that determine the necessary current and potential needed to interpret results accurately. Critical to this process are parameters of electrochemical analysis, such as cyclic voltammetry, a widely used technique that explores the redox properties of various chemical solutions.

Sensors that utilize such electrochemical techniques are classified as electrochemical sensors or biosensors [10]. Within this context, the article delves into the fundamental components of these biosensors, drawing on findings from cyclic voltammetry and aligning them with other significant performance indicators, such as logarithmic current measurements, the Nernst equation, and diffusion coefficients. By harnessing advanced digital simulation techniques, researchers can enhance their understanding of the electrochemical systems at play within these biosensors.

MATLAB, a robust computational tool, serves as an invaluable resource for validating the intricacies of sweat analysis. This analysis is particularly focused on assessing hydration levels by evaluating the concentrations of crucial sweat analytes such as sodium, potassium, and chloride. Given that sweat shares similar components with bodily fluids, it serves as an effective medium for verifying hydration status. A comprehensive evaluation of sweat analysis through MATLAB allows for precise quantification of various analytes, with a special focus on cyclic voltammetry (CV), which provides a powerful approach to measurement precision. The latest innovations in biosensor technology have targeted sweat analysis, especially within integrated wearable devices that leverage electrochemical applications [11].

The discussion extends to how these sensors respond dynamically as the concentration of target analytes rises. This includes the application of logarithmic analysis, Nernst validation, and diffusion coefficient assessments, establishing a robust theoretical foundation for comprehending the electrochemical behavior of sensors and their intricate interactions with different analytes. This enhanced visualization aids researchers and developers in understanding how these factors collectively enhance the sensitivity and accuracy of biosensors. Ultimately, the article emphasizes that the evolution of biosensors, particularly in the field of sweat analysis, is closely intertwined with crucial electrochemical properties such as selectivity and stability, ensuring their effectiveness in real-world applications, and paving the way for future innovations in health monitoring.

2. Literature Review

The advancement of biosensor technology has greatly broadened its applications, especially in health monitoring and diagnosis. In the context of health, biosensors are utilized to detect biomarkers, which are then analyzed and interpreted to assess various health conditions. The transducer, also referred to as the recognition element, plays a crucial role in identifying these biomarkers. Commonly monitored biomarkers include sodium, potassium, chloride, glucose, and heavy metabolites [12]. By measuring the concentrations of these biomarkers, we can gain valuable insights into an individual's health status.

Sweat analysis has earned the reputation of being “the new blood” because it captures the wealth of biomarkers present in sweat, similar to those found in blood [3]. This innovative process uses a biosensor, typically a patch or wearable device, placed conveniently on the body, commonly on the arm or leg. These sensors collect sweat and analyze the rich array of biomarkers they contain, providing valuable insights into various physiological conditions. The analysis predominantly employs two sensing methodologies: optical and electrochemical. Among these, electrochemical sensing stands out for its versatility and depth, offering a broad range of characterization applications. This method is essential for the use of advanced electrical systems, such as electrochemical test systems and electrochemical impedance spectroscopy, which meticulously probe the electrochemical behavior of biosensors [13]. Through electrochemical analysis, specific biomarkers can be

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detected using innovative biosensors. These sensors are designed to identify targets, such as drugs, directly from the sweat's biochemical environment. For instance, researchers such as Diouf and colleagues have pioneered a sensor with electrochemical reactivity to aspirin, enabling its application in both human subjects and pharmaceutical tablets [14]. Their work showcases the integration of electrochemical principles for health monitoring.

In this research, biosensor characterization involves sophisticated electrochemical techniques, with particular emphasis on Cyclic Voltammetry (CV). This renowned methodology serves as a cornerstone of electrochemical analysis, enabling dynamic evaluation of electrochemical systems [15]. By systematically varying the potential of a cell within a defined range, researchers can observe the resultant current responses—providing a detailed window into the underlying electrochemical reactions, including crucial reduction and oxidation processes that occur as the biosensor engages with active analyte species. Furthermore, the biosensor's characterization also extends to logarithmic behaviors, as illustrated by the investigations of Montes, Céspedes, Gabriel, and Baeza [16]. They delved into the inhibitory effects of various pesticides through their developed biosensor, demonstrating its practical applications. Logarithmic methods are equally significant in electrochemical assays, successfully identifying pharmaceutical compounds such as Rosuvastatin (ROS) and Ezetimibe (EZE) from human urine and serum samples, thereby underscoring the biosensor's clinical relevance [17]. In addition to these techniques, incorporating Nernst response principles, as demonstrated by Q. An and colleagues, offers the potential to develop wearable sensors that facilitate real-time sweat analysis by monitoring ion concentrations in biofluids [18]. Analysis of the diffusion coefficient further enhances our understanding of how analytes reach the biosensor's surface, providing crucial insights into molecular interactions and transport mechanisms [19]. By harmonizing these comprehensive approaches—which include logarithmic analysis, Nernst response principles, and diffusion coefficient assessments—with Cyclic Voltammetry, researchers can develop a highly sophisticated and reliable sensor. Such advancements are achieved through meticulous modifications to the sensor's electrode, resulting in enhanced performance and greater sensitivity for real-time health monitoring [20].

In conjunction with experimental characterization, numerous studies have effectively employed MATLAB-based simulations to both validate and illuminate various electrochemical behaviors. As a powerful computational tool, MATLAB provides an extensive set of capabilities for simulating and analyzing electrochemical data, with a particular emphasis on cyclic voltammetry (CV) [21]. Its capabilities enable researchers to model complex electrochemical systems in detail, facilitating a deeper understanding of the intricate outcomes of CV experiments. The integration of MATLAB for data simulation and analysis significantly enhances our understanding of electrochemical phenomena, which is pivotal for advancing biosensor technology, particularly in health-monitoring applications. For instance, Kinkelin et al. (2024) meticulously developed a dynamic Butler-Volmer simulation model using MATLAB, enabling a thorough investigation of the behavior of porous electrodes under cyclic voltammetry conditions [22]. Similarly, researchers Xue (2024) and Madagalam (2020) utilized MATLAB to numerically fit experimental CV data, applying both the Randles-Sevcik and Butler-Volmer equations [23, 24]. This approach not only enabled precise extraction of diffusion coefficients but also enhanced the determination of kinetic parameters, yielding valuable insights into electrochemical processes.

Further emphasizing this trend, studies by Scaramuzza (2021) and Mai (2022) highlight the importance of integrating multi-channel MATLAB platforms with tailored graphical user interfaces (GUIs) designed for real-time voltammetry analysis [25, 26]. This innovative computational paradigm reduces reliance on costly potentiostat systems while simultaneously improving the consistency and reproducibility of experimental methodologies. Additionally, Chan (2020) made substantial contributions by introducing an automated voltage control mechanism implemented in MATLAB, thereby enriching the interaction between hardware and software interfaces and kinetic modeling frameworks [27]. Table 1 presents a comprehensive summary of relevant works on biosensor applications, specifically focusing on electrochemical analysis through MATLAB. This body of research delves into the characterization of electrochemical properties, using cyclic voltammetry as its foundation, and encompasses analyses of logarithmic current views, Nernst validation, and diffusion coefficient assessments to optimize biosensor design and enhance performance.

To make the literature review more supportive for the reader, Fig. 1 summarizes the conceptual relationship between sweat electrolyte biomarkers, wearable electrochemical sensing, and MATLAB-based electrochemical interpretation. The reviewed studies collectively indicate that sweat-based sensing requires three components: a reliable biological sample, a selective transducer/electrode interface, and a data-processing method that converts current-potential behavior into meaningful analytical parameters. In the present work, these components are integrated using CV simulation, logarithmic current analysis, Nernstian validation, and diffusion coefficient estimation.

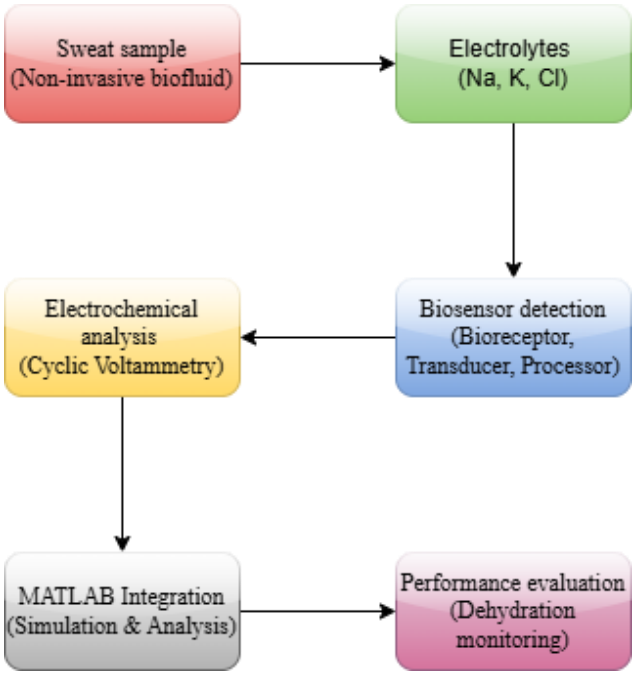


Fig. 1 *Literature-supported framework for sweat electrolyte biosensing and MATLAB electrochemical analysis*

From a sensing perspective, variations in sodium, potassium, and chloride concentration affect the charge-transfer and mass-transport environment near the electrode surface. A higher electrolyte concentration increases the availability of ionic species at the electrode interface, thereby increasing the measurable current response until saturation, ohmic effects, or kinetic limitations become significant. This concentration-response relationship is central to dehydration monitoring because electrolyte imbalance is reflected by measurable changes in sweat composition. Klous et al. (2021) further emphasized the relevance of sweat electrolyte composition by examining sodium, chloride, potassium, and other analytes under different sample storage conditions, supporting the importance of controlled sweat handling and quantitative interpretation in sensor studies [28].

Fig. 2 provides a conceptual visualization of the expected concentration effect in CV-based sensing. The figure is included to guide the reader before the results section: the main feature to observe is the increase in the anodic/cathodic peak current as concentration increases from low to high levels. Therefore, the principal contribution of concentration is not merely a change in curve shape, but the amplification of electrochemical signal magnitude, which directly supports the use of the sensor response as a concentration-sensitive indicator for hydration-related electrolyte monitoring.

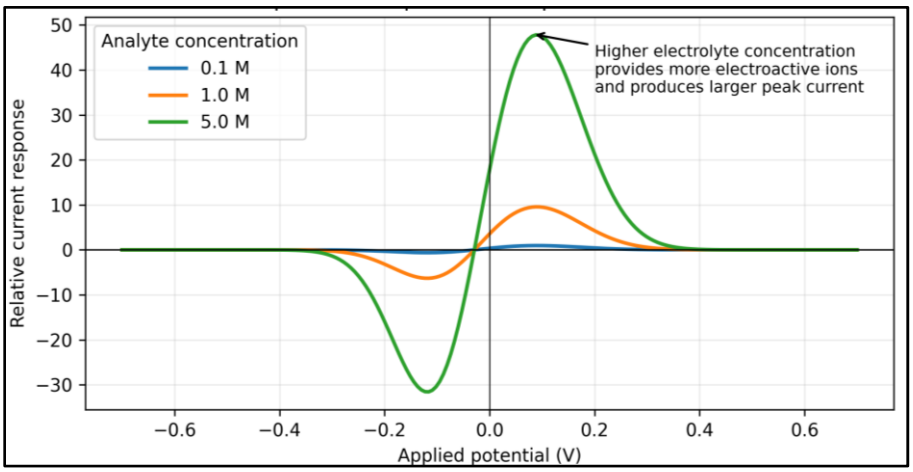


Fig. 2 *Conceptual concentration effect showing current amplification with increasing electrolyte concentration*

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Table 1 *Summary of related work using MATLAB for electrochemical analysis on biosensors*

