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A novel multi-set differential pulse voltammetry technique for improving precision in electrochemical sensing

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ABSTRACT

Over the years, electrochemical sensors have achieved high levels of sensitivity due to advancements in electrical circuits and systems, and calibration standards. However, little has been explored towards developing ways to minimize random errors and improve the precision of electrochemical sensors. In this work, a novel electrochemical method derived from differential pulse voltammetry termed multi-set differential pulse voltammetry (MS-DPV) is proposed with the goal of reducing random errors in chemical- and bio-sensors and thereby improve precision. The proposed MS-DPV improves precision without the need to replicate measurements. Therefore, saving energy use, time consumed, and/or materials required. The method is especially suited for portable or in-field sensing solutions that have strict constraints on sampling, time and energy use. To realize the proposed method, a custom designed plug-and-play-type electrochemical sensing system was employed which was then used for detecting salicylic acid (SA). SA is a key phytohormone deployed during defense responses in plants against biotic stresses. Additionally, SA is widely used in the pharmaceutical and healthcare industry due to its anti-inflammatory and analgesic properties. Using a "4-set-DPV", an error reduction of up to 12% was observed in SA detection when compared to conventional differential pulse voltammetry. In general, the error variance reduces linearly with the number of readings taken in a single scan of the proposed MS-DPV.

1. Introduction

Electrochemical (EC) measurements form the basis of *electrochemistry*, a branch of chemistry that encompasses the study of oxidation and reduction (redox) reactions involving electron/ion transfers. Electrochemical methods refer to techniques applied in analytical chemistry for studying the characteristics of a chemical reaction through electrical probing. Developing sensors is a key application of the EC methods where a specific analyte is detected based on the prior knowledge obtained about its unique electrochemical reaction kinetics using EC measurements. Such sensors are applied in a multitude of applications spanning healthcare, pharmaceutical, disease diagnostics, agriculture, and environmental monitoring. Among the EC sensing methods, differential pulse voltammetry (DPV) is an important technique that is applied extensively in biosensing and chemical-sensing due its superior sensitivity. The reason behind DPV's superior sensitivity is that the background (due to interfacial capacitance) current is minimally affected by small changes in the applied potential. Therefore, by sampling the currents before and after relatively small potential increments, and subtracting the two, the effect of background current is minimized providing greater sensitivity towards the faradaic current (current due to electron transfer in a chemical reaction).

Sensitivity, selectivity, limit of detection, and accuracy/precision are among of the key performance metrics of any sensor, including the ones based on EC methods, where sensitivity and selectivity are analytical parameters, while accuracy, precision and limit of detection are statistical parameters. Analytical parameters primarily depend on the physical and chemical properties of the sensor which are largely constant for a given/developed system, where as statistical parameters depend on variables like random noise in measurement (electrical, thermal, chemical and mechanical etc.), calibration error of the equipment, and changes in the ambient environment. For a given system, one key way to reduce random measurement error is through averaging where multiple outputs can be recorded for any given input that can be averaged later to obtain a final data point. Numerically, the relationship between the number of measurements (N) and the standard deviation of the single versus N measurements is given by:

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$$\sigma_N = \frac{\sigma}{\sqrt{N}}, \tag{1}$$

where σ and σ_N are standard deviation for a single measurement and N number of measurements for a given input, respectively. It can be observed from (1) that the standard deviation can be reduced by a factor of $\sqrt{N}$ resulting in higher precision.

For obtaining N measurements for the same input, the experiment has to be repeated N number of times. However, for sensing applications, recording multiple measurements may present challenges such as excessive time consumption, battery/energy use (of great significance in portable and in-situ sensing), and increased cost due to the use of consumable resources like disposable electrodes. Accordingly for N number for measurements, the time span, energy-use and consumable product-use increases by N-fold. For example, DPV-based sensors commonly require between 30 seconds to a few minutes to record a single voltammogram, and in our case of salicylic acid (SA) sensing it takes 60 seconds and one disposable electrode.

In this article, a novel *multi-set DPV* (or MS-DPV) method is proposed for improving the precision in quantitative sensing through multiplicity in measurement, without incurring any additional expense on time, energy or cost. The proposed system utilizes the unique working principle of DPV for obtaining multiple voltammograms from a single potential scan. The MS-DPV operation is enabled by custom-developed sensing electronics based on an application-specific potentiostat circuit. The developed sensing platform is used to demonstrate the MS-DPV operation applied towards detecting SA.

SA (or 2-hydroxybenzoic acid) plays an important role across several industries including agriculture, food, healthcare and pharmaceutical. In plants, SA is one of the primary defense-related phytohormones responsible for the activation of systemic acquired resistance (SAR) when a plant is under stress (mainly biotic stress). During SAR, the concentration of SA increases at the attack-site and the accumulated SA (acting as a signaling molecule) is transported to other parts of the plant through phloem which leads to systemic immune response Spoel and Dong (2012); Fu and Dong (2013). Therefore monitoring SA levels can provide a way for early detection of stress in plants leading to effective and timely measures for minimizing plant and yield losses. Among the several plant disease detection methods ranging from imagery, laboratory-based analytical techniques, and phytohormone monitoring, SA (a phytohormone) sensing for in-field plant health monitoring applications is still being developed having potential for specific biotic stress detection in plants/crops Kashyap and Kumar (2021a).

SA salts (Salicyates) are known for their analgesic, antiseptic and anti-inflammatory properties, that make them a critical ingredient in many over-the-counter non steroidal anti-inflammatory drugs like Aspirin (one of the most commonly used pain medication for acute as well as chronic pains), and cosmetics for skin and body-care. According to the American Association of Poison Control Centers (AAPCC), 24% of analgesic-related deaths can be attributed to aspirin overdose (alone or in combination with other drugs) Mowry et al. (2016), and so a timely detection of SA levels in human serum and urine samples may have a life saving impact.

Several works have been reported in literature for sensing SA spanning laboratory-based methods involving LC/MS and GC/MS, biosensing methods as overviewed in our prior work Kashyap and Kumar (2021b).

As a part of this work, a brand new voltammetry technique, termed MS-DPV, has been developed and demonstrated where *four voltammograms* (based on the data storage capacity of the employed MCU) for SA-oxidation reaction were recorded simultaneously in the same time as it takes to record one using the conventional DPV. The MS-DPV method along with its application for sensing SