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Sensing Safety: Developing a Flexible, Portable Alcohol Detection Patch for Community Wellness

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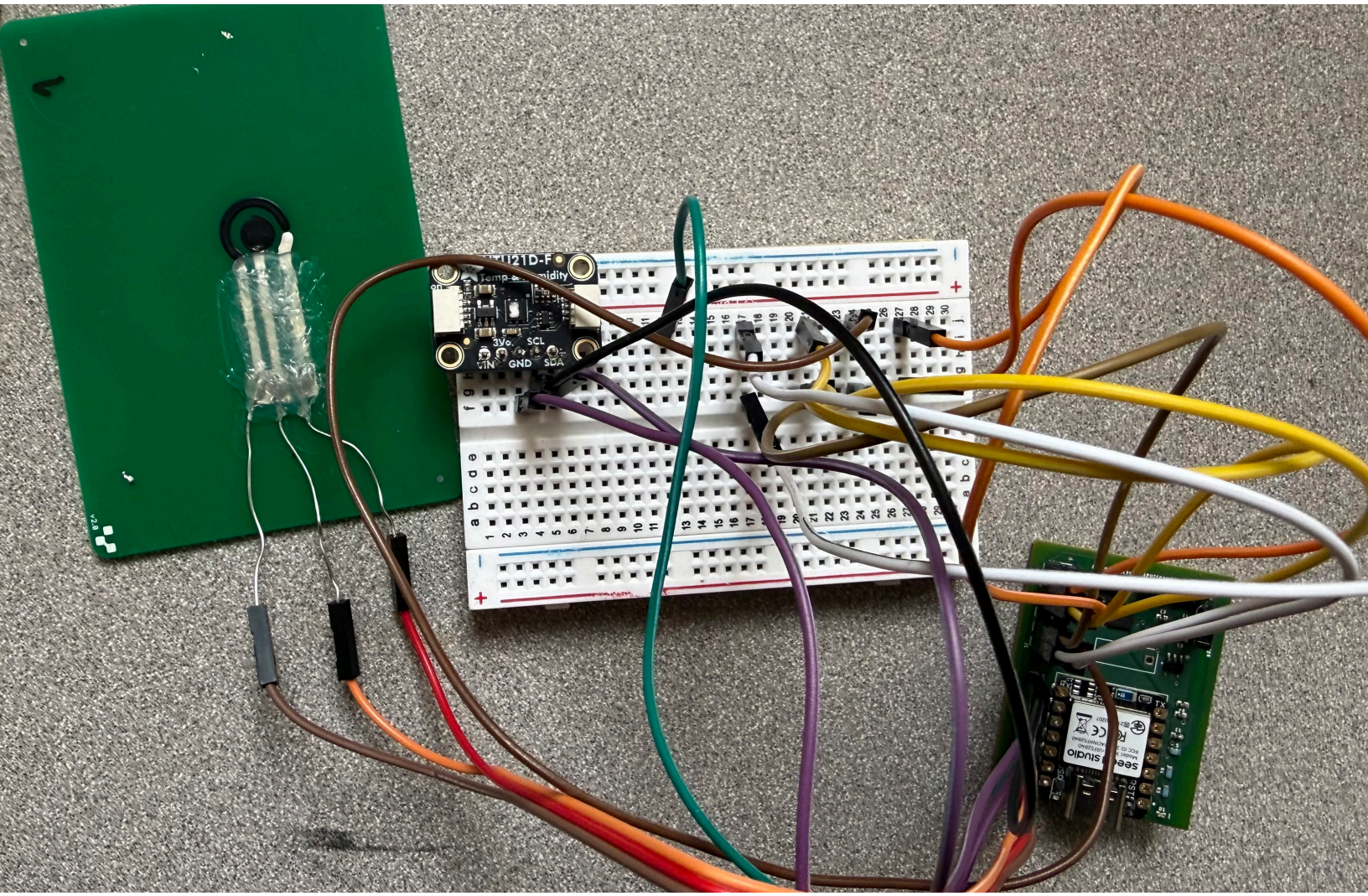

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MTI conducts multi-disciplinary research focused on surface transportation that contributes to effective decision making. Research areas include: active transportation; planning and policy; security and counterterrorism; sustainable transportation and land use; transit and passenger rail; transportation engineering; transportation finance; transportation technology; and workforce and labor. MTI research publications undergo expert peer review to ensure the quality of the research.

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Report 26-30

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16. Abstract Alcohol-impaired driving remains one of the leading causes of traffic fatalities and serious injuries in the United States, posing significant challenges to transportation safety and imposing substantial social and economic costs. Although breathalyzers and wearable alcohol monitoring devices can help detect alcohol consumption, many existing technologies are expensive, bulky, or impractical for continuous, long-term monitoring. This study investigates a low-cost electrochemical sensing platform that could support future wearable alcohol monitoring systems for transportation safety applications. Specifically, the report presents the design, fabrication, and experimental evaluation of a custom screen-printed electrode (SPE) integrated with the Texas Instruments LMP91000 potentiostat. Each disposable electrode was fabricated at an estimated material cost of approximately **US$0.10** and successfully detected ethanol concentrations ranging from **0% to 30%** using cyclic voltammetry and chronoamperometry. Flexible carbon and silver conductive inks were used to fabricate the electrode, which was evaluated using artificial sweat solutions containing varying ethanol concentrations. Experimental results demonstrated repeatable electrochemical responses that increased systematically with ethanol concentration, validating both the fabrication approach and sensing methodology. By combining inexpensive disposable electrodes with reusable electronics, the proposed system provides a scalable foundation for future wearable alcohol monitoring technologies that could support impaired-driving prevention, workplace safety, and transportation research.			
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1. Introduction

Alcohol-impaired driving remains one of the leading causes of traffic fatalities and serious injuries in the United States and throughout California. According to the National Highway Traffic Safety Administration (NHTSA), thousands of fatalities each year involve drivers operating vehicles under the influence of alcohol. In California, impaired driving continues to place significant burdens on transportation safety, emergency response systems, public health, and economic productivity. Reducing alcohol-impaired driving is therefore a major transportation safety priority consistent with California Senate Bill 1 (SB1), which supports research that improves the safety, reliability, and efficiency of transportation systems [1–3].

Recent advances in wearable sensing technologies have created opportunities for continuous, non-invasive monitoring of physiological biomarkers, including transdermal alcohol concentration. Unlike conventional breathalyzers, wearable alcohol sensors provide continuous monitoring without requiring active user participation. Such technologies have potential applications in impaired driving prevention, fleet safety monitoring, rehabilitation programs, and transportation workforce safety.

This research develops a low-cost flexible electrochemical alcohol sensor capable of detecting ethanol concentrations representative of human perspiration. By reducing the cost and increasing the accessibility of wearable alcohol monitoring, this work supports future transportation safety technologies aimed at reducing alcohol-impaired driving and improving roadway safety for Californians. This project aligns with the mission of the Mineta Transportation Institute by investigating sensing technologies that may contribute to safer transportation systems. Although this study focuses on the development of the sensing platform rather than deployment within vehicles, the technology represents a foundational component for future wearable systems capable of identifying alcohol impairment before individuals operate motor vehicles. Such technologies support California SB1's goals of improving transportation safety and protecting the mobility of people and goods.

2. Literature Review

Despite decades of legislation, enforcement, and public education campaigns, alcohol-impaired driving remains a major contributor to roadway fatalities in the United States. According to the National Highway Traffic Safety Administration (NHTSA), 13,524 people were killed in alcohol-impaired traffic crashes in 2022, representing 32% of all roadway fatalities, or approximately one death every 39 minutes. In addition to the human toll, alcohol-impaired crashes resulted in an estimated $58 billion in economic costs, including medical care, emergency response, property damage, traffic congestion, and lost productivity. These persistent impacts have motivated continued research into technologies capable of preventing impaired driving before a vehicle is operated rather than relying solely on post-incident enforcement strategies [4–6].

Recent transportation research has therefore expanded beyond traditional roadside breath testing toward continuous and passive alcohol monitoring systems that can provide objective measures of alcohol exposure during everyday activities. Wearable alcohol sensing technologies have emerged as a promising research direction because they offer the possibility of continuously monitoring alcohol consumption without requiring active user participation. Such systems could support transportation safety through voluntary self-monitoring, fleet safety programs, rehabilitation monitoring, ignition interlock alternatives, and future intelligent transportation systems capable of identifying impairment before driving occurs. Within this context, researchers have increasingly investigated wearable electrochemical sensors that combine portability, low power consumption, and continuous physiological monitoring. Most wearable alcohol sensors detect ethanol either through transdermal vapor released from the skin or through direct electrochemical analysis of sweat, each offering distinct advantages and technical challenges [7–10].

Transdermal alcohol monitoring systems measure ethanol vapor that diffuses through the skin following alcohol consumption. Commercial devices such as the Secure Continuous Remote Alcohol Monitor (SCRAM) and the BACtrack Skyn employ fuel-cell electrochemical sensing to estimate transdermal alcohol concentration (TAC), enabling continuous and passive alcohol monitoring without active user intervention. The SCRAM system has demonstrated high reliability and has been widely adopted in forensic supervision, legal compliance, and alcohol rehabilitation programs. More recently, the BACtrack Skyn was introduced as a lightweight wrist-worn alternative that improves user comfort while maintaining acceptable agreement with self-reported alcohol consumption and established transdermal monitoring techniques. Courtney et al. [11] reported that participants strongly preferred the BACtrack Skyn over the bulkier SCRAM monitor during a 28-day field study and concluded that the device is suitable for continuous alcohol monitoring in naturalistic environments. Similarly, Ash et al. [12] demonstrated that the

BACtrack Skyn provides promising sensitivity and specificity for alcohol detection while exhibiting substantially greater user comfort than conventional ankle-mounted monitors.

Despite these advances, transdermal alcohol sensing continues to face several practical limitations. Because ethanol must diffuse through body tissues before reaching the skin's surface, transdermal measurements exhibit physiological delays ranging from approximately 30 minutes to several hours relative to blood alcohol concentration. Furthermore, sensor performance is influenced by environmental temperature, humidity, perspiration rate, skin properties, and motion artifacts, which contribute to measurement variability and reduce quantitative accuracy [11,13,14]. Although commercial devices have significantly improved the practicality of continuous alcohol monitoring, they remain relatively expensive and integrate reusable sensing components directly into the wearable device.

To overcome the inherent limitations of transdermal alcohol monitoring, researchers have developed sweat-based electrochemical biosensors capable of directly detecting ethanol present in perspiration. Many of these systems utilize enzymatic reactions involving alcohol oxidase or alcohol dehydrogenase to catalyze ethanol oxidation and generate electrochemically measurable signals proportional to alcohol concentration. Enzymatic biosensors generally provide faster response times, improve skin conformity, and enhance sensitivity compared with transdermal vapor sensing approaches. However, their performance depends heavily on enzyme stability, which deteriorates because of temperature fluctuations, pH changes, dehydration, and prolonged operation. In addition, enzyme immobilization, mediator layers, and protective membranes increase fabrication complexity and manufacturing cost, as well as reduce long-term device reliability [8,9,15].

Recent developments in printed electronics have motivated increasing interest in non-enzymatic electrochemical sensing approaches. Non-enzymatic sensors eliminate biological recognition elements by directly measuring ethanol oxidation at conductive electrode surfaces, thereby simplifying fabrication while improving chemical stability and operational lifetime. Screen-printed electrodes fabricated using conductive carbon and metallic inks have emerged as attractive platforms because they are inexpensive, mechanically flexible, scalable for mass production, and compatible with wearable electronics [7–10]. Nevertheless, most existing wearable alcohol monitoring systems permanently integrate the sensing interface into the wearable device. During repeated use, these sensing surfaces are continuously exposed to perspiration, salts, skin oils, and other biological contaminants that may degrade sensor performance over time. In addition, reusable sensing surfaces require cleaning or long-term reuse, creating practical maintenance and hygiene challenges for wearable alcohol monitoring systems.

The present work addresses these limitations by developing a low-cost disposable screen-printed carbon electrode integrated with a reusable electronic measurement platform based on the Texas Instruments LMP91000 analog front-end. Unlike existing wearable alcohol monitoring systems, only the electrochemical sensing element is discarded after use while the potentiostat, microcontroller, and supporting electronics are retained. The electrode is fabricated using commercially available carbon and silver conductive inks through a printed electronics process, resulting in an estimated material cost of approximately US$0.10 per electrode. This disposable sensing architecture reduces manufacturing cost, minimizes performance degradation caused by repeated exposure to perspiration, eliminates the need to reuse sweat-exposed sensing surfaces, and enables practical large-scale deployment of wearable alcohol sensors. By combining inexpensive disposable electrodes with reusable electronics, the proposed system establishes a scalable platform for future wearable alcohol monitoring technologies that can support transportation safety, workplace monitoring, and early intervention strategies aimed at reducing alcohol-impaired driving.

3. Materials and Methods

3.1. Materials

Flexible carbon conductive ink (Voltera, Canada) was used to fabricate the working and counter electrodes, while silver conductive ink was used to print the reference electrode and electrical interconnects. The electrodes were fabricated on a fiberglass substrate using a Voltera V-One printed electronics system. A Texas Instruments LMP91000 analog front-end potentiostat served as the electrochemical interface, and a Seeeduino XIAO microcontroller controlled sensor operation and data acquisition. An HTU21D digital temperature and humidity sensor was incorporated to monitor environmental conditions during testing. Additional materials included deionized (DI) water, reagent-grade ethyl alcohol, commercially available 0.9% saline solution, and ethylene-vinyl acetate (EVA) adhesive for insulating the printed electrodes.

3.2 Sensor Design and Fabrication

The printed circuit board (PCB) was designed using Autodesk EAGLE with emphasis on compact size, low-noise signal routing, and compatibility with low-current electrochemical measurements. The LMP91000 potentiostat was selected as the analog front-end because of its programmable bias voltage and transimpedance amplifier, making it well suited for electrochemical sensing applications. Supporting passive components, including pull-up resistors, decoupling capacitors, and filtering circuitry, were incorporated to ensure stable operation and reliable I^2C communication between the potentiostat, microcontroller, and environmental sensors.

Special consideration was given to PCB layout to minimize electrical noise. Analog and digital traces were routed separately, while continuous ground planes were implemented to reduce electromagnetic interference and provide low-impedance return paths. Short trace lengths were maintained between the potentiostat and sensor interface to minimize parasitic resistance and capacitance that could distort the small currents generated during ethanol oxidation. Design Rule Checks (DRC) and Electrical Rule Checks (ERC) were completed within Autodesk EAGLE prior to fabrication to verify manufacturability and electrical integrity (Figure 1).

The screen-printed electrode (SPE) geometry was also designed using Autodesk EAGLE. The design consisted of three electrodes: a carbon working electrode, a carbon counter electrode, and a silver reference electrode. Electrode dimensions and spacing were selected to promote uniform current distribution while minimizing electrical resistance and preventing short circuits during fabrication (Figure 2).

The completed electrode layout was exported as a Gerber file and fabricated using a Voltera V-One printer. Silver conductive ink was printed first to form the reference electrode and conductive traces, followed by curing at 90°C for 5 minutes and 170°C for 15 minutes according to the manufacturer's recommendations. Carbon conductive ink was subsequently deposited to form the working and counter electrodes and cured at 80°C. The carbon electrodes were intentionally overlapped with the printed silver traces to ensure reliable electrical contact (Figure 3).

Following fabrication, a thin layer of ethylene-vinyl acetate (EVA) was applied to insulate the conductive traces while leaving only the active sensing region exposed. This insulation defined the electrochemical reaction area and prevented unintended electrical contact. Fine-gauge wires were attached to the silver contact pads using controlled-temperature soldering, and continuity measurements were performed to verify electrical connectivity before experimental testing (Figure 4).

Figure 1. PCB Designed Using EAGLE

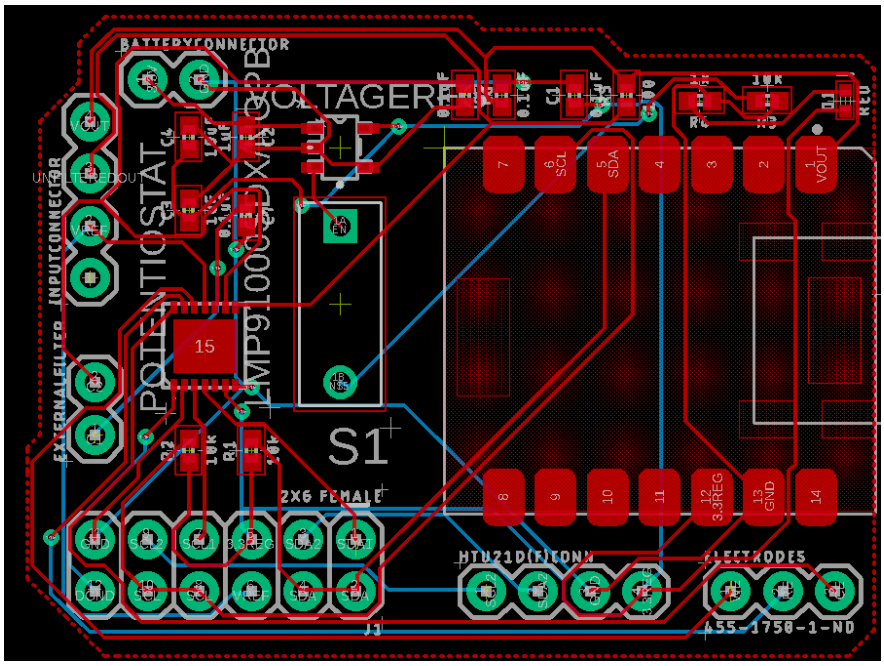


Figure 2. Electrode Layout on EAGLE

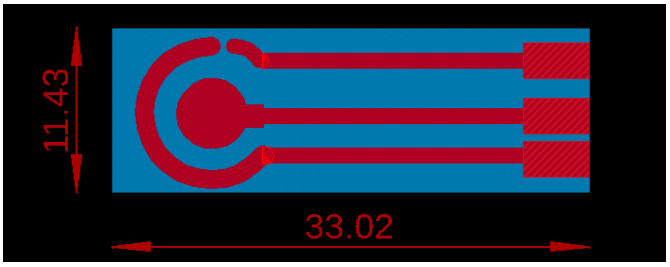


Figure 3. SPE Printed on Fiberglass Substrate Using Voltera V-One Printer

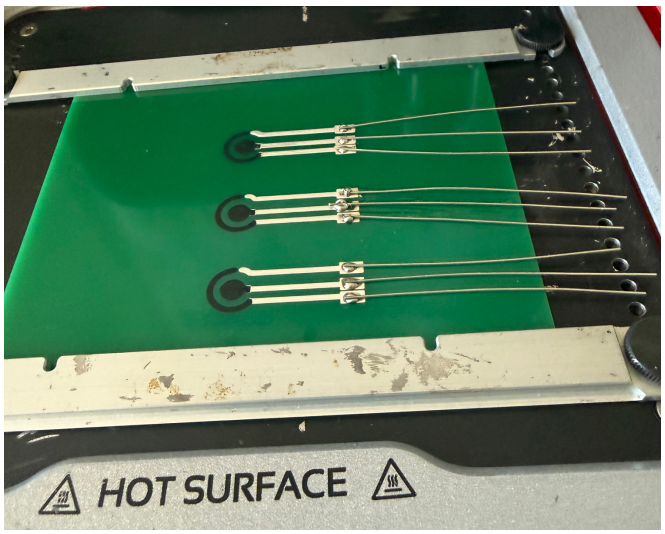
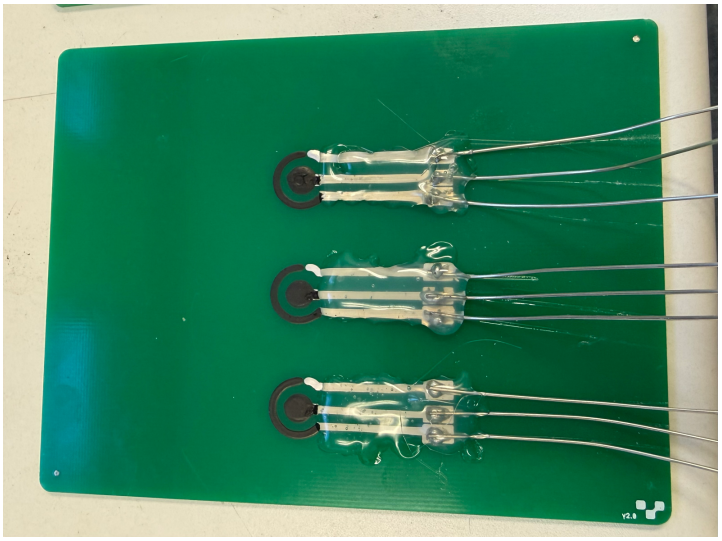


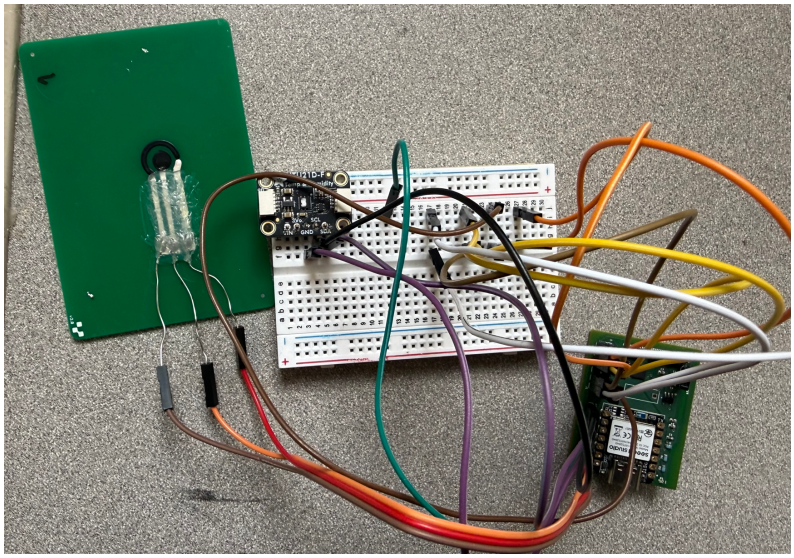
Figure 4. Insulating Coat Applied to the Electrodes



3.3 Experimental Setup

The fabricated screen-printed electrode was interfaced with the LMP91000 potentiostat for electrochemical characterization. The carbon working electrode, silver reference electrode, and carbon counter electrode were connected directly to the corresponding working (WE), reference (RE), and counter (CE) terminals of the potentiostat. The LMP91000 and HTU21D environmental sensor communicated with the Seeeduino XIAO microcontroller through a shared I^2C interface. The microcontroller configured the potentiostat, acquired measurement data, and transmitted the recorded signals to a host computer for analysis (Figure 5).

Figure 5. Experimental Setup for Electrochemical Testing



For each experiment, a small droplet of the prepared ethanol solution was dispensed onto the active sensing region of the electrode, ensuring complete coverage of the working, counter, and reference electrodes while avoiding the exposed electrical contacts. Uniform droplet placement was maintained throughout testing to minimize measurement variability resulting from inconsistent electrode coverage.

Because ethanol is highly volatile, prolonged exposure to ambient conditions can alter analyte concentration through evaporation. Although evaporation is commonly reduced by enclosing the sensing region, measurements in this study were completed immediately after sample deposition. The relatively short measurement duration minimized evaporation effects and ensured consistent electrochemical responses among successive experiments.

3.4 Preparation of Ethanol Test Solutions

Electrochemical testing was performed using ethanol solutions prepared to simulate the ionic composition of human sweat. A 0.9% sodium chloride solution (approximately 0.154 M NaCl)

served as the stock electrolyte and was diluted with deionized water to produce an electrolyte concentration of approximately 0.1 M NaCl. This concentration was selected because reported sodium chloride concentrations in human sweat typically range from 0.05 M to 0.15 M depending on environmental conditions and individual physiology.

The required dilution was calculated using the standard dilution relationship

$$M_1V_1 = M_2V_2$$

where M_1 and V_1 represent the concentration and volume of the stock saline solution and M_2 and V_2 represent the desired final concentration and volume.

Six ethanol solutions containing 0%, 5%, 10%, 15%, 20%, and 30% ethanol by volume were prepared. Each solution consisted of diluted saline, deionized water, and the appropriate volume of ethyl alcohol, as summarized in Table 1. The prepared solutions served as artificial sweat samples for evaluating sensor performance across increasing ethanol concentrations (Figure 6).

Figure 6. Solutions for Different Concentrations of Deionized Water, Ethyl Alcohol, and Normal Saline Solution