Author (Year)	Methodology Used	Target Analytes	Key Findings	Ref.
Kinkelin et al. (2024)	CV, Butler-Volmer, Randles-Sevcik	No analyte-specific	Demonstrated deviations from ideal Randles-Sevcik using porous carbon thin-film electrodes and solved Butler-Volmer with ode15s to model non-ideal CV curves.	[21]
Xue, H. (2024)	CV, Randles-Sevcik, Butler-Volmer	Ferrocyanide	Extracting diffusion and kinetic parameters for reaction modeling, simulating and fitting CV curves using MATLAB functions.	[22]
Madagalam, M. (2020)	CV, Randles-Sevcik, Butler-Volmer	Glucose analogs	Utilized confint() in MATLAB to non-linearly fit kinetic data from nanocomposite-modified electrodes for biosensing analysis.	[23]
Scaramuzza, M. (2013)	CV, Electrochemical modeling	Not specific	Simulated e-skin sensors and electrochemical reactions using a GUI-based MATLAB interface for CV and Butler-Volmer.	[24]
Mai, B.Y.T. (2022)	CV, Multi-channel voltammetry	General biosensor setup	Implemented multi-channel control and modeling using MATLAB to create a multi-channel CV platform for high-throughput diagnostics.	[25]
Chan, Y.S.G. (2020)	CV, EIS, Randles-Sevcik, Butler-Volmer	Electrolytes	Adaptive electrolysis platform was designed with CV diagnostics and real-time MATLAB interface control for voltammetric operations.	[26]
This work	CV, Logarithm Current, Nernst validation, Diffusion coefficient	Sweat electrolytes (Na+, Cl-, K+)	Designed and instrumented biosensor platform for electrochemical properties measurements using MATLAB.	-

3. Methodology

3.1 Materials

This project harnesses MATLAB, a sophisticated programming environment renowned for its versatility in simulating a wide range of operations. These operations include mathematical modeling, numerical computation, data analysis, and image processing, all of which are essential in today's research and engineering applications. In this simulation, we focus specifically on electrochemical analysis to replicate the intricate behaviors of a biosensor. This analysis examines how the biosensor responds to various chemical stimuli, offering valuable insights into its functionality and performance in real-world applications. Using MATLAB enables precise modeling and visualization, enhancing our understanding of the electrochemical processes at work.

3.2 Methods

Electrochemical analysis is performed using Cyclic Voltammetry (CV), a powerful technique for studying the sensor's electrochemical properties. The original cyclic voltammetry (CV) code used in this process was adapted from a model developed by Peter M. Attia, which is publicly available on the Mathworks website (Baud & Fauklner). To optimize the code for our specific application, several modifications were made to enhance its overall functionality. These adjustments were particularly focused on addressing the challenges posed by varying analyte concentrations, as fluctuations in the concentration can significantly impact the biosensor's response. Moreover, the code now includes expanded potential windows and adjustable scan rates during CV measurements, as shown in Fig. 3. These enhancements are essential for accurately capturing the system's dynamics, especially during dehydration. In such scenarios, changes in analyte concentration can occur rapidly, making it crucial to adapt the simulated parameters in real-time. By implementing these improvements, the modified CV code enables more precise and reliable analysis, ultimately improving the performance and interpretation of biosensor results in environments with unstable analyte concentrations.

```
87
88      % Initialize Results Storage
89      results = struct('C',{}, 'v',{}, 'eta',{}, 'Z',{}, 'ip',{}, 'RS',{});
90
91      % Main Simulation Loop
92      for C_idx = 1:length(C_range)
93          for v_idx = 1:length(v_range)
94              C = C_range(C_idx);
95              v = v_range(v_idx);
96
97              [eta, Z, ip] = runCVSimulation(C, v, etai, etaf, n, alpha, k0, kc, DM, max_grid, max_iter);
98
99              % Store Results
100             results(end+1) = struct(...
101                 'C', C, ...
102                 'v', v*1000, ... % Convert to mV/s
103                 'eta', eta, ...
104                 'Z', Z, ...
105                 'ip', ip, ...
106                 'RS', 2.69e5 * n^1.5 * sqrt(1e-5) * (C/1000) * sqrt(v) * 1000);
107         end
108     end
109
110     % Plotting Sections
111     plotCVResults(results, C_range, v_range, 'CV_Data.xlsx');
112     plotRandlesSevcik(results, C_range, n);
113     plotButlerVolmerComparison(results, C_range, v_range, n, alpha, k0, etai, etaf);
114     plotNernstValidation(results, v_range, n);
115     plotCVCompareConcentrations(results, C_range, v_range);
116     toc;
117
118     % CORE FUNCTIONS
119     function [eta, Z, ip] = runCVSimulation(C, v, etai, etaf, n, alpha, k0, kc, DM, max_grid, max_iter)
120         F = 96485;
121         R = 8.3145;
122         T = 298.15;
123         f = F/(R*T);
124         D = 1e-5;  % Fixed diffusion coefficient
125
126         tk = 2*(etai - etaf)/v;
127         L = min(ceil(tk/(D/(DM*(sqrt(D*tk/(DM*max_grid))^2)))), max_iter);
128         Dt = tk/L;
129         Dx = sqrt(D*Dt/DM);
```

Fig. 3 *Modified code of cyclic voltammetry*

The CV simulation uses a range of concentrations: 0.1 M, 1.0 M, and 5.0 M. For each concentration, various scan rates ranging from 1 mV/s to 100 mV/s are used to assess how the current response changes with the rate of potential sweep. In addition to the CV analysis, the logarithmic current view, the Nernst equation, and the relationship between diffusion coefficient and concentration are applied to the CV graphs. The logarithmic current view and the Nernst equation indicate a nonlinear relationship between analyte concentration and generated current, which can linearize responses and improve the performance and validation of electrochemical biosensors. It is crucial to analyze the diffusion coefficient in biosensors, as it directly affects the rate and overall response performance of the biosensor. To ensure accurate observation and reliable analysis of the resulting graphs, specific parameters are tightly controlled. The potential window is set from -0.7 V to 0.7 V, allowing a comprehensive view of redox reactions that may occur within this range. Additionally, the simulation is configured to monitor the number of electron transfers in the reactions, establish data-collection grid limits, and set iteration limits to enhance the precision and repeatability of the measurements. This comprehensive approach enables a thorough characterization of the biosensor's electrochemical performance, providing valuable insights into its operational efficacy under varying conditions.

