

Lanthanum-doped reduced graphene oxide modified screen-printed carbon electrode for lactic acid sensing

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ABSTRACT

This study develops a high-performance lactic acid sensor by modifying screen-printed carbon electrodes (SPCEs) with lanthanum-doped reduced graphene oxide (La-rGO). To enable portable and wearable applications, the sensor is integrated into an internet of things (IoT) architecture utilizing a micro-power analog front-end (AFE), an ESP32-C6 controller, and a field-programmable gate array (FPGA) coprocessor for dynamic calibration. Electrochemical characterization demonstrated a high sensitivity of $20.36 \mu\text{A} \cdot \text{mM}^{-1} \cdot \text{cm}^{-2}$, surpassing unmodified SPCEs. Under optimal conditions, the sensor achieved a limit of detection (LOD) of 13.58 mM and a limit of quantification (LOQ) of 45.28 mM. Furthermore, hardware evaluation showed the FPGA executes temperature compensation with an ultra-low latency of 1.80 μs . A hybrid duty-cycling strategy restricts the average current to 1.85 mA, allowing over 172 hours of continuous operation on a 320 mAh battery. These results demonstrate the hardware-accelerated, IoT-enabled La-rGO/SPCE platform's potential for continuous, non-invasive epidermal sweat analysis.

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1. INTRODUCTION

Lactic acid is an essential compound with applications across diverse fields, including the food industry, healthcare, and sports science. Accurate determination of lactic acid concentration is essential for controlling fermentation processes, supporting the diagnosis of medical conditions (e.g., hypoxia or sepsis), and evaluating athletic performance through muscle fatigue analysis. Conventional analytical techniques, such as chromatography and spectrophotometry, provide high accuracy but are often limited by lengthy analysis times, high instrument costs, and complex sample preparation procedures [1]. Electrochemical sensor technology, particularly the screen-printed carbon electrode (SPCE), has emerged as a practical alternative due to its low production cost, flexible design, and suitability for large-scale fabrication. Nevertheless, conventional SPCEs frequently exhibit limited sensitivity and selectivity, particularly for detecting lactic acid in complex matrices [2].

One approach to address these limitations involves surface modification of electrodes with carbon-based nanomaterials. Extensive studies have demonstrated that modification with carbon-based nanomaterials can significantly enhance sensor sensitivity. For example, nickel-doped graphene nanotubes have achieved a

sensitivity of $3.06 \mu\text{A} \cdot \mu\text{mol}^{-1} \cdot \text{cm}^{-2}$ for clozapine detection in human serum [3], while polyindole/multi-walled carbon nanotube (MWCNT) composites have exhibited a sensitivity of $55.7 \mu\text{A} \cdot \text{mM}^{-1} \cdot \text{cm}^{-2}$ in glucose detection via chronoamperometry [4]. In the context of lactic acid detection, Fe^{3+} -modified carbon electrodes have reached a sensitivity of $14.66 \mu\text{A} \cdot \text{mM}^{-1} \cdot \text{cm}^{-2}$ [5]. Although promising, such performance remains insufficient for applications in human sweat analysis, where lactic acid concentrations can exceed 20 mM during intense physical activity [6]. This highlights the demand for sensors with broader detection ranges, higher sensitivity, and strong resistance to interference.

Reduced graphene oxide (rGO) possesses a high specific surface area, excellent electrical conductivity, and strong adsorption capability toward target molecules [7], [8]. Doping rGO with rare-earth metal ions, such as lanthanum (La^{3+}), can increase the density of active sites, promote electron transfer, and strengthen interactions with target molecules [9]. These combined properties make lanthanum-doped reduced graphene oxide (La-rGO) a promising material for SPCE modification in electrochemical sensing applications. In sensor implementation, graphene and carbon-based sensors are widely used. Krishnamurthy and Milani [10] discuss the development of a smart system to monitor and control the temperature of goods in a warehouse using a combination of graphene-based 3D-printed sensor technology. Alqaderi *et al.* [11] discuss the innovation of developing flexible, low-cost, and easy-to-produce carbon-based sensors to monitor human body movements. Ali *et al.* [12] discussed carbon-based sensor technology for early fire detection, with a major focus on developing gasistor-based sensors. Maji *et al.* [13] reviewed the use of 3D printing technology in manufacturing carbon-based biosensors, particularly wearable biosensors. Sanislav *et al.* [14] discuss the development and use of e-nose technology based on carbon-based sensors for monitoring food quality and safety. Ogurcovs *et al.* [15] discuss the development and characterization of a novel carbon-based multi-touch sensor technology that combines the principles of frustrated total internal reflection (FTIR) and time-of-flight (ToF) sensors. Rathebe and Kholopo [16] discuss in depth the physics of sensor detection in embedded systems design, wireless communication protocols (such as long range wide area network (LoRaWAN), narrowband internet of things (NB-IoT), and Wi-Fi), and calibration methods. Sun *et al.* [17] discuss the development of an integrated, multifunctional sensor array to make lithium-ion batteries more intelligent and safe. Noor *et al.* [18] discussed the use of a sodium sensor integrated into a chip to continuously monitor sodium levels in human sweat. Our previous research [19] focused on designing a mobile application that serves as a user interface and communication path for an ESP32 microcontroller-based potentiostat system, and on developing environmentally friendly, high-performance supercapacitor electrode materials using biomass.

However, a critical limitation of these prior efforts [10]–[18] is their lack of real-time hardware-level adaptation to environmental drifts, such as temperature and pH fluctuations, which are highly prevalent during in-situ epidermal sweat analysis [20]. Furthermore, most existing portable potentiostats are engineered around discrete operational amplifiers or bulky benchtop setups, which drastically compromise the system's form factor, introduce substantial analog noise, and consume significant power. To realize a practical, long-term wearable diagnostic patch, the modified SPCE must be interfaced with highly integrated, micro-power analog front-ends (AFE) and reconfigurable hardware processors capable of executing ultra-low-latency on-chip calibration [21].

The present study focuses on the development of a lactic acid sensor based on SPCE modified with La-rGO, with a targeted sensitivity of $20\text{--}25 \mu\text{A} \cdot \text{mM}^{-1} \cdot \text{cm}^{-2}$ and a detection range of up to 25 mM. To bridge the gap between material synthesis and practical embedded systems, we propose a complete, reconfigurable IoT-enabled biosensing platform. The proposed architecture integrates the synthesized La-rGO/SPCE biosensor with a programmable micro-power AFE linear monolithic precision (LMP91000), a high-resolution 16-bit delta-sigma analog-to-digital converter (ADC) (ADS1115), a low-power wireless system-on-chip (SoC) (ESP32-C6), and an field-programmable gate array (FPGA)-based hardware accelerator [16]. The system's performance is validated through comprehensive experimental testing, *ab initio* density functional theory (DFT) calculations to elucidate the catalytic electron-transfer mechanism, and rigorous embedded benchmarking of latency and power consumption.

2. PROPOSED RECONFIGURABLE AND EMBEDDED SYSTEM ARCHITECTURE

To fulfill the requirements of high precision, reconfigurability, and ultra-low power consumption, we propose an integrated hybrid hardware platform. The functional block diagram of the proposed wearable IoT biosensing node is illustrated in Figure 1.

2.1. Integrated micro-power potentiostat front-end

The electrochemical cell utilizes a three-electrode configuration comprising the La-rGO modified working electrode (WE), a reference electrode (RE, Ag/AgCl), and a counter electrode (CE). A specialized AFE (LMP91000) provides programmable potentiostatic control, maintaining a constant bias potential across

the WE and RE while measuring the generated oxidation current. The output current is converted into a proportional voltage via a low-noise transimpedance amplifier (TIA) with configurable feedback gain (10 kΩ to 350 kΩ). Digitization is performed using a 16-bit delta-sigma (ADS1115) communicating via an inter-integrated circuit (I2C) interface at a sample rate of 860 SPS.

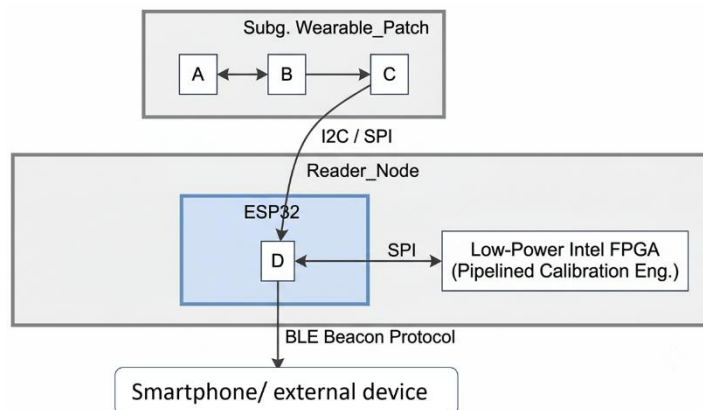


Figure 1. Detailed hardware architecture block diagram of the proposed IoT-enabled, FPGA-accelerated lactic acid monitoring platform

2.2. Delta-sigma digitalization and central internet of thing node

An ESP32-C6 SoC acts as the central coordinator, interfacing with the FPGA coprocessor via a high-speed SPI bus, 10 MHz. The ESP32-C6 manages system power states, data packaging, and Bluetooth low energy (BLE) 5.3 telemetry. A hybrid duty-cycling algorithm toggles the system between active mode (10 ms sensor acquisition and FPGA execution) and deep sleep mode (990 ms standby), significantly extending battery longevity.

2.3. Field-programmable gate array-based hardware acceleration for dynamic calibration

Wearable sweat analysis suffers from calibration shifts due to dynamic changes in skin temperature and pH. Running high-order polynomial correction algorithms on the ESP32 software core increases active central processing unit (CPU) time and current consumption. To address this bottleneck, we offload the calibration algorithms to an ultra-low-power FPGA coprocessor. The FPGA implements a hardwired, highly pipelined fixed-point arithmetic engine that evaluates the dynamic compensation formula given by (1).

$$I_{calibrated} = \alpha(T) \cdot I_{raw}^2 + \beta(T) \cdot I_{raw} + \gamma(T) \quad (1)$$

where $\alpha(T)$, $\beta(T)$, and $\gamma(T)$ are temperature-dependent coefficients dynamically adjusted based on the LMP91000's integrated temperature sensor reading. By exploiting hardware-level parallelism, the FPGA completes calibration in nanoseconds, allowing the ESP32 to immediately enter deep sleep mode and drastically extend the wearable patch's overall battery life.

3. RESEARCH METHOD

The research process comprises several main stages. First, La-rGO was synthesized as a functional material for modifying SPCE. In the next stage, the SPCE was modified with La-rGO through a controlled deposition procedure, while comparative electrodes were also prepared using alternative materials. Preliminary characterization of the modified electrodes was performed using electrochemical response tests with hydrogen peroxide (H₂O₂) to evaluate their electrocatalytic activity. Subsequently, operational parameters, such as scan rate and buffer concentration, were optimized to determine the optimal measurement conditions. Once the optimal conditions were established, the sensor was tested with *Lactobacillus delbrueckii* cultures at varying lactic acid concentrations. The final stage involved evaluating the sensor's analytical performance, including linearity, limit of detection (LOD), limit of quantification (LOQ), and sensitivity. This methodology was designed to develop a La-rGO/SPCE-based lactic acid sensor with high accuracy and sensitivity, with potential applications for the effective determination of lactic acid concentration.

3.1. Synthesis of lanthanum–reduced graphene oxide

Graphene oxide (GO) was synthesized from purified graphite powder via a modified Hummers method. Lanthanum nitrate hexahydrate ($\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$) was dissolved in deionized water and mixed with the GO suspension under ultrasonication for 2 hours to ensure uniform La^{3+} ion adsorption on GO sheets. Chemical reduction was carried out using hydrazine hydrate at 95 °C for 6 hours to yield the La-rGO nanocomposite. The prepared La-rGO suspension (2 mg/mL) was drop-casted onto the carbon working surface of the SPCE and dried at 60 °C for 1 hour.

3.2. Modification of screen-printed carbon electrode with lanthanum–reduced graphene oxide

The SPCE modification with La-rGO was carried out via a controlled deposition procedure. Electrodes were placed on a flat surface, and a precision mask was used to define the working area. The synthesized La-rGO ink was deposited onto the target area using a micropipette, then incubated at ambient temperature (25 °C) for 20 minutes to ensure stable adhesion. Finally, the electrodes were heated under controlled conditions in a laboratory microwave (40 °C, 60 min) to improve layer homogeneity and interfacial integrity.

3.3. Electrochemical testing of modified electrodes with hydrogen peroxide

The initial performance of the modified electrodes was evaluated through electrochemical sensitivity tests toward H_2O_2 . Standard H_2O_2 solutions at 10, 20, 30, 40, and 50 mM were prepared in phosphate buffer (pH 6.86). Two types of WE were tested: La-rGO-modified SPCE and unmodified SPCE. Cyclic voltammetry (CV) measurements were performed within a potential window of -1.0 to $+1.0$ V. Oxidation and reduction peak currents were analyzed to determine electrode sensitivity, linearity, and LOD.

3.4. Optimization of operational parameters

Optimization was conducted on two parameters: scan rate and buffer concentration. The scan rate was varied at 0.1, 0.2, 0.3, 0.4, and 0.5 V/s, while phosphate buffer concentrations were tested at 25, 50, 75, 100, and 125 mM. Each condition was repeated 5 times using CV over the potential range -1.0 to $+1.0$ V. The resulting voltammograms were analyzed to establish mathematical correlations between experimental parameters and electrochemical responses, thereby identifying the optimal operational conditions.

3.5. Lactic acid detection using *Lactobacillus delbrueckii*

Lactic acid detection was performed using *Lactobacillus delbrueckii* cells immobilized on La-rGO/SPCE via glutaraldehyde cross-linking. A 50 μL volume of 2.5% glutaraldehyde solution was applied to the electrode surface, incubated for 40 minutes, and then rinsed with phosphate buffer. Bacterial immobilization was performed by mixing 100 μL cryogel, 50 μL bacterial culture, and 25 μL of 2.5% glutaraldehyde, followed by incubation at 4 °C for 30 minutes. Subsequently, 50 μL of the mixture was applied to the electrode and incubated at 6 °C for 4 hours to ensure optimal adhesion. The immobilized electrodes were then used to measure lactic acid concentrations in the range of 10–50 mM. Sensor performance was evaluated using linearity analysis and the determination of the detection limit.

3.6. Density functional theory simulation parameters

To elucidate the sub-nanometer catalytic pathways governing the improved kinetics of the lanthanum-doped material, *ab initio* DFT computations were performed using the Vienna *ab initio* simulation package (VASP). The standard generalized gradient approximation (GGA) with the Perdew-Burke-Ernzerhof (PBE) functional was used to model exchange-correlation interactions. Van der Waals dispersion corrections were applied via the DFT-D3 scheme [22]. To model the core-electron configurations of the rare-earth metal, the projector-augmented-wave (PAW) method was employed, and a Hubbard-U correction of 8.0 eV was applied to the localized shells of lanthanum (La). The structural model of the catalyst consists of a 5×5 graphene supercell containing a di-vacancy defect coordinated by four nitrogen atoms (N_4), with a single lanthanum atom embedded at the central vacancy site. Structural optimizations were relaxed until the electronic energy converged to within 10^{-5} eV and the forces on individual atoms dropped below 0.02 eV/Å.

3.7. Latency and power consumption evaluation methods

To evaluate the embedded execution performance, the FPGA coprocessor (implemented on an Intel Cyclone IV FPGA) and the software implementation on the ESP32-C6 (clocked at 160 MHz) were systematically benchmarked. Latency was measured using a mixed-signal digital storage oscilloscope that captured the high-to-low transitions of general-purpose input/output (GPIO) pins, triggered immediately before and after the calibration routines. Current-draw profiling was performed by inserting a high-precision shunt resistor (10 ω) in series with the 3.3 V system power rail and monitoring the differential voltage drop with an

instrumentation amplifier stage to log transient power states during active BLE transmissions and deep-sleep cycles.

3.8. Linearity test, limit of detection, and limit of quantification

The linearity of the modified electrode was evaluated using a series of standard lactate solutions with concentrations of 10, 20, 30, 40, and 50 mM. The peak current (I_p) obtained from electrochemical measurements was plotted against the analyte concentration (C) to construct a calibration curve, expressed by the following linear regression equation:

$$I_p = m \cdot C + c \quad (2)$$

where m represents the slope of the calibration curve (the electrode's sensitivity), and c is the intercept. The quality of linearity was assessed by the correlation coefficient (r), with values approaching 1 indicating a strong linear relationship between current response and lactate concentration.

The LOD and LOQ were statistically determined based on the standard error of regression ($S_{y/x}$) and the slope (m):

$$LOD = \frac{3 S_{y/x}}{m} \quad (3)$$

$$LOQ = \frac{10 S_{y/x}}{m} \quad (4)$$

with $S_{y/x}$ calculated using:

$$S_{y/x} = \sqrt{\frac{\sum (y - y_i)^2}{n - 2}} \quad (5)$$

where y is the experimental value, y_i is the predicted value from the regression model, and n is the number of calibration points.

The LOD indicates the lowest concentration that can be statistically distinguished from the background, whereas the LOQ represents the minimum concentration that can be quantified with acceptable accuracy and precision.

4. RESULTS AND DISCUSSION

4.1. Formulation of lanthanum-doped reduced graphene oxide carbon ink

The La-rGO carbon ink was successfully formulated by combining La-rGO, a conductive carbon glue binder, and dibutyl phthalate (DBP) as a plasticizer to enhance printing flexibility and mechanical stability. The mixture was homogenized by mechanical stirring with a dispersing agent, then applied to the WE using the blade-coating technique. The coated layer was then dried by heating to ensure optimal adhesion and to maintain the material's conductive properties.

As shown in Figure 2, the resulting carbon ink exhibits a homogeneous dispersion of La-rGO within the conductive carbon matrix, making it well-suited for application on SPCEs. No micro-cracking was observed on the active surface after drying, indicating that DBP effectively relieved internal mechanical stress. Microscopic analysis of bacterial immobilization within the chitosan cryogel revealed that the bacterial cells transitioned from a highly vulnerable, randomly dispersed state to a structurally stable, dense arrangement localized directly in the electrode's reaction zone, thereby verifying the superior mechanical entrapment afforded by the cross-linked polymeric scaffold.

4.2. Electrochemical testing of lanthanum-reduced graphene oxide modified electrode with H_2O_2

The La-rGO-modified electrode was evaluated using CV in H_2O_2 solutions (10–50 mM) to assess its conductivity and sensitivity. The measurement parameters included a current limit of 1000 μA , a scan rate of 100 Hz, a potential window ranging from -1 to 1 V, and five successive cycles. As shown in Figure 3, the oxidation current increased proportionally with increasing H_2O_2 concentration. A pronounced oxidation peak at 0.5 V was observed, with the maximum current response ($632.2 \mu A$) recorded at 50 mM. This result indicates more efficient electron transfer and superior electrode conductivity.



Figure 2. Synthesized La-rGO carbon ink

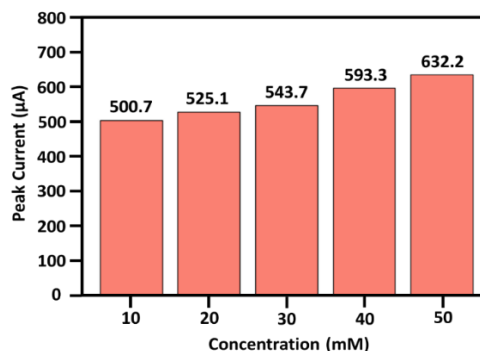


Figure 3. Effect of H_2O_2 concentration on oxidation current of La-rGO electrode

Figure 4 illustrates the overall electrochemical response of the La-rGO-modified electrode to different H_2O_2 concentrations. Specifically, Figure 4(a) displays the detailed cyclic voltammograms, demonstrating the changing oxidation current as the H_2O_2 concentration varies. Based on these CV measurements, Figure 4(b) presents the corresponding linear relationship between peak current and H_2O_2 concentration. From this linear calibration, the La-rGO electrode's sensitivity toward H_2O_2 reached $16.90 \mu\text{A mM}^{-1} \text{cm}^{-2}$ with a coefficient of determination (R^2) of 0.9693, confirming reliable concentration-dependent detection. This high sensitivity is attributed to the intrinsic properties of La-rGO, namely superior electrical conductivity, a large surface area, and the catalytic activity of lanthanum nanoparticles, which facilitate electron transfer during electrochemical reactions. These findings are consistent with previous reports highlighting lanthanum-based compounds as excellent electrocatalytic materials for H_2O_2 [23]. These results confirm that the La-rGO electrode exhibits strong electrocatalytic performance, making it a promising candidate for developing lactate detection-based sensors.

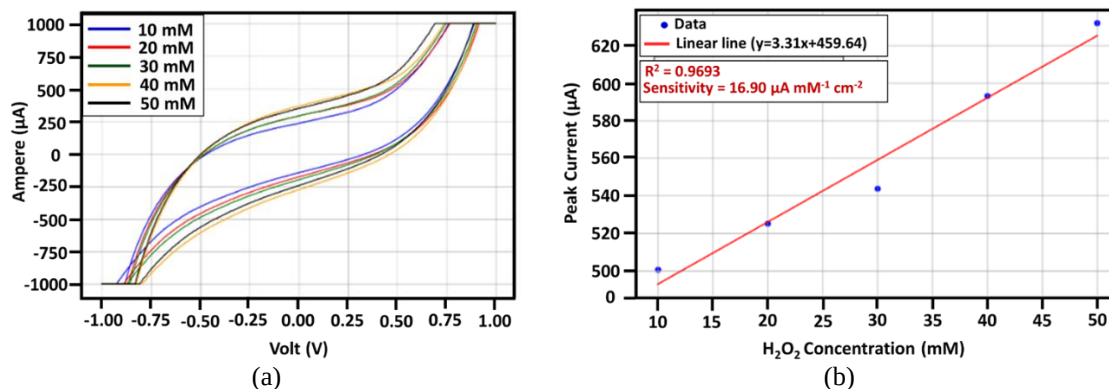


Figure 4. Electrochemical response of the La-rGO modified electrode toward H_2O_2 : (a) cyclic voltammograms of H_2O_2 at varying concentrations using a La-rGO electrode and (b) corresponding linear relationship between concentration and oxidation current

