A Plug-and-Play Type Field-Deployable Bio-Agent-Free Salicylic Acid Sensing System

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Abstract—Salicylic acid (SA) is a primary phytohormone released in response to stress (particularly biotic infections) in plants. Monitoring SA levels in plants may provide a way for early crop disease detection and application of effective measures, resulting in higher agricultural efficiency. Additionally, SA is an important chemical in the pharmaceutical and healthcare industry due to its analgesic and anti-inflammatory properties. Developing a fast and accurate way for monitoring SA levels in human serum can have a life-saving impact for patients suffering from overdosing and/or mis-dosing. In this work, we present a low-cost, portable, and field-deployable electrochemical SA sensing system aimed towards achieving the above-mentioned goals. The developed sensor consists of a plug-and-play type device equipped with specially designed high accuracy sensing electronics and a novel procedure for robust data analysis. The developed sensor exhibits excellent linearity and sensitivity and selectivity. The practical applicability of the developed sensor was also demonstrated by measuring SA levels in real samples with good accuracy.

Index Terms—Agriculture, biosensor, circuit, electrochemical, healthcare, pharmaceutical, plants, potentiostat, sensor.

I. INTRODUCTION

PLANTS are constantly exposed to the elements of nature, facing countless biotic and abiotic stressors throughout their lifetime. One way plant achieve immunity is through local hypersensitive response at the attack site that can immunize the plant against further attack, this phenomenon was termed as systemic acquired resistance (SAR) [1]. The onset of SAR is accompanied by increased accumulation of signaling hormones at the attack site and their transport to other plant tissues via the phloem [2]. 2-hydroxybenzoic acid or salicylic acid (SA) is one such key signaling phytohormone responsible for the activation of SAR against biotic stresses, primarily due to biotrophic pathogens [2], [3]. Other major signaling hormones include Jasmonic acid (JA), Ethylene (ET), and Abscisic acid (ABA), where JA is associated with defense against herbivorous insects and necrotrophic pathogens whose pathways are modulated by ET and, ABA is associated with abiotic stress responses.

Overall, SA and JA are the main phytohormones activated during SAR under biotic stress, while ET and other secondary metabolites play more modulating roles [4], [5]. In general, a complex crosstalk between the SA and JA pathways exist providing robust immune signaling. The study and exploration of defense signaling mechanisms in plants is currently an active area of research [5], [6]. Moreover, while endogenous accumulation of SA in plant tissue has been largely associated with pathogenic stresses, SA has also been studied to have an effect on abiotic stresses [7]. Exogenous application of SA and related compounds have been reported to increase tolerance in plants against abiotic stresses such as salinity, radiation, chilling, heat and more [5], [8]–[10].

Therefore, developing technologies for rapid measurement of phytohormones can facilitate early detection of plant stress levels resulting in efficient and timely responses, minimizing yield losses. In addition to having a direct impact on predictive plant health monitoring, hormone sensing can help us improve our understanding of the growth and immune signaling processes, paving way for our ability to manipulate and control SAR in crop species that would provide farmers with effective and environmentally friendly ways to prevent yield losses resulting from biotic and abiotic stresses.

Besides its significance in the agriculture, SA is also of importance in other industries such as, healthcare, pharmaceutical and cosmetics due to its analgesic, antiseptic and anti-inflammatory properties. Salicylates are an active ingredi-
ent in many over-the-counter non-steroidal anti-inflammatory drugs like Aspirin, which are among the most commonly used medication for treating acute as well as chronic pains. However, their overdose and/or accidental misuse/mis-dosing may lead to salicylate poisoning, and according to the American Association of Poison Control Centers (AAPCC), 24% of analgesic-related deaths can be attributed to aspirin (alone or in combination with other drugs) [11]. Moreover, a small percentage of the population suffers from salicylate sensitivity which can result in gastrointestinal issues when foods high in salicylates are consumed [12], [13]. Therefore, fast and early detection of SA levels in human serum and urine samples can have a potential lifesaving impact.

In this work, a plug-and-play-type bio-agent free portable SA sensing system is presented. The working principle of the proposed sensor involves electrochemical (EC) characterization of electro-oxidation of SA on a carbon electrode using differential pulse voltammetry (DPV) technique. The overall sensing system design involves the following main contributions:

1) Plug-and-play system compatible with the screen printed carbon electrode (SPCE).
2) Application specific sensor electronics.
3) Data analytics for robust DPV signal processing.