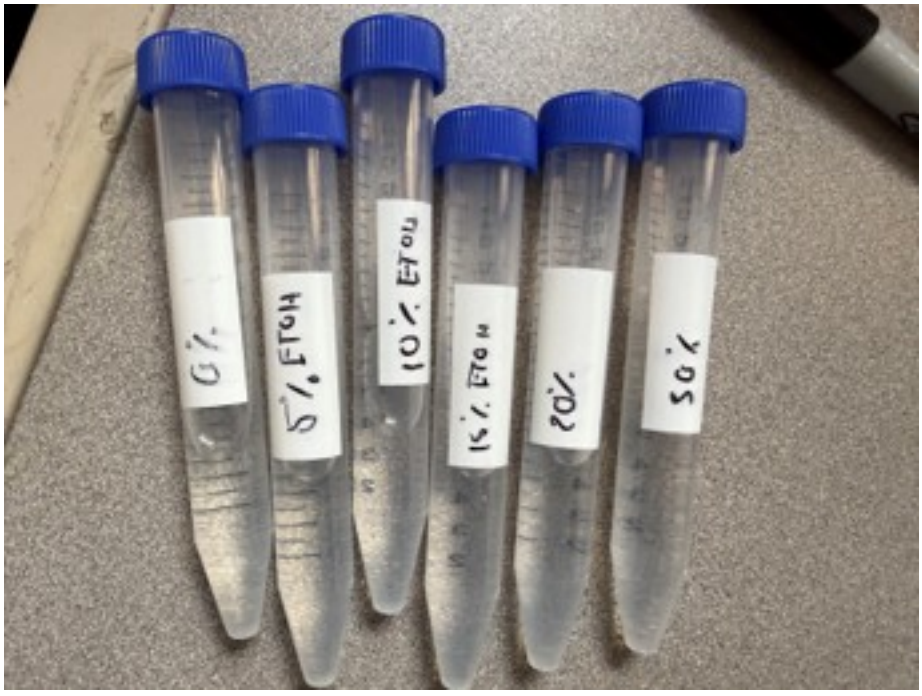


Table 1. Solutions for Different Concentrations of Deionized Water, Ethyl Alcohol, and Normal Saline Solution

Alcohol Concentration	0.9% Saline (ml)	DI Water (ml)	Ethyl Alcohol (ml)
0	20	10	0
5%	20	10	1.6
10%	20	10	3.
15%	20	10	4.7
20%	20	10	6.3
30%	20	10	9.5

4. Tests and Results

4.1 Cyclic Voltammetry (CV) Test

Cyclic voltammetry (CV) was employed to characterize the oxidation and reduction behavior of ethanol on the surface of the printed carbon electrode. During CV testing, the electrode potential was linearly swept between predetermined voltage limits while continuously recording the resulting current. This procedure generated a current–potential (I–E) curve, which exhibits characteristic oxidation and reduction peaks associated with the electrochemical reactions of ethanol at the electrode interface (Figure 7).

Each ethanol concentration (0%, 5%, 10%, 15%, 20%, and 30%) was tested independently. For each test, the potential was swept from −330 mV to +330 mV during each cycle. The resulting CV curves were then compared with the expected cyclic voltammetry behavior typically observed for ethanol oxidation reactions. The raw data collected during the experiments were exported and processed using MATLAB to generate graphical representations of the electrochemical response.

Figure 7. Expected CV Graph

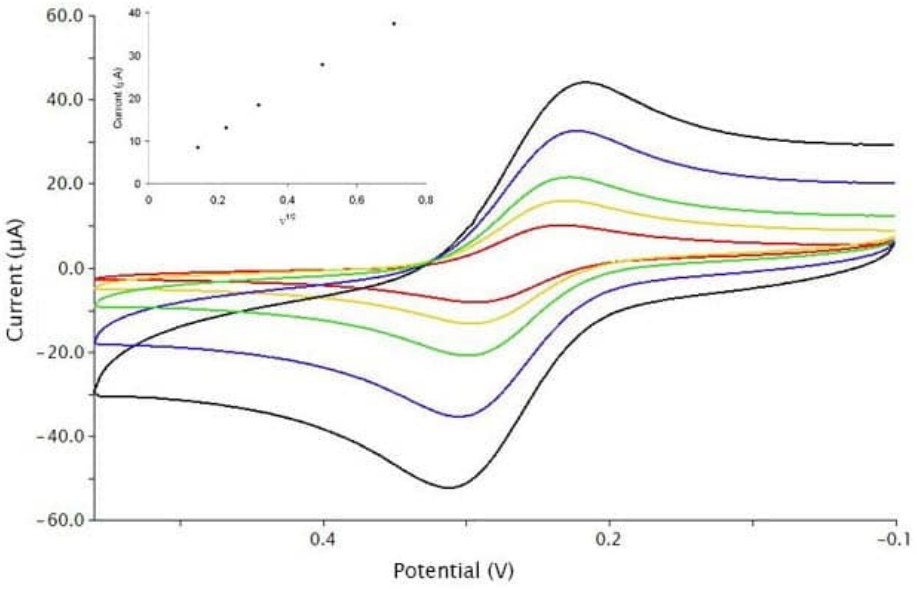
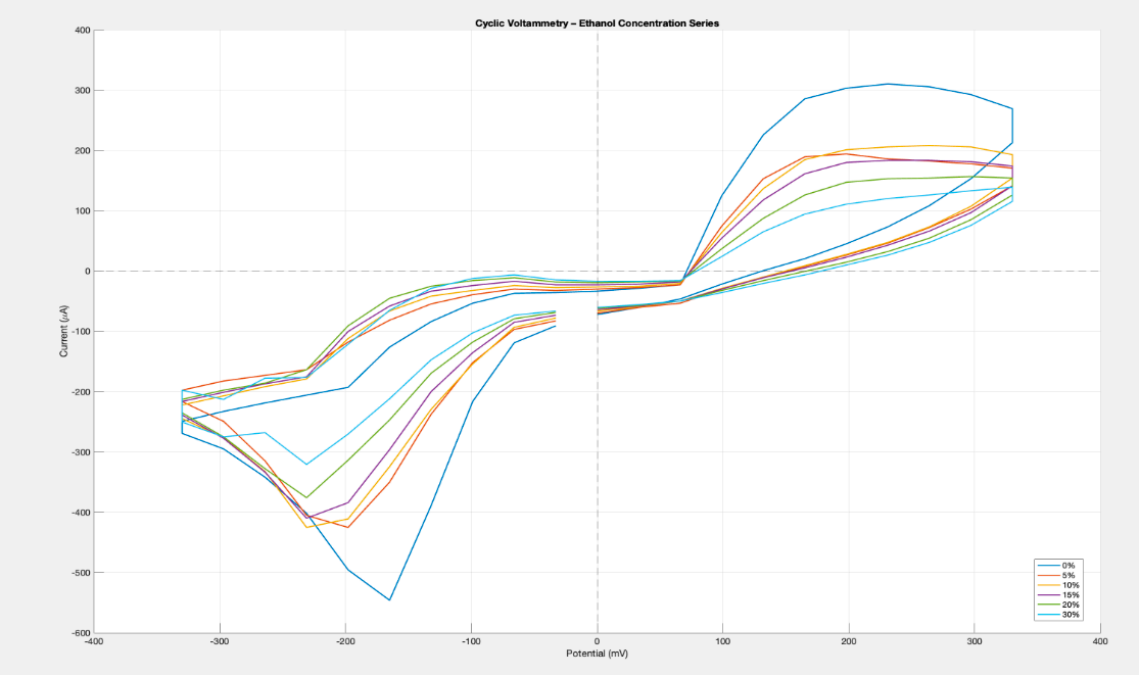