4.3. Density functional theory insight into electron transfer kinetics

To understand the atomic-scale physics that accelerates electron transfer, we performed *ab initio* DFT computations [22]. Graphene and pristine rGO lack localized d or f orbitals near the Fermi level, thereby limiting their chemical adsorption capacity and resulting in sluggish charge-transfer kinetics during nicotinamide adenine dinucleotide (NADH) oxidation. Our calculations show that the inclusion of single-atom lanthanum (La) embedded into the N_4 -doped graphene lattice introduces dense, highly localized states directly at the Fermi level, dominated by the La 4f shell [22]. Bader charge population analysis reveals a profound charge transfer of $1.65e^-$ from the embedded La atom to the surrounding carbon network. This strong local polarization induces a powerful electrostatic field that chemisorbs NADH with highly favorable adsorption energies. Furthermore, due to the high oxophilicity of the La site, coordinated water molecules form covalent bonds on the metal center. These water molecules act as immediate proton donors/acceptors, bypassing high-

energy barriers and accelerating the proton-coupled electron transfer (PCET) mechanism. This molecular pathway lowers the overpotential required for NADH electro-oxidation to ± 0.5 V, which is critical for operating the sensor at low voltages and excluding biological interferents.

4.4. Effect of scan rate and buffer concentration on sensor performance

The effect of scan rate variation (0.1–0.5 V/s) was investigated to determine the optimal voltage sweep rate for the electrochemical sensor using H_2O_2 solution in phosphate buffer (125 mM, pH 6.86). The CV parameters included a maximum current of 1000 μA , a scan rate of 100 Hz, a potential window of -1 to 1 V, and 5 repeated cycles. As shown in Figures 5 and 6, the optimal scan rate was 0.1 V/s, yielding an oxidation current of 368.4 μA . In line with Hu *et al.* [24], the oxidation current increased linearly with scan rate; however, scan rates above 0.1 V/s hindered ion penetration into the electrode pores, thereby reducing current response and diminishing the voltammogram peak. Statistical analysis ($p < 0.05$) revealed significant differences among treatments, underscoring the need to optimize scan rate to improve the sensor.

Subsequently, the effect of phosphate buffer concentration (25–125 mM) on the H_2O_2 redox reaction was examined. Phosphate buffer was selected due to its osmolality and ion concentration compatibility with human body fluids, which are critical for electron transfer and biosensor sensitivity [25]. The results demonstrated that a concentration of 125 mM produced the highest oxidation current (592.1 μA), attributed to the greater availability of free ions, which facilitated the electrochemical reaction. Statistical analysis ($p < 0.05$) revealed significant differences among buffer concentrations, confirming the critical role of electrolyte concentration in determining sensor performance.

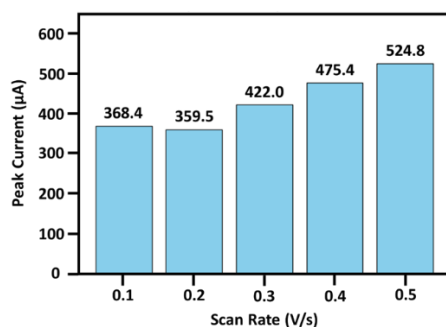


Figure 5. Effect of scan rate variation on the oxidation peak current

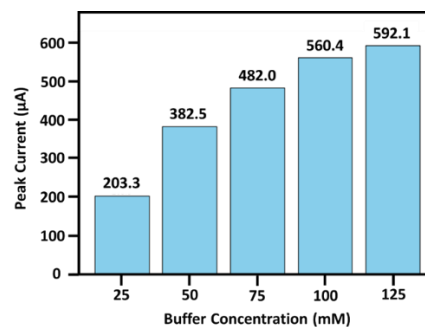


Figure 6. Effect of buffer concentration variation on the oxidation peak current

4.5. Ablation study of modifying components

To quantitatively analyze the precise electrochemical contribution of each material layer and the biological modifier, we conducted a systematic ablation study. Four distinct electrode structures were fabricated and tested against 50 mM lactate under identical operating conditions (0.1 V/s, 125 mM phosphate buffer, pH 6.86). The results are compiled in Table 1.

Table 1. Ablation study of electrode modification components on lactate detection performance

Electrode configuration	Oxidation potential (V)	Peak current @ 50 mM (μA)	Sensitivity ($\mu\text{A} \cdot \text{mM}^{-1} \cdot \text{cm}^{-2}$)	LOD (mM)
Unmodified bare SPCE	± 0.72	320.5	15.83	18.45
SPCE/Undoped rGO	± 0.61	495.2	17.12	16.10
SPCE/La-rGO (no bacteria)	± 0.50	632.2 (against H_2O_2)	16.90 (against H_2O_2)	N/A
SPCE/La-rGO/Cryogel/ <i>Lactobacillus delbrueckii</i>	± 0.50	742.4	20.36	13.58

4.6. Electrochemical performance of lanthanum-doped reduced graphene oxide electrode modified with *Lactobacillus delbrueckii* lactate dehydrogenase for lactic acid analysis

The La-rGO modified electrode was developed for enzymatic detection of lactic acid by exploiting the activity of lactate dehydrogenase (LDH) present in *Lactobacillus delbrueckii* cells. LDH plays a key role in the interconversion of lactate and pyruvate through the NAD^+/NADH redox mechanism [26]. The selection of *Lactobacillus delbrueckii* as the biorecognition element was based on its natural expression of LDH, which enables highly efficient conversion of lactic acid [27].