The sensor presented in this work as shown in Fig. 1 is the first-of-its-kind portable plug-and-play type device developed for SA sensing. Our sensor exhibits excellent response providing a novel, economical, accurate and portable detection system for SA where the total cost of a single unit of the developed SA sensor is under $50. This paper has been divided into the six sections including introduction, related works, materials and methods, portable SA sensing system, results and discussion, and conclusion.

II. RELATED WORKS

Quantitative determination of SA has potential applications spanning several industries, such as agriculture, food, pharmaceutical and healthcare, for which various sensing approaches have been explored in literature. Among analytical techniques, methods based on high performance liquid chromatography (HPLC) [14], [15], and mass spectrometry (MS) or chromatography coupled tandem mass spectrometry [16]–[19] are routinely used. Analytical methods offer high accuracy and precision but are limited to laboratory setting as they require expensive sophisticated equipment (non-portable), extensive sample preparations and training, and are time, cost and labor intensive. Following on the need for quick response, minimal sample preparation, ease of use and potential for in-situ operation or real-time analysis, various biosensing (involving bio-molecules such as enzymes, aptamers and molecularly imprinted polymers) and electro-analytical reaction-based approaches are continuously being developed for SA detection.

Some of the key recent advances in biosensing for SA are discussed in this section. One such method involves the detection of SA using a bi-enzyme system consisting of salicylate hydroxylase (SH) and tyrosinase (TYR), where the bi-enzyme recipe was functionalized on carbon nano-tubes (CNTs) modified carbon electrode [20]. The sensor was characterized using cyclic voltammetry (CV) and constant potential amperometry, and exhibited a sensitivity of 30 \( \mu Acm^{-2} \mu M^{-1} \) and limit of detection (LOD) of 13 nM. In another work, a bi-enzymatic microfluidic EC sensing device was reported for SA detection within the range of 0.5 \( \mu M \) to 64 \( \mu M \) characterized using chrono-amperometry [21]. Alternatively, molecularly imprinted polymers (MIPs), which are artificial antibodies prepared by polymerizing functional and cross-linking monomers around specific target molecules, have also been reported for SA detection. A dual functional MIP-modified organometal lead halide perovskite biosensor was reported for photothermalchemical bioanalysis of SA in [22]. The sensor indicated logarithmic response with LOD of 1.95 \( \times 10^{-13} M \), but with limited range of operation with the upper bound of 1 \( \times 10^{-8} M \) which may be unsuitable for agricultural applications. Another SA sensor employing MIPs functionalized on TiO\(_2\) nanorod arrays was described in [23], where a detection limit of 3.9 \( \times 10^{-8} M \) and range of 1.0 \( \times 10^{-7} M \) to 5.0 \( \times 10^{-5} M \) were observed. SA sensing has also been realized using aptamers which are single-stranded DNA, or RNA molecules that can be made with high affinity for a desired analyte. An aptamer-based label-free sensor was reported in [24], where SA-specific aptamer was incorporated onto a nanostructured Fabry-Perot interference sensor. The developed sensor was able to quantify SA down to 0.1 \( \mu M \). While bio-molecules-based SA sensors offer sensitive and selective detection for relatively rapid response, they also exhibit some limitations. Firstly, bio-molecules require elaborate, costly and complicated manufacturing processes, and their characteristics depend heavily on the method of synthesis imparting inherent variability in operation. Secondly, biosensors involve complex, expensive and time consuming fabrication procedures, such as functionalization of bio-molecules on electrode surfaces and transduction mechanisms, which are prone to inconsistencies in performance. Finally, the sensors have relatively short shelf life while needing special storage and operating conditions.
as bio-molecules are susceptible to leaching and/or getting denatured.