Figure 8. Experimental CV Response



Analysis of the CV results (Figure 8) showed that the oxidation peak current varied systematically with ethanol concentration. This change in peak current indicates differences in electrochemical activity at the electrode surface and confirms the sensitivity of the sensor to varying ethanol levels. Additionally, the separation between the oxidation and reduction peaks provided insight into the reversibility of the electrochemical reaction and the kinetics of electron transfer. Minor variations in peak shape and magnitude were attributed to diffusion effects, the surface condition of the printed electrode, and small differences in droplet placement and contact area between measurements.

4.2 Chronoamperometry (CA) Test

Following cyclic voltammetry characterization, chronoamperometry (CA) was performed to evaluate the time-dependent current response of the sensor at fixed applied potentials. This technique is particularly useful for quantitative analysis, as it allows direct comparison of steady-state current levels across different ethanol concentrations as a function of time (Figure 9).

During CA testing, the applied potential was stepped from an initial value of 0 mV to 60 mV and subsequently to 250 mV. Upon each potential step, the resulting current was recorded over several seconds to capture both the initial transient response and the subsequent decay toward a stable, saturated current value. Each ethanol concentration (0%, 5%, 10%, 15%, 20%, and 30%) was tested individually. The recorded data were exported to Microsoft Excel and subsequently processed and plotted using MATLAB for analysis and visualization.

Figure 9. Expected CA Graph

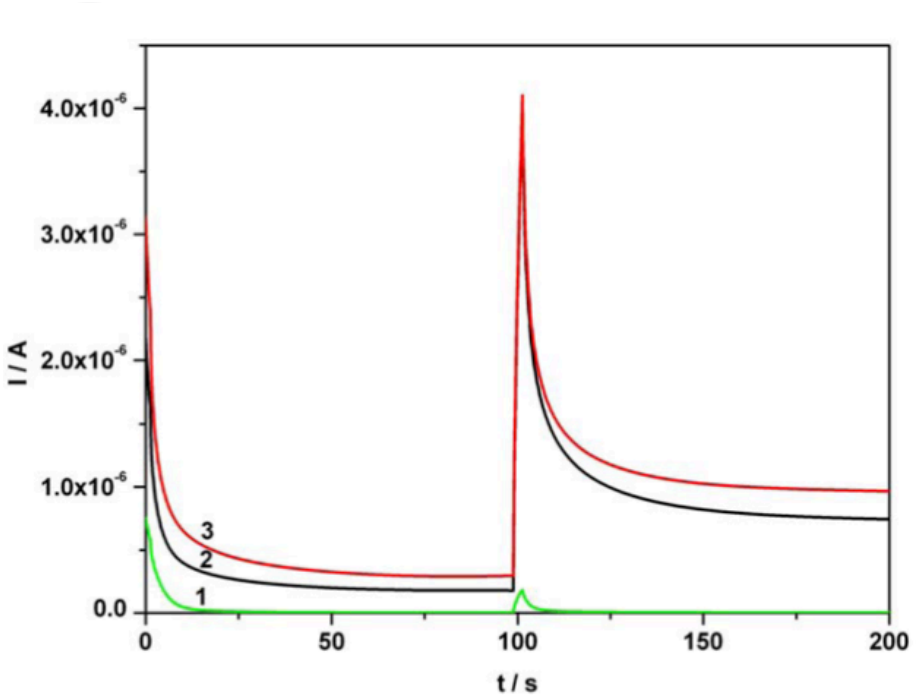
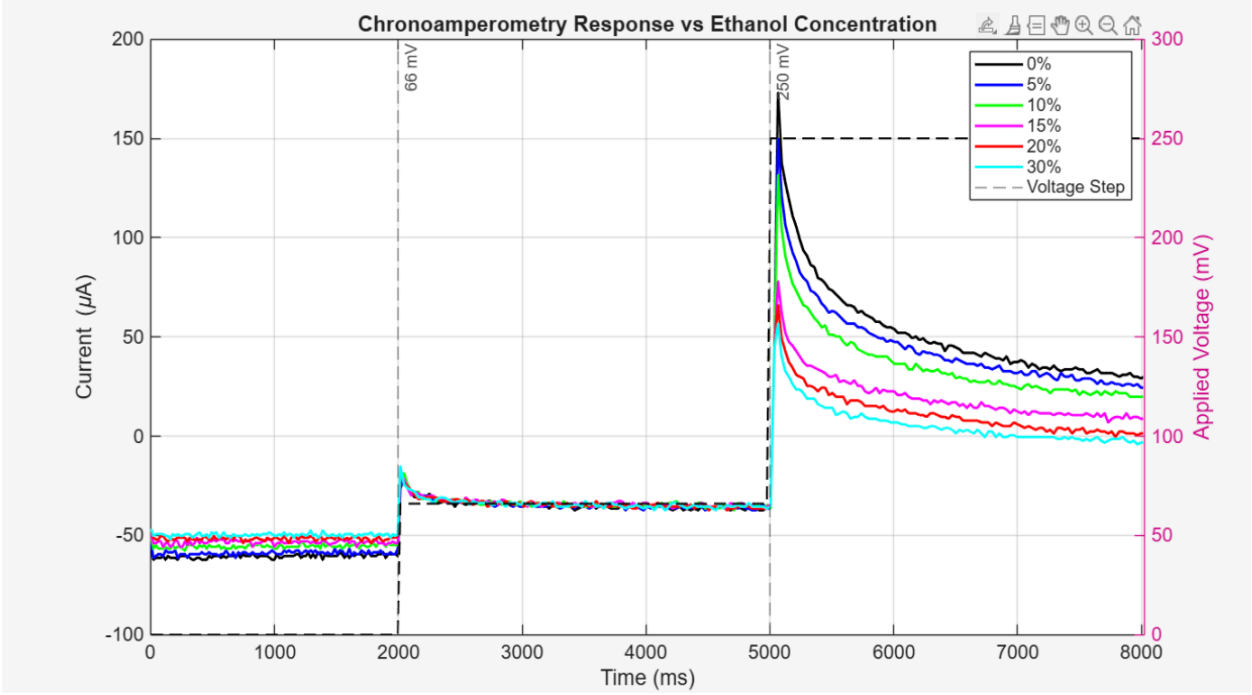