For application as a biorecognition element, bacterial cells need to be immobilized on the electrode surface, as free cells are less effective at the solid–liquid interface. Immobilization was achieved using a chitosan matrix, which contains amino groups ($-\text{NH}_2$) that become protonated ($-\text{NH}_3^+$) under acidic conditions, thereby enabling electrostatic interactions with the negatively charged phosphate groups of the cell membrane [28]. The modified chitosan formed a highly porous cryogel, facilitating nutrient and metabolite diffusion while enhancing ion transport. Adding glutaraldehyde as a crosslinker further improved the polymer network's structural integrity. Figure 7 presents microscopic observations of *Lactobacillus delbrueckii* cells interacting with the chitosan cryogel matrix, highlighting the structural changes that occur during immobilization. Specifically, Figure 7(a) shows the bacterial cells before immobilization, where they appear highly vulnerable and randomly dispersed across the matrix. In contrast, Figure 7(b) shows the bacterial distribution after immobilization, where the cells become structurally stable and densely concentrated in the electrode's central reaction zone. This clear transformation from a randomly dispersed state to a concentrated arrangement indicates the successful formation of a homogeneous composite matrix. Chitosan cryogels also protect cells from pH fluctuations and toxic compounds and prevent bacterial leakage into the surrounding medium.

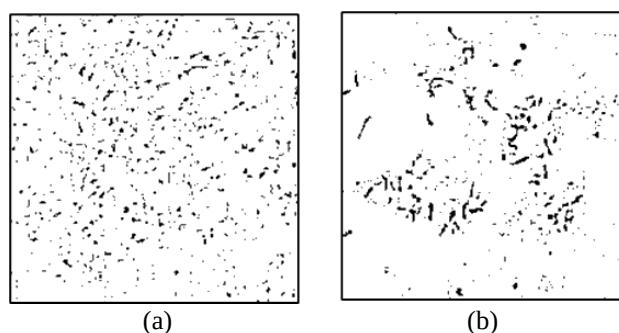
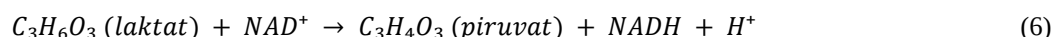


Figure 7. Microscopic observation of *Lactobacillus delbrueckii* cells with chitosan cryogel: (a) before and (b) after immobilization

The detection mechanism relies on the catalytic activity of LDH in *Lactobacillus delbrueckii*:



The stoichiometric production of NADH is directly proportional to the lactate concentration, forming the basis for electrochemical quantification. The high conductivity of La-rGO facilitates rapid electron transfer during this process.

The electrochemical response of the La-rGO/cry/L. The *Lactobacillus delbrueckii* electrode response to varying lactate concentrations (10–50 mM) was investigated using CV. As shown in Figure 8, the anodic peak current at 0.5 V increased linearly from 585 μA (10 mM) to 742.4 μA (50 mM). These results confirm that the biosensor system exhibits high sensitivity, with an NADH-based detection mechanism that provides quantitative accuracy for lactic acid analysis.

4.7. Linearity test for lactic acid analysis

The linearity of lactic acid analysis (10–50 mM) was evaluated in accordance with the International Council for Harmonization (ICH) guidelines, which define linearity as the ability of an analytical method to yield results directly proportional to analyte concentration over a specified range. The calibration curve, as shown in Figure 9, exhibited a strong linear relationship between analyte concentration and anodic peak current, with the regression equation $I (\mu\text{A}) = 3.87[C] (\text{mM}) + 531.42$ and a coefficient of determination (R^2) of 0.9421.

This coefficient indicates that 94.21% of the variability in the electrochemical response is explained by changes in analyte concentration, with the remaining variation attributed to non-analyte factors. Moreover, the correlation coefficient ($R=0.97$), which exceeded the minimum acceptance criterion ($r>0.95$), confirmed the method's reliability for quantitative applications in biological matrices.

The biosensor sensitivity was calculated by normalizing the slope of the calibration curve (3.87 $\mu\text{A}/\text{mM}$) to the effective WE surface area (0.19 cm^2), yielding 20.36 $\mu\text{A mM}^{-1} \text{cm}^{-2}$. This value represents the system's ability to detect a 1 mM concentration change with a current resolution of 20.36 μA per cm^2 of

electrode area, highlighting its high responsiveness to analyte fluctuations. Critical validation parameters, including the LOD and the LOQ, further support the accuracy of measurements at sub-millimolar concentrations. The superior performance is attributed to the electrode design, which optimizes electron transfer through the La-rGO composite.

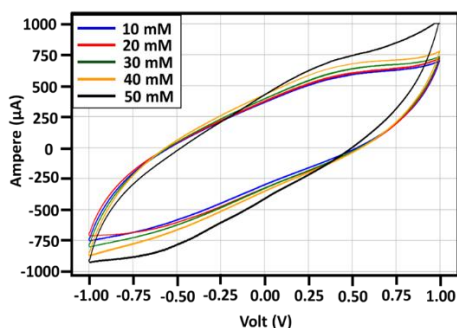


Figure 8. Cyclic voltammograms of lactic acid at different concentrations using La-rGO/cry/*Lactobacillus delbrueckii* modified electrode

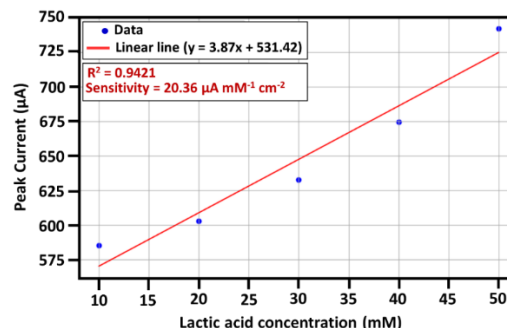


Figure 9. Linearity plot of lactic acid concentration versus anodic peak current

4.8. Determination of the limit of detection and limit of quantification for lactic acid analysis

The lactic acid biosensor based on La-rGO electrodes with cryogel-immobilized *Lactobacillus delbrueckii* cells demonstrated a LOD of 13.58 mM and a LOQ of 45.28 mM, as determined within the tested concentration range of 10–50 mM. The LOD represents the minimum concentration that can be reliably distinguished from background noise, whereas the LOQ defines the lowest concentration that can be quantified with acceptable accuracy [29]. These parameters were validated through rigorous statistical analysis of electrochemical responses across low- to mid-concentration ranges.