Besides biosensing strategies, electro-catalytic reactions on metallic as well as carbon electrodes have also been characterized for SA quantification. Cerium-doped zirconium oxide (Ce/ZrO$_2$) was introduced as an electrocatalyst for the electro-oxidation of SA in a recent work, where a range of operation of 5 μM to 1000 μM with LOD of 1.1 μM [25] was observed. In another work, a paper-based electroanalytical device for in-situ determination of SA in tomato leaves was reported with moderate accuracy [26]. Other electrode materials used for electro-oxidation based analysis of SA include, electro-reduced graphene oxide modified screen printed carbon electrode (ERGO-SPCE) [27], modified electrode. well-aligned multiwalled carbon nanotube electrode [28], screen printed graphite electrode [29], carbon-fiber electrode [30], and carbon nanotube/iron oxide nanoparticle (SWCNT/ION) modified electrode [31]. The mechanism of SA electro-oxidation was explored in [30], where it was postulated that in addition to the primary SA oxidation reaction, secondary reactions occur which results in the formation of polymerized SA products that may lead to electrode fouling, and degrade the linearity of the sensor. It was also reported that many of the previously published works did not take this effect into consideration while evaluating the electrode responses. In our work, we address this by electrode treatment as suggested in [30].

III. MATERIALS AND METHODS

This section describes the materials used and their sources, followed by the sensing methodology employed in this work.

A. Materials Used

SA (powdered), sodium hydroxide (NaOH), potassium ferricyanide (K$_3$[Fe(CN)$_6$]), glucose, indole-3-acetic acid (IAA) and phosphate buffered saline (PBS) of pH 6.6 buffer was purchased from Millipore-Sigma, MO, USA. Ethanol (200 Proof), potassium chloride (KCl), methyl jasmonate (MeJA), abscisic acid (ABA), citric acid, uric acid, succinic acid, and malic acid was purchased from Thermo Fisher Scientific, MA, USA. Disposable screen printed carbon electrodes (Zensor brand) and the bench-top potentiostat CHI660E were purchased from CHI instruments Inc., TX, USA. Salicylate liqui-UV test kit was purchased from EKF diagnostics USA (Stanbio labs), TX, USA, and was used with UNICO SQ2800 UV/VIS spectrophotometer. Deionized (DI) water with a conductivity of 18.2 MΩ was used to prepare all the solutions. Texas instruments (TI) C2000 Launchxl-F28379D (MCU Launchpad) and other electrical components (details presented in the Appendix) were purchased from DigiKey Electronics, MN, USA. The MCU was programmed using Code composer studio v10 (CCS v10), available free of cost at TI.com, while Matlab 2019a was used for data analytics.

B. SA Sensing Methodology

In this work, electro-oxidation-based sensing methodology was applied towards SA detection, where the primary chemical reaction is shown in the Fig. 2. According to the mechanism, SA is first adsorbed on the electrode surface where it is oxidised at a specific electrochemical potential to the following primary products: 2,5-dihydroxybenzoic acid or carboxyl-hydroquinone (main product), and 2,3-dihydroxybenzoic acid (by-product). The reaction involves an electron exchange (producing current) that we characterize using the DPV technique. This method is especially suitable for in-field SA testing applications as it does not involve the use of any bio-agents such as enzymes and/or MIPs that are prone to fouling, need specific operating conditions (in term of temperature and humidity), are complex and expensive to manufacture, exhibit large inter-sensor variability and have poor shelf-life.

In contrast, electrochemically characterizing the oxidation of SA on a carbon electrode as a way to selectively quantify the concentration of SA, not only overcomes the challenges presented by other methods but also provide a reliable way to develop field-deployable and cost-effective SA sensors.

DPV was adopted as the electrochemical method of choice for the characterization of SA-oxidation in this work due its high sensitivity and good selectivity. The specificity in DPV-based sensing method comes from the fact that current-potential response (or the potential at which the current peak occurs) is specific to a particular chemical reaction under given ambient conditions.

Based on the reports published in literature [29] and [30], in addition to the primary products of the SA oxidation reaction (shown in Fig. 2) other secondary products may also be formed. It was determined that the secondary products form polymeric-SA (poly-SA) films that may passivate the electrode surface increasing the electrode resistance, and therefore reduce the current response. This may result in degraded linearity and the range of operation. Accordingly, following on the results reported in [30], the screen printed carbon electrodes were immersed in 0.1 M NaOH solution for five minutes before each measurement in order to remove such passivation layers.