The implementation workflow of the MATLAB model is illustrated in Fig. 4. The model begins by defining the electrochemical input variables, including analyte concentration, scan rate, potential window, electron-transfer number, diffusion coefficient, temperature, and kinetic constants. A triangular potential waveform is then generated to represent the forward and reverse CV scans. At each time step, the current response is computed using a modified Butler-Volmer relationship, allowing concentration- and scan-rate-dependent changes to be observed. The resulting current-potential data are subsequently processed to extract peak current, logarithmic current behavior, Nernstian response, and trends in diffusion coefficient.

This modeling workflow improves reproducibility by applying the same set of electrochemical assumptions across all concentration levels and scan rates. It also enables the biosensor's performance to be interpreted before

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physical fabrication by identifying whether the response is diffusion-controlled, kinetically limited, or saturated at high concentration. In this study, MATLAB is therefore used not only for graph generation, but also as a computational validation platform for understanding the electrochemical behavior of sweat electrolyte detection.

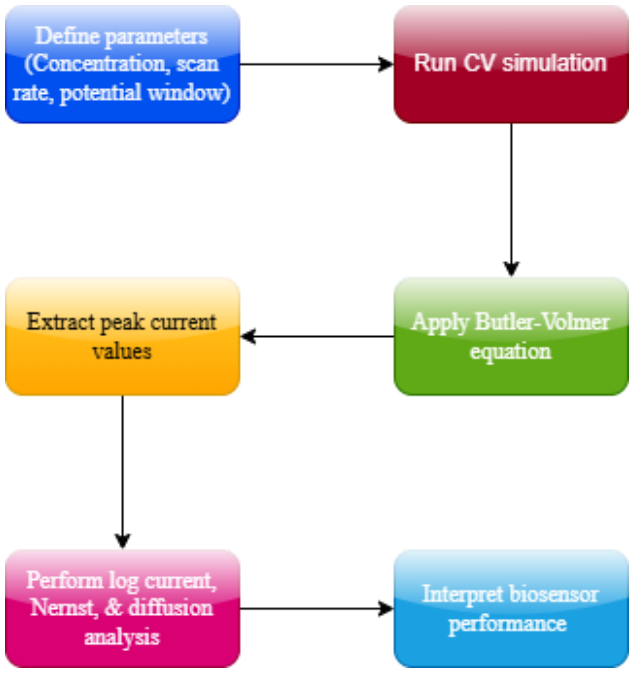


Fig. 4 *MATLAB implementation workflow used for CV simulation and post-processing of electrochemical biosensor parameters*

Table 2 *MATLAB simulation parameter settings and their role in electrochemical biosensor interpretation*

Model component	Setting used in this study	Purpose in analysis
Analyte concentration	0.1 M, 1.0 M, and 5.0 M for Na+, K+, and Cl- representation	Evaluates whether the sensor current changes with low, moderate, and high electrolyte loading.
Scan rate	1, 3.162, 10, 31.622, and 100 mV/s	Determines whether the electrochemical response follows diffusion-controlled behavior or shows kinetic limitation.
Potential window	-0.7 V to +0.7 V	Covers the forward and reverse sweep needed to observe oxidation and reduction peaks in CV.
Electron transfer number	n = 1 for monovalent ion-based electrochemical interpretation	Supports Nernstian and Butler-Volmer calculations for single-charge ion behavior.
Kinetic model	Modified Butler-Volmer formulation	Connects applied potential, overpotential and concentration-dependent current response.
Post-processing outputs	Peak current, logarithmic current, Nernst response, and diffusion coefficient	Provides quantitative indicators for sensitivity, reversibility and mass-transport behavior.
Interpretation focus	Change in current magnitude with concentration and scan rate	Clarifies the main contribution of concentration for dehydration-related sweat electrolyte sensing.

Table 2 presents both the numerical values employed in the MATLAB model and the scientific significance of each parameter in interpreting the biosensor response. This facilitates an understanding of the connection between the input settings and the outputs discussed in the results section. In particular, the concentration and scan rate were considered the two primary factors because they directly affect diffusion, charge transfer, and the measurable peak current. By maintaining a fixed potential window and consistent kinetic assumptions, the differences in the electrochemical response observed in simulations primarily result from variations in electrolyte concentration and from transport behavior that depends on the scan rate.

4. Results

4.1 Cyclic Voltammetry

As depicted in Fig. 5, a series of measurements was conducted at varying concentrations of 0.1 M, 1.0 M, and 5.0 M, with scan rates spanning from a slow 1 mV/s to a rapid 100 mV/s. The results showcased distinct variations in both peak current and potential, reflecting the dynamic nature of the electrochemical processes involved. During the simulation, it was observed that as the scan rate increased with the concentration, the peak current of the cyclic voltammetry (CV) curve showed a significant upward trend. More specifically, at higher scan rates, particularly at 100 mV/s, a marked peak separation became evident. This separation indicates kinetic limitations, suggesting that electron-transfer processes were slower than ideal, thereby reducing the reaction's overall efficiency. At the highest concentration (5.0 M), an impressive peak current was observed, indicating enhanced electrochemical activity. However, this increased concentration also led to a notable potential shift, which can be attributed to the greater mass transport resistance at such high concentrations. The comprehensive peak current values obtained from the CV analysis at each concentration level are meticulously summarized in Table 3, providing a clear overview of the experimental findings.