Figure 10. Experimental CA Response



The chronoamperometry results demonstrate the time-dependent current response of the fabricated screen-printed electrode at applied potentials of approximately 60 mV and 250 mV (Figure 10). Immediately following each voltage step, a rapid increase in current was observed, corresponding to the oxidation of ethanol at the electrode surface and the establishment of charge transfer between the electrode and electrolyte. This initial current spike was followed by a gradual exponential decay toward a steady-state current, consistent with diffusion-controlled electrochemical behavior.

Distinct current responses were observed for each ethanol concentration, indicating that the fabricated sensor was capable of differentiating between varying ethanol levels. As ethanol concentration increased, the magnitude of the measured current also changed, confirming that the electrochemical response was directly influenced by ethanol concentration within the artificial sweat electrolyte. Although minor fluctuations and electrical noise were present in several measurements, the overall response remained consistent across repeated tests and followed the expected chronoamperometric behavior.

Combined with the cyclic voltammetry results, these findings demonstrate that the screen-printed carbon electrode successfully detected ethanol through electrochemical oxidation. The reproducible current responses obtained using both electrochemical techniques validate the proposed fabrication method and confirm the suitability of the printed electrode for low-cost alcohol sensing applications. These results establish a foundation for future work involving sensor calibration, optimization, and integration into flexible wearable alcohol monitoring systems.

5. Conclusion

This study demonstrated the successful development of a portable electrochemical alcohol sensing platform based on a custom screen-printed electrode and the LMP91000 potentiostat. Experimental results confirmed that the fabricated sensor responds consistently to varying ethanol concentrations, demonstrating the feasibility of the proposed design for wearable alcohol sensing applications. Beyond the laboratory validation presented in this work, the proposed sensing platform has significant potential for transportation safety applications. Continuous wearable alcohol monitoring could provide early warning systems that discourage impaired driving, assist commercial fleet operators in promoting workplace safety, support court-ordered alcohol monitoring programs, and contribute to reducing alcohol-related traffic crashes. These applications directly support the objectives of California Senate Bill 1 by advancing technologies that improve the safety and reliability of the state's transportation system. Future research will focus on improving sensor sensitivity, calibration with human sweat, wireless communication, miniaturization, and integration into wearable devices suitable for real-world transportation safety applications.

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About the Authors

Dr. Ava Hedayatipour is an Assistant Professor in the Department of Electrical Engineering at California State University, Long Beach (CSULB). Her research focuses on flexible and printed electronics, wearable biomedical sensors, embedded systems, point-of-care diagnostic devices, and microfabrication technologies. She leads research on the development of low-cost sensing platforms for healthcare and transportation safety applications and has authored numerous publications in wearable sensing, biosensors, and electronic systems.

Ryan Huynh is an undergraduate student in the Department of Electrical Engineering at CSULB. His research interests include printed electronics, embedded systems, electrochemical sensing, and wearable sensor technologies. His work on this project focused on the design, fabrication, and experimental evaluation of low-cost screen-printed electrodes for wearable alcohol sensing.

Wahaab Ademola received his Bachelor of Science degree in Electrical Engineering from CSULB in Fall 2024. As an undergraduate researcher, he contributed to the development of flexible electrochemical sensing platforms, including printed electrode fabrication, embedded hardware integration, and experimental testing for wearable alcohol monitoring systems. His interests include embedded systems, sensor design, and biomedical instrumentation.

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