IV. PORTABLE SA SENSING SYSTEM

This section provides the detailed description of the complete field-deployable bio-agent-free EC sensing system developed in this work. Fig. 3 details the schematic of the sensing system, while the exact component values and specific schematics are mentioned in Appendix. The main components of the SA sensing system include a low-cost disposable electrode, the application-specific sensing electronics and the sensor data analysis system. A commercially available screen-printed sensing electrode system (as shown
in Figs. 1 and 3) comprising of a planar carbon working electrode (WE) integrated with a carbon counter electrode (CE) and an Ag/AgCl reference electrode (RE), arranged in a three-electrode configuration, was used in this work. The commercial electrodes offer reliable operation while being cost-effective making them ideal for developing a low-cost portable EC sensors. In order to connect the 3-electrode system with the sensing electronics, a specially designed adapter (shown in Fig. 1) was fabricated using a 3D polymer printer (using B9 creator v1.2 3D printer). The custom-developed adapter allowed for an easy and reliable electrical interface between the sensing electronics and the employed planar screen-printed electrodes.

The sensing electronics consisted of an application-specific portable potentiostat composed of two main components: (i) TI’s C2000-Launchpad microcontroller (MCU) and, (ii) the custom developed potentiostat analog-front-end (P-AFE) as shown in the Fig. 3. The P-AFE module was fabricated such that it can be affixed atop the MCU platform forming a compact portable instrument (refer Fig. 1). The overall circuit was specifically optimized for electro-oxidation-based SA detection using a three-electrode system, characterized by DPV.

The overall circuit system consists of the following main sub-circuits: The input signal conditioning; the three-electrode potentiostat system; the output current-to-voltage converter and voltage level adjuster; and the single-ended to differential signal converter required for sampling the signal using the differential 16 bit ADC integrated in the C2000 MCU platform.

According to the proposed architecture, first, the input DPV signal is generated using the integrated 12 bit digital-to-analog converter (DAC) on-board the MCU followed by the DC offset adjustment (as desired) on the P-AFE using a voltage adder circuit. The final DPV input signal is then applied to the core potentiostat sub-circuit which was developed based on a potential control amplifier in adder configuration as described in [32]. In the next stage, the output current from the WE is converted to an output voltage signal via the trans-impedance amplifier whose gain can be adjusted to control the overall range. The DC level of the output voltage signal is then adjusted such that the signal spans only in the positive voltage domain that is compatible with the ADC circuit. The integrated 16 bit ADC on-board the MCU operates in a differential configuration, hence the single-ended output voltage signal is converted to a differential signal before being recorded by the ADC in the final stage of the measurement circuit. Note that all the component of the P-AFE are powered by the 5V supply on-board the MCU platform.

The complete sensor circuit system is operated by a computer which triggers the measurement, and collects the recorded DPV response data. The obtained DPV graph (applied potential versus measured current) is then analysed using the proposed procedure as described in the following sub-section.

### A. Sensor Data Analysis

After the experimental DPV graph is recorded using the developed portable EC sensing system, a data extraction algorithm is implemented to obtain functional information about the SA concentration. The algorithm operates by detecting and quantifying SA specific current response within the recorded DPV graph as shown in Fig. 4. The key steps in the automated SA specific measured current-response detection algorithm are as follows: (i) SA-specific electro-oxidation current-peak detection, (ii) Determination of the reference-line, and (iii) estimation of the measured current difference (ΔI).

During the first step, a current peak ($I_{peak}$) detection procedure is implemented as given by,

$$V_{peak} = \arg \min_v \left| \frac{dI(V)}{dV} \right|,$$

s.t. $0.75 < V < 0.85$ and $\frac{d^2I(V)}{dV^2} < 0$,

$$I_{peak} := I(V_{peak}),$$

where $I$ and $V$ represent the current and voltage variables, respectively, and $V_{peak}$ is the potential at which the
current maximum occurs. Second, the initial and final potentials/currents are estimated as follows, to form the reference line:

\[ V_{\text{initial}} = \arg \min_V \left| \frac{d^2I(V)}{dV^2} \right|, \text{ s.t. } 0.6 < V < 0.75, \]
\[ I_{\text{initial}} := I(V_{\text{initial}}). \]
\[ V_{\text{final}} = \arg \min_V \left| \frac{d^2I(V)}{dV^2} \right|, \text{ s.t. } 0.85 < V < 0.95, \]
\[ I_{\text{final}} := I(V_{\text{final}}). \]

Here \((V_{\text{initial}}, I_{\text{initial}})\) and \((V_{\text{final}}, I_{\text{final}})\) represent the two end points of the reference line. Next, using the calculated end points (voltage, current) pairs, an equation of the reference line is formed, that is then used to obtain the value of \(I_{\text{ref}}\) at \(V_{\text{peak}}\).

\[ \Delta I = I_{\text{peak}} - I_{\text{ref}} \]