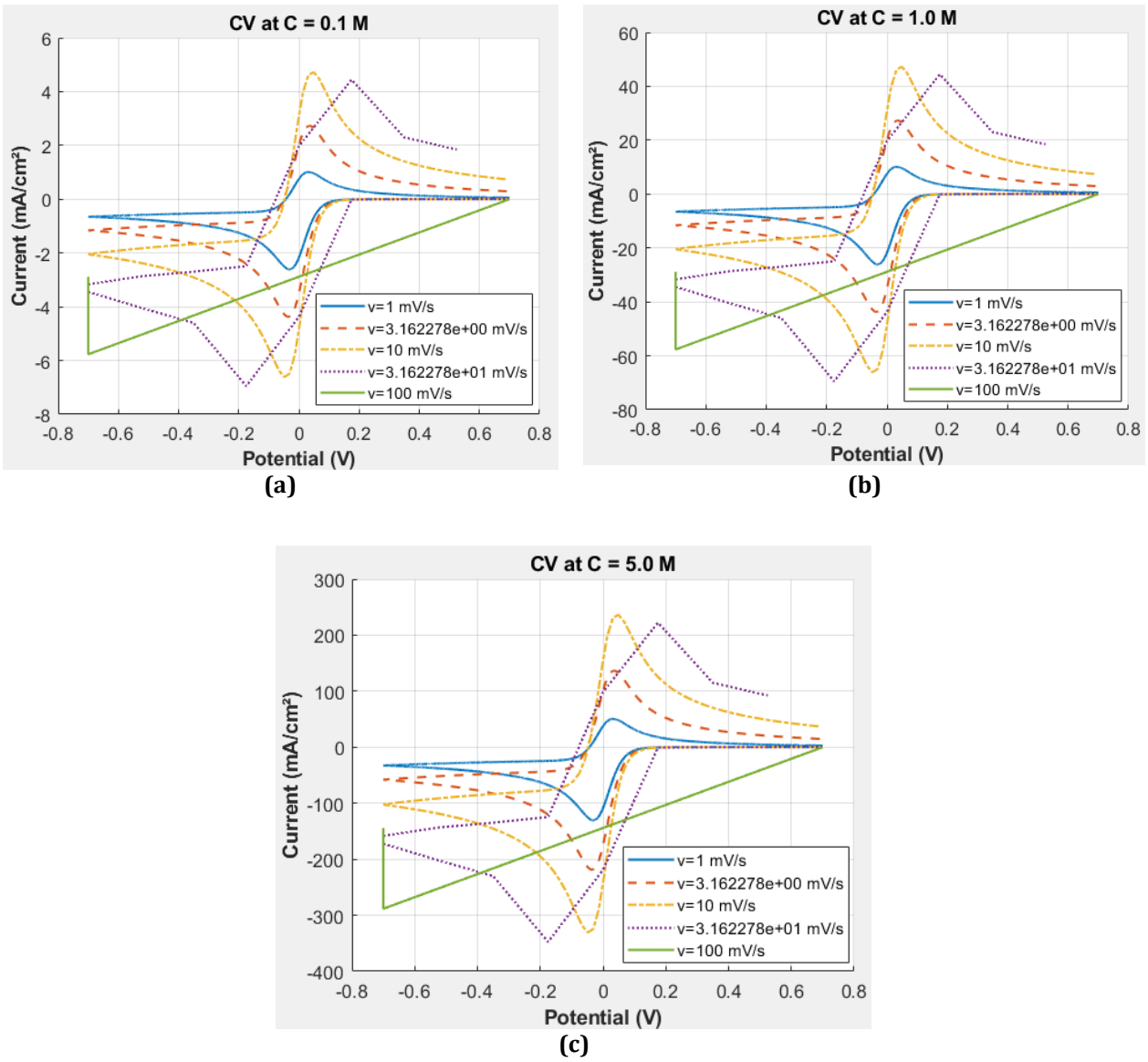


Fig. 5 *Cyclic voltammetry at different analyte concentrations (a) 0.1 M; (b) 1.0 M; and (c) 5.0 M*

The figure above indicates that the increase in peak current magnitude with rising analyte concentration from 0.1 M to 5.0 M and with increasing scan rates from 1 mV/s to 100 mV/s should be emphasized. The primary concentration effect observed is that enhanced electrolyte availability near the electrode surface improves charge

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transfer and results in a diffusion-limited current response. Additionally, the broader peak separation observed at higher scan rates is indicative of quasi-reversible behavior and suggests the onset of kinetic or mass-transport limitations.

Table 3 *Summary of peak current values and diffusion coefficient obtained from simulated cyclic voltammetry*

Concentration (M)	Scan rate (mV/s)	Peak Current (mA/cm^2)	Diffusion Coefficient (cm^2/s)
0.1	1	-2.608390172	9.40244×10^{-6}
0.1	3.16227766	-4.372318703	8.35447×10^{-6}
0.1	10	-6.618102493	6.05288×10^{-6}
0.1	31.6227766	-6.950320409	2.11108×10^{-6}
0.1	100	-5.766081201	4.5947×10^{-7}
1	1	-26.08390172	9.40244×10^{-6}
1	3.16227766	-43.72318703	8.35447×10^{-6}
1	10	-66.18102493	6.05288×10^{-6}
1	31.6227766	-69.50320409	2.11108×10^{-6}
1	100	-57.66081201	4.5947×10^{-7}
5	1	-130.4195086	9.40244×10^{-6}
5	3.16227766	-218.6159351	8.35447×10^{-6}
5	10	-330.9051246	6.05288×10^{-6}
5	31.6227766	-347.5160205	2.11108×10^{-6}
5	100	-288.30406	4.5947×10^{-7}

4.2 Logarithmic Current Results

The logarithmic analysis is a powerful tool for investigating the electron-transfer mechanism and accurately determining the reaction rate. This analysis uncovers a clear linear relationship between the scan rate and all concentration levels, effectively indicating the current values. Such insights are crucial for distinguishing between diffusion-controlled and surface-controlled processes in assessing biosensor performance, ultimately leading to optimization, as vividly illustrated in Fig. 6. The figure shows that the slope approaches 0.5, which aligns well with theoretical expectations, suggesting that the current behavior is primarily diffusion-limited. At high concentrations, the biosensor shows a notably strong current response, indicative of a robust redox process with rapid, efficient electron transfer. Conversely, at lower concentrations, the current values exhibit relative stability, remaining low; this phenomenon suggests minimal background noise and a remarkable capacity for effective signal distinction. Moreover, the peaks within the mid-range potential are noticeably sharper in the logarithmic view, emphasizing the precision of the redox transitions occurring within the system. These enhanced characteristics highlight the potential for further optimization in biosensor design and deepen our understanding of overall performance capabilities.