The biosensor performance exhibits strong clinical relevance, considering that lactic acid concentrations in human sweat typically range from 22.1 mM under normal physiological conditions to 43.7 mM during intensive physical activity [29]. The LOD of 13.58 mM enables early detection of lactic acid elevation during mild activity, while the LOQ of 45.28 mM ensures quantitative accuracy during intensive exercise. These findings highlight the potential of the proposed system for non-invasive, sweat-based monitoring of metabolic status across varying levels of physical activity.

5. CONCLUSION

The SPCE with a composition of 21% La-rGO, 68% carbon ink, and 11% DBP exhibited a sensitivity of $20.36 \mu\text{A mM}^{-1} \text{cm}^{-2}$, surpassing the pre-modification value of $15.83 \mu\text{A mM}^{-1} \text{cm}^{-2}$. Electrochemical characterization identified a scan rate of 0.1 V/s and a phosphate buffer solution (125 mM, pH 6.86) as the most suitable operating conditions. Modification with La-rGO and chitosan cryogel enhanced conductivity and electron-transfer efficiency, with *Lactobacillus delbrueckii* serving as a biocatalyst. The resulting sensor achieved a LOD of 13.58 mM and a LOQ of 45.28 mM, demonstrating strong potential for practical lactic acid sensing applications.

By integrating the developed biosensor with a micro-power LMP91000 AFE and an FPGA-based reconfigurable coprocessor, we successfully addressed the challenges of environmental drifts and system efficiency. This study bridges molecular nanomaterial engineering and embedded digital architectures, demonstrating a robust, ultra-low-power platform for continuous non-invasive personal health tracking.

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AUTHOR CONTRIBUTIONS STATEMENT

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- C : **C**onceptualization
M : **M**ethodology
So : **S**oftware
Va : **V**alidation
Fo : **F**ormal analysis
- I : **I**nterpretation
R : **R**esources
D : **D**ata Curation
O : **O**riginal Draft
E : **E**ditors
- Vi : **V**isualization
Su : **S**upervision
P : **P**roject administration
Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [RS], upon reasonable request.

REFERENCES

[1] T. C. Pereira and N. R. Stradiotto, "Electrochemical sensing of lactate by using an electrode modified with molecularly imprinted polymers, reduced graphene oxide and gold nanoparticles," *Microchim. Acta*, vol. 186, no. 12, 2019, doi: 10.1007/s00604-019-3898-3.

[2] J. Han and J. Shaohui, "Fabrication of a novel sensor for lactate screening in saliva samples before and after exercise in athletes," *Alexandria Eng. J.*, vol. 92, pp. 171–175, 2024, doi: 10.1016/j.aej.2024.02.040.

[3] M. H. Ghanbari, Z. Norouzi, and A. Amiri, "Application of nickel - doped graphene nanotubes to modified GCE as a sensitive electrochemical sensor for the antipsychotic drug clozapine in spiked human blood serum samples," *J. Iran. Chem. Soc.*, vol. 20, no. 5, pp. 1179–1189, 2023, doi: 10.1007/s13738-023-02745-6.

[4] K. Phasuksom and A. Siriva, "Chronoampermetric detection of enzymatic glucose sensor based on doped polyindole/MWCNT composites modified onto screen-printed carbon electrode as portable sensing device for diabetes," *RSC Adv.*, vol. 44, pp. 28505–28518, 2022, doi: 10.1039/d2ra04947c.

[5] Y. Shen *et al.*, "Recent Advances in Wearable Biosensors for Non-Invasive Detection of Human Lactate," *Biosensors*, vol. 12, no. 12, 2022, doi: 10.3390/bios12121164.

[6] N. Rasitanon, S. Ittisoponpisan, K. Kaewpradub, and I. Jeerapan, "Wearable Electrodes for Lactate: Applications in Enzyme-Based Sensors and Energy Biodevices," *Anal. Sens.*, vol. 3, no. 4, 2023, doi: 10.1002/anse.202200066.

[7] M. A. Deshmukh, B.-C. Kang, and T.-J. Ha, "Non-enzymatic electrochemical glucose sensors based on polyaniline/reduced-graphene-oxide nanocomposites functionalized with silver nanoparticles," *J. Mater. Chem.*, vol. 8, no. 15, pp. 5112–5123, 2020, doi: 10.1039/c9tc06836h.

[8] H. Ren, "Graphene and Its Derivatives for Electrochemical Sensing," *Sensors*, vol. 25, no. 7, 2025, doi: 10.3390/s25071993.

[9] M. M. Abdelrazek, A. E. Hannora, R. M. Kamel, I. Morad, and M. M. El-Desoky, "Effect of lanthanum doping on the structure and optical properties of nanocrystalline vanadium pentoxide films prepared by sol–gel method," *Opt. Quantum Electron.*, vol. 55, no. 6, 2023, doi: 10.1007/s11082-023-04764-2.

[10] R. J. Krishnamurthy and A. S. Milani, "Graphene – PLA Printed Sensor Combined with XR and the IoT for Enhanced Temperature Monitoring : A Case Study," *Sens. Actuators Netw.*, vol. 14, no. 4, 2025, doi: 10.3390/jsan14040068.