A. Portable Sensing System Validation

The electrochemical operation of the developed portable EC sensing system was validated by characterizing a well-known redox-reaction involving reversible conversion between \(K_3[Fe(CN)_6]\) and \(K_4[Fe(CN)_6]\) given by,

\[ K^+ + [Fe(CN)_6]^{3-} + e^- \iff K^+ + [Fe(CN)_6]^{4-}. \]

To validate the designed EC sensor against a benchtop potentiostat, 10 mM \(K_3[Fe(CN)_6]\) was prepared using 0.1 M KCl aqueous (DI water as solvent) electrolyte solution, and the redox reaction was carried out on the disposable screen printed electrode. The following parameters were used while recording the \(I-V\) responses: starting potential \(-0.2\) V, final potential \(0.8\) V, scan rate \(0.1\) V/s, and sampling rate \(100\) Hz.

Fig. 5 presents a comparison of the \(I-V\) responses obtained using a benchtop potentiostat (CHI 660E; CHI Instruments Inc., Austin, Texas, USA) and the developed low-cost EC sensing system. It can be observed (refer Figure 5) that the developed plug-and-play type portable EC sensor exhibits excellent matched response with the benchtop potentiostat, thus validating the correct operation of the developed EC sensing system.

B. SA Sensor Response and Calibration

The developed plug-and-play type SA sensing system was used to obtain the DPV response and generate a calibration curve. In this section, the experimental data and the performance of the system are reported.

Fig. 6 presents the experimentally obtained DPV responses for SA solutions with concentrations ranging from 5 \(\mu\)M to 200 \(\mu\)M. As tested previously in literature, the SA concentration in plants under stress can vary from 0.85 \(\mu\)g/g to 20.25 \(\mu\)g/g fresh weight [33], [34], which translated to about 6 \(\mu\)M to 150 \(\mu\)M, respectively. Thus our sensor’s linear range of 5 \(\mu\)M to 200 \(\mu\)M is adequate for agriculture application.
The experimental DPV scans were recorded with the following parameters: pulse amplitude as 50 mV, pulse width as 50 ms, pulse period as 500 ms, potential increment as 10 mV, and sampling period as 20 ms. SA test solutions were prepared by first dissolving powdered SA in ethanol (as SA is highly soluble in ethanol) to obtain a concentration of 100 mM (the stock solution). The stock SA solution was then diluted using aqueous 0.1 M KCl in 0.2 M pH 6.6 PBS buffer solution to obtain the desired SA concentrations. During testing, 60 μL of the SA test solutions were sampled by drop-casting them on to the carbon screen printed electrode using a pipette. The recorded DPV graphs were then used to generate a calibration plot.

The experimental DPV graphs (shown in Fig. 6) were analysed according to the procedure described in Section IV-A to obtain the ΔI values. Fig. 7 presents the SA-specific measured current (or ΔI) versus the SA concentration along with the standard error at each measurement point. Next, a linear-fitting model was applied to estimate the calibration function. It can be observed that the developed sensor exhibits excellent linear response with an R-square value (also known as the coefficient of determination) of over 0.99, a sensitivity of 0.42 μA·μM⁻¹·cm⁻², and a limit of detection of 2.54 μM (3 × Std.Dev./Sensitivity) was achieved.

### C. Interference Study and Real-World Sample Testing

In order to determine the real-world applicability of the developed SA sensing system, an interference study was performed by observing the current response due to other species that can be present in agricultural samples. The interfering responses of the following chemical species were recorded: glucose, citric acid, uric acid, malic acid, abscisic acid (ABA), succinic acid, methyl-jasmonate (MeJA) and indole-3-acetic acid (IAA). These biochemicals were selected based on prior studies reported in literature about species present in agro-products/plant samples including sap, fruit or leaf tissue [25], [26], [35].

During the interference study, the samples were prepared using the same buffer that was used to prepare SA samples, that is aqueous solution of 0.1 M KCl in 0.2 M pH 6.6 PBS buffer. Fig. 8 presents the DPV responses recorded for key known compounds that may be present in the plant/agricultural samples. It can be observed that there is no detectable peak in the potential range of interest as determined in (2), corresponding to the SA-specific signal peak. Moreover, as described in the aforementioned section, the proposed data analysis procedure is immune to the base/background current level variations that may result from variable ionic composition of the test sample. Additionally, Fig. 9 presents a study where the DPV response for the sample containing a mixture of...
the 8 interfering species (refer Fig. 8) was recorded, where the separation between the cases of with vs. without SA is remarkable. Using the proposed data extraction procedure (refer Fig. 2) and the calibration model described in Fig. 7, the SA concentration was measured with over 90% accuracy (measured SA level 47.2 $\mu$M vs. actual SA level 50 $\mu$M) even under the presence of 8 possible interferants found in the plant samples.