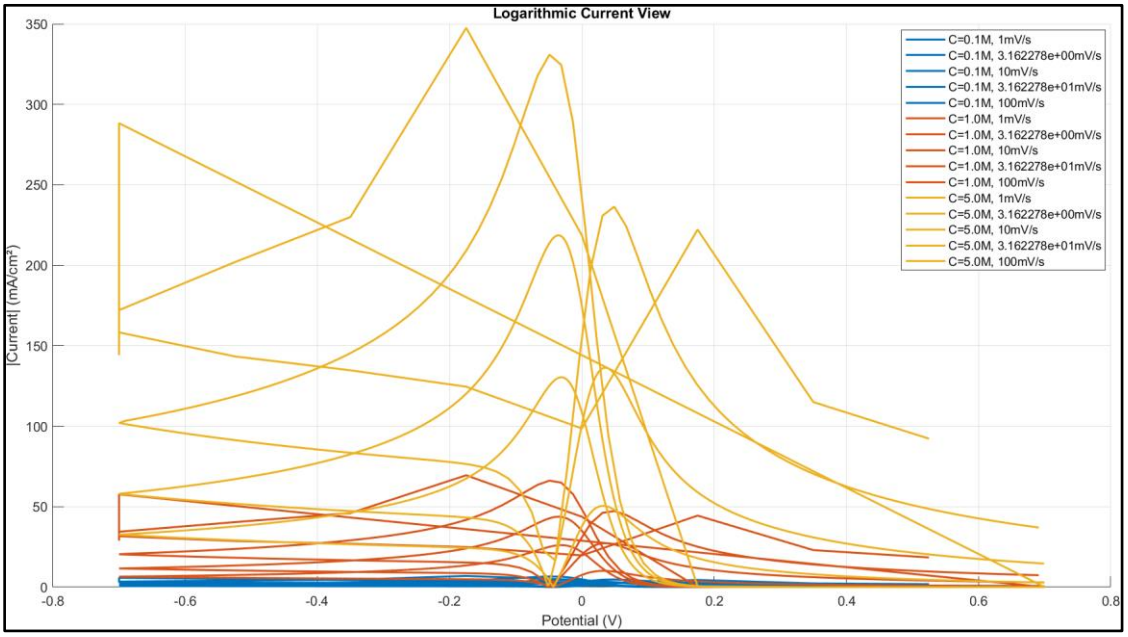


Fig. 6 *Logarithmic current view of biosensor based on cyclic voltammetry*

The key insight lies in the fact that representing the current on a logarithmic scale significantly improves the ability to distinguish signals based on their concentration levels. This approach is especially useful in regions where the raw cyclic voltammetry (CV) curves overlap at low current intensities, making it difficult to differentiate signals. As the concentration increases, stronger current bands become more prominent and easier to identify. Additionally, a nearly linear relationship with the scan rate is observed, which collectively indicates that the transport process is dominated by diffusion. This also suggests that the concentration not only affects the magnitude of the signal but also its kinetic visibility, providing a more comprehensive understanding of the electrochemical behavior.

4.3 Nernst Equation Validation

The validation of the Nernst equation is considered essential for the confirmation of electrochemical reversibility, which is recognized as a fundamental characteristic in the assessment of sensor performance. The experimental data clearly demonstrate a linear relationship between potential and current, strongly suggesting that reversible electron transfer processes are occurring within the system. This concept is exemplified in Fig. 7, which depicts the biosensor's operation under conditions that closely resemble ideal Nernstian behavior. Such alignment is believed to enhance the reliability and accuracy of the sensor's response to varying analyte concentrations. This validation is regarded as crucial for ensuring that measurements obtained in electrochemical applications are both precise and consistent, thereby contributing to the overall performance and trustworthiness of the biosensor in real-world scenarios.

This also interprets that the predictability of the potential response under varying scan rates and concentrations should be assessed. The primary contribution involves validating the electrochemical consistency of the sensor, with deviations observed at extreme potentials interpreted as non-idealities arising from ohmic resistance, capacitive contributions, or fast-scan kinetic limitations rather than random sensor behavior.

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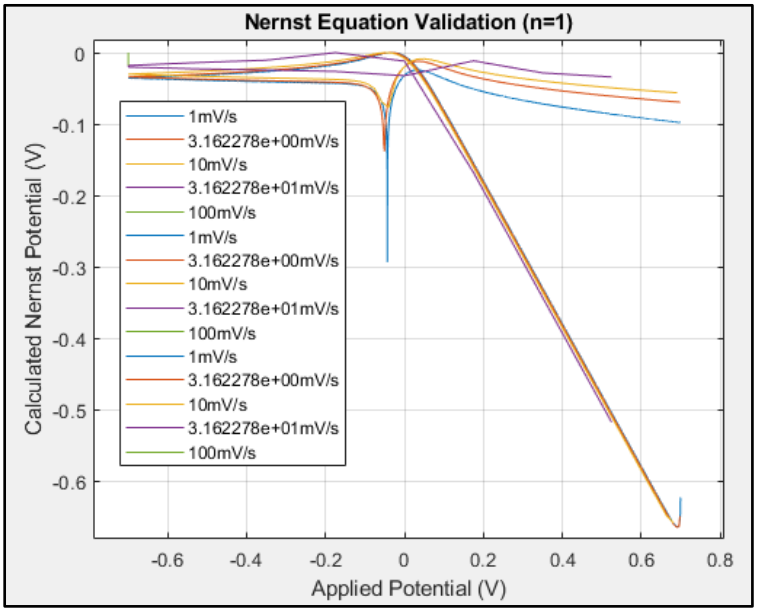


Fig. 7 *Nernstian response of biosensor under different potentials*

4.4 Diffusion Coefficient

The diffusion coefficient, a vital parameter reflecting the transport properties of analytes, is influenced by varying scan rates and concentrations. As depicted in Fig. 8, a notable increase in this coefficient is observed with rising scan rates and concentrations. This rise is attributed to an increased availability of analytes, which enhances the electric-field effect at higher scan rates, thereby facilitating more efficient transport of analytes. At elevated concentrations, variability in the diffusion coefficient occurs due to saturation effects, leading to a reduction in the expected diffusion enhancement. This suggests that, despite the greater presence of analytes, the efficiency of transport decreases owing to the overcrowding of analyte molecules. It is also shown that at lower scan rates, the diffusion coefficient remains relatively stable across concentrations of 0.1 M, 1.0 M, and 5.0 M. Conversely, at higher scan rates, a decline in the diffusion coefficient is observed, primarily caused by interference that disrupts the electroflow within the biosensor, ultimately impacting its performance and responsiveness.