[11] A. Alqaderi *et al.*, "Frugally inventive carbon fabric-based wearable sensor for monitoring human body movements," *Wearable Technol.*, vol. 6, no. e35, 2025, doi: 10.1017/wtc.2025.10020.

[12] M. Ali *et al.*, "A Comprehensive Review of Advanced Sensor Technologies for Fire Detection with a Focus on Gasistor-Based Sensors," *Chemosensors*, vol. 13, no. 7, pp. 1–52, 2025, doi: 10.3390/chemosensors13070230.

[13] S. Maji, M. Kwak, and R. Kumar, "3D Printing Assisted Wearable and Implantable Biosensors," *Biosensors*, vol. 15, no. 9, 2025, doi: 10.3390/bios15090619.

[14] T. Sanislav, G. D. Mois, S. Zeadally, S. Folea, T. C. Radoni, and E. A. Al-suhaimi, "A Comprehensive Review on Sensor-Based Electronic Nose for Food Quality and Safety," *Sensors*, vol. 25, no. 14, 2025, doi: 10.3390/s25144437.

[15] A. Ogurcovs, I. Aulika, and S. Cartiel, "Advancing Multi-Touch Sensing : Integrating FTIR and ToF Technologies for Precise and Large-Scale Touch Interfaces," *Sensors*, vol. 25, no. 17, 2025, doi: 10.3390/s25175503.

[16] P. C. Rathebe and M. Kholopo, "Radon Exposure Assessment : IoT-Embedded Sensors," *Sensors*, vol. 25, no. 19, 2025, doi: 10.3390/s25196164.

[17] N. Sun *et al.*, "Fully printable integrated multifunctional sensor arrays for intelligent lithium-ion batteries," *Nat. Commun.*, vol. 16, no. 1, 2025, doi: 10.1038/s41467-025-62657-2.

[18] A. M. Noor *et al.*, "Wearable Device for Continuous and Real-Time Monitoring of Human Sweat Sodium," *Sensors*, vol. 25, no. 11, 2025, doi: 10.3390/s25113467.

[19] R. Supriyanti, W. Widanarto, P. D. Susanto, M. A. Wicaksono, and S. Rais, "Design of mobile application for communication and

- user interface of ESP32 potentiostat system,” *Int. J. Reconfigurable Embed. Syst.*, vol. 14, no. 3, pp. 725–733, 2025, doi: 10.11591/ijres.v14.i3.pp725-733.
- [20] S. Karthikeyan, M. Selvapandian, and A. Sankar, “Electrochemical performance of reduced graphene oxide (rGO) decorated lanthanum oxide (La₂O₃) composite nanostructure as asymmetric supercapacitors,” *Inorg. Chem. Commun.*, vol. 139, 2022, doi: 10.1016/j.inoche.2022.109331.
- [21] E. W. Hill, A. Vijayaraghavan, and K. Novoselov, “Graphene Sensors,” *IEEE Sens. J.*, vol. 11, no. 12, pp. 3161–3170, doi: 10.1109/JSEN.2011.2167608.
- [22] A. J. Abbas, A. A. Ghazzay, and H. A. Walli, “A Green Approach by Employing Two Bacterial Strains (*Streptococcus thermophilus*) and (*Bacillus coagulans*) to Reduce Graphene Oxide,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1371, no. 2, 2024, doi: 10.1088/1755-1315/1371/2/022034.
- [23] Y. Li, Y. Zhong, and J. Huang, “The synthesis of a lanthanum metal – organic framework and its sensitivity electrochemical detection of H₂O₂,” *Chem. Pap.*, vol. 71, no. 5, pp. 913–920, 2016, doi: 10.1007/s11696-016-0011-9.
- [24] J. Hu, X. Wang, Z. Xiao, and W. Bi, “Effect of chitosan nanoparticles loaded with cinnamon essential oil on the quality of chilled pork,” *LWT - Food Sci. Technol.*, vol. 63, no. 1, pp. 519–526, 2015, doi: 10.1016/j.lwt.2015.03.049.
- [25] M. N. Noorhashimah, K. A. Razak, and Z. Lockman, “Effect of Concentration and pH of PBS to the Electrocatalytic Performance of Enzymatic Glucose Biosensor,” *Solid State Phenom.*, vol. 290, pp. 193–198, 2019, doi: 10.4028/www.scientific.net/SSP.290.193.
- [26] K. Wang, J.-J. Xu, and H.-Y. Chen, “Biocomposite of cobalt phthalocyanine and lactate oxidase for lactate biosensing with MnO₂ nanoparticles as an eliminator of ascorbic acid interference,” *Sensors Actuators B Chem.*, vol. 114, no. 2, pp. 1052–1058, 2006, doi: 10.1016/j.snb.2005.07.066.
- [27] E. Canbay, A. Habip, G. Kara, Z. Eren, and E. Akyilmaz, “A microbial biosensor based on *Lactobacillus delbrueckii* sp. bacterial cells for simultaneous determination of lactic and pyruvic acid,” *Food Chem.*, vol. 169, pp. 197–202, 2015, doi: 10.1016/j.foodchem.2014.07.140.
- [28] D. Berillo, and J. Caplin, “Polymeric Materials Used for Immobilisation of Bacteria for the Bioremediation of Contaminants in Water,” *Polymers*, vol. 13, no. 7, 2021, doi: 10.3390/polym.
- [29] P. J. Derbyshire, H. Barr, F. Davis, and S. P. J. Higson, “Lactate in human sweat : a critical review of research to the present day,” *J. Physiol. Sci.*, vol. 62, no. 6, pp. 429–440, 2012, doi: 10.1007/s12576-012-0213-z.

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