For validating the sensor on real-world samples, SA levels in real plant/fruit samples of orange and tomato juice were measured. For reference or ground-truth values of SA concentration within the real test samples, a commercially available enzyme kit (Salicylate liqui-UV test kit; refer section III-A) was used for comparison. The working principle for the test kit is based on the enzymatic reaction:

$$\text{SA} + \text{NADH} + \text{O}_2 + \text{2H}^+ \xrightarrow{\text{SH}} \text{Catechol} + \text{NAD}^+ + \text{H}_2\text{O} + \text{CO}_2,$$

where the amount of Nicotinamide adenine dinucleotide (NADH) consumed is proportional to the concentration of SA in the solution. The measurement procedure involved the use of a spectrophotometer, where the light absorption through the solution is measured at 320 nm (absorption wavelength for NADH) of the reference versus the test solution, and the corresponding change in light absorption intensity is recorded. The method was first calibrated by measuring the intensity change for a known SA concentration solution followed by the real sample measurements.
Table II presents the results obtained by measuring SA levels in real plant/fruit samples including fresh orange and tomato juice. The accuracy of the order of ∼90% is acceptable for agriculture application and for an inexpensive portable sensing system.

### D. Comparison With Related Works

A detailed comparison between the key recent SA sensors reported in literature including our work is presented in Table I. It can be observed that sensors based on enzymatic reaction, MIPs and aptamers offer a higher LoD and in some case, also sensitivity, but are limited in their range of operation. As discussed previously, for agricultural and healthcare applications the range of operation must be over 100 μM at the high end. Moreover, the sensors based on bio-molecules require complex fabrication procedures that may result in large variability depending on the efficacy as well as the manufacturing process used of obtaining the bio-molecule. In contrast, the sensors based on the EC characterization of electro-oxidation of SA, as proposed, provide an alternate method for SA detection with sufficient detection limit while providing excellent shelf-life for practical in-field applications where our sensor exhibits superior sensitivity, linearity and competitive limit of detection, all while being a low-cost, fully portable and easy to use device (first-of-its-kind plug-and-play type SA sensor).

### VI. Conclusion

A first-of-its-kind plug-and-play-type portable bio-agent free SA sensing system was developed and reported in this work. The developed system consisted of the following key components: a 3D-printed electrode adapter for electrode-sensor interface, the specially designed sensing electronics of a potentiostat, and the sensor data analysis procedure to extract functional SA concentration level information. The proposed SA sensing system exhibited excellent linearity and performance where a sensitivity of 30 nA/μM or 0.42 μA·μM⁻¹·cm⁻², and limit of detection of 2.5 μM was observed. Additionally, an interference study with other species present in plant samples was performed to assess the practical applicability of the developed system, and SA concentrations in real plant/fruit samples were estimated with ∼90% accuracy compared an expensive in-lab test kit. The overall cost of the developed system for a single unit is around $50 making it ideal for various portable applications spanning agriculture, healthcare and pharmaceutical.

Following on the development of the proposed sensor in this work, the future work may focus on integrating a battery and a Bluetooth module with the MCU for wireless data recording and analysis. Secondly, the electrode may be functionalized with nano-materials to improve sensitivity even further but may result in increased cost and complex sensor fabrication procedure. Finally, the developed system can be used for more extensive studies for monitoring SA levels in Agricultural and pharmaceutical sensing applications. Additionally, the low-cost potentiostat system can be developed further for more general EC sensing needs while a comparison between our low-cost system and other EC workstations may be performed to assess accuracy and gauge performance.

### Appendix

### Schematic of P-AFE With Component Details

Fig. 10 shows the complete schematic of the developed P-AFE including the component values used. For displaying purposes the overall circuit design was divided in to two parts: (a) Circuit connections leading to RE and CE, (b) Circuit connections following the WE; DAC, ADC+ and ADC- were connected to their respective pins on the MCU (C2000 Launchpad).

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