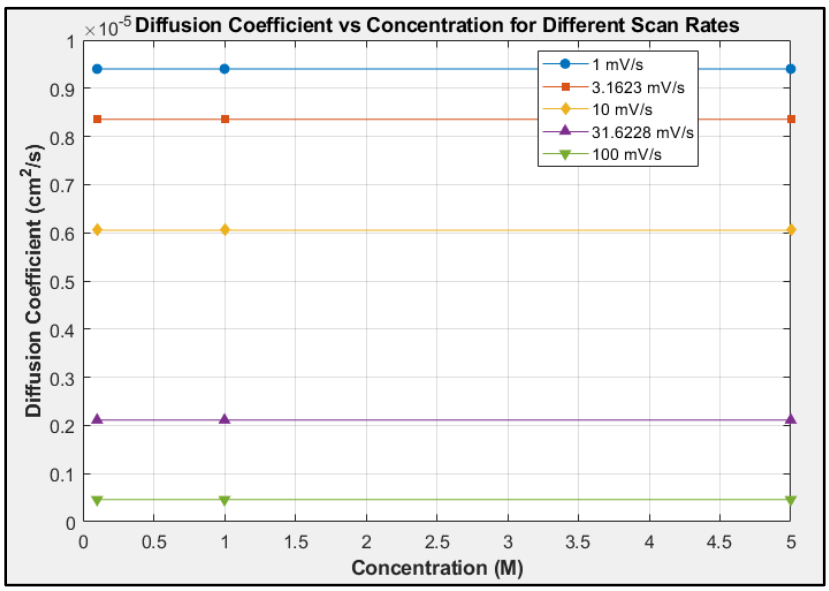


Fig. 8 *Diffusion coefficient effect on different concentrations*

5. Discussion

This study highlights the essential role of cyclic voltammetry (CV) and electrochemical methods in assessing a sweat biosensor for detecting sodium (Na^+), chloride (Cl^-), and potassium (K^+) ions. These electrolytes are key indicators for monitoring hydration and are clinically significant for diagnosing dehydration and electrolyte imbalances. However, their electrochemical behavior in sweat under dynamic conditions remains underexplored. This research offers new insights into their electrochemical responses at varying concentrations and scan rates.

Cyclic voltammetry (CV) identified distinct redox peaks associated with sodium (Na^+), chloride (Cl^-), and potassium (K^+) ions. These peaks increased with higher analyte concentrations and scan rates, demonstrating the sensor's sensitivity to electrolyte levels. As dehydration progresses, sodium and chloride levels rise in sweat, reflected in more intense peaks, while potassium levels decrease, leading to lower peak currents. These patterns align with clinical conditions such as hypernatremia (elevated Na^+ and Cl^-) and hypokalaemia (reduced K^+), indicating electrolyte imbalances due to fluid loss.

The influence of scan rate on sensor performance was significant. As the scan rate increased from 1 mV/s to 100 mV/s, anodic and cathodic peak currents rose linearly, indicating a diffusion-controlled process. However, higher scan rates led to greater peak separation, suggesting quasi-reversible kinetics and potential limitations in electron transfer. At the highest scan rates and concentrations (notably 5.0 M), cyclic voltammetry (CV) curves exhibited broadening and capacitive current effects, indicating mass-transport limitations or electrode saturation, as commonly observed in high-flux electrochemical systems.

The logarithmic transformation of current values improved the clarity of kinetic transitions and redox activity at high concentrations. This log-scale representation highlighted subtle variations in current and onset potential, enabling precise differentiation of electrolyte behaviors. The linear relationships in the ln(current) versus ln(scan rate) plots confirmed diffusion-dominated kinetics, with slope values near the theoretical ideal of 0.5, validating the sensor's consistent, predictable response.

Validation of Nernstian behavior via potential-concentration plots confirmed that the biosensor operates under near-equilibrium electrochemical conditions. The response curve's slope closely matched the expected value for monovalent ions, indicating ideal reversibility. Some deviations at extreme potentials or scan rates were attributed to capacitive effects or ohmic resistance, common in rapid-sweep biosensing, and do not indicate sensor malfunction.

Diffusion coefficient analysis revealed key insights into analyte transport dynamics. Initially, diffusion coefficients increased with concentration, indicating greater ion availability. However, at high concentrations, this trend plateaued, suggesting a saturation point beyond which additional analyte does not enhance transport. This highlights the sensor's practical range and the need for calibration boundaries in real-world applications.

The electrochemical evidence shows that the biosensor is responsive, stable, and effective at measuring sodium (Na^+), chloride (Cl^-), and potassium (K^+) concentrations in relevant physiological ranges. Its diffusion-controlled redox behavior and linear responses confirm its suitability for continuous, non-invasive sweat analysis. These findings are important for monitoring dehydration, as timely detection of electrolyte imbalances is essential for athletic performance and clinical intervention.

5.1 Concentration-Dependent Contribution to Biosensor Performance

The central contribution of this study is highlighted by the conversion of sweat electrolyte variation into a measurable electrochemical signal. In the simulated CV responses, a larger peak current is produced by higher concentration, as a greater number of ionic species are made available to participate in the interfacial electrochemical process. In practical biosensor interpretation, it is implied that the current response can serve as an analytical indicator of electrolyte loading in sweat. Since dehydration is associated with changes in sweat electrolyte balance, the concentration-sensitive response underpins the scientific basis for linking the simulated biosensor output to hydration assessment.

The combined interpretation of CV peak current, logarithmic current behavior, Nernstian response, and diffusion coefficient demonstrates that concentration influences the biosensor through two mechanisms: signal amplification and transport limitation. At moderate concentration, an increase in current is caused by diffusion supplying more analyte to the electrode. At very high concentration and scan rate, the response is rendered less ideal due to saturation, peak broadening, and increased peak separation. These observations contribute to defining the biosensor's useful operating range and are used to explain the necessity of calibration prior to future experimental or wearable implementation.

5.2 Practical Implications for Dehydration-Oriented Sweat Sensing

The concentration effect observed in this work is considered to have significant practical implications for the assessment of hydration based on sweat. In a wearable biosensor, manual interpretation of the entire CV curve by the user is not expected; instead, the device is designed to extract representative electrochemical features such as

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peak current, onset potential, peak separation, and diffusion-related slope. Among these features, the peak current, which depends on concentration, is identified as the most direct indicator, as it demonstrates an increase with higher concentrations of ionic species at the electrode surface.

Consequently, the simulated trend supports a future sensing strategy wherein changes in electrolyte concentration are translated into a measurable current-based output suitable for hydration screening. It is further shown why reliance on a single peak current value is insufficient; rather, multiple electrochemical indicators are necessary. At low and moderate concentrations, the availability of analytes is strongly indicated by the peak current. However, at high concentrations and with a fast scan rate, the CV response may be broadened or shifted due to kinetic limitations, capacitive effects, and mass-transport resistance. In such situations, the use of a logarithmic current view, Nernstian validation, and diffusion-coefficient analysis serve to confirm whether increases in current are attributable to true concentration changes or to non-ideal electrochemical behavior. Such a multi-parameter interpretation enhances the reliability of the analysis and increases the usefulness of the proposed MATLAB model for future calibration experiments.

From a sensor design perspective, the findings point to the need for a balance between concentration sensitivity and stability. While a biosensor exhibiting a very high response at elevated concentrations may appear sensitive, it may also exhibit decreased linearity as the electrode interface nears saturation. Therefore, the development of future sensors should include the definition of a calibration window during which the current response remains predictable and the Nernstian and diffusion trends are maintained consistently. This consideration is particularly relevant for sweat analysis, due to the variability in sweat composition caused by exercise intensity, ambient temperature, sweat rate, sampling location, and individual physiology.

As a computational study, the present work does not claim to provide a direct clinical diagnosis of dehydration; instead, a basis for electrochemical modeling is provided to enhance the understanding of how sweat electrolyte concentration influences biosensor response. Validation through experimental work using artificial and human sweat samples will be necessary to confirm selectivity, repeatability, stability, interference resistance, and long-term performance of wearable devices. Nevertheless, the current findings are valuable as they identify the expected relationship between current and concentration and highlight the electrochemical conditions that should be controlled during future development and testing.

Overall, the main contribution of concentration is clarified: it governs the quantity of ionic species reaching the electrode, amplifies the current response, influences diffusion behavior, and defines the biosensor's calibration range. These relationships are emphasized to facilitate interpretation by readers and to demonstrate how MATLAB-based CV analysis contributes to the development of sweat electrolyte biosensors for hydration monitoring.

6. Conclusion

This study successfully demonstrated the use of MATLAB-driven electrochemical analysis as a means to evaluate a sweat-based biosensor designed for hydration and electrolyte monitoring. Through the application of cyclic voltammetry simulations, the electrochemical behavior of sodium, chloride, and potassium was examined across various concentrations and scan rates. The results confirmed that the current response is directly influenced by concentration, with higher analyte levels resulting in larger CV peak currents, and increased scan rates enhancing the magnitude of the current and revealing kinetic limitations through greater peak separation. The analysis further indicated that the biosensor's response is primarily controlled by diffusion, a conclusion supported by the logarithmic current response, which showed a relationship between current and scan rate consistent with diffusion-controlled behavior. Validation based on Nernstian principles demonstrated that an expected electrochemical response was maintained over the selected potential range, although slight deviations at elevated scan rates and concentrations suggested the presence of non-ideal effects such as capacitive interference, ohmic resistance, or mass-transport limitations. The evaluation of the diffusion coefficient provided additional insights into analyte transport at the electrode interface, indicating that at lower and moderate concentrations, ion transport is facilitated, resulting in a stronger measurable signal.

Conversely, at higher concentrations, a decline in response efficiency was observed due to saturation effects, emphasizing the necessity for a defined calibration range to ensure accurate operation in real-world applications. This aspect is particularly relevant for sweat-based dehydration monitoring, where the ability to distinguish significant concentration changes from saturation-induced signal distortion depends on reliable interpretation of electrolyte levels. The study contributes a computational framework for understanding the influence of sweat electrolyte concentration on biosensor behavior.

A systematic basis for evaluating sensitivity, stability, and concentration responsiveness has been established through the integration of CV simulation, logarithmic current analysis, Nernstian validation, and diffusion-coefficient assessment, which collectively support the development of biosensors prior to experimental fabrication. The findings have implications for the future design of wearable sweat biosensors intended for real-time hydration assessment in contexts such as exercise, heat exposure, and clinical monitoring. Future work is

suggested to include experimental validation using artificial and human sweat samples, the optimization of electrode materials and geometries, and calibration against physiologically relevant electrolyte ranges.

Additionally, the MATLAB model is to be integrated with COMSOL-based mass-transport simulations to enhance the understanding of electrode-surface reactions, concentration gradients, and current-density distributions. Such improvements are expected to facilitate the translation of the proposed biosensor from computational analysis to practical wearable applications.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Uzair Soomro, Nurmiza Binti Othman, Intan Sue Liana Binti Abdul Hamid;* ***data collection:*** *Uzair Soomro;* ***analysis and interpretation of results:*** *Uzair Soomro, Nurmiza Binti Othman, Intan Sue Liana Binti Abdul Hamid;* ***draft manuscript preparation:*** *Uzair Soomro. All authors reviewed the results and approved the final version of the manuscript.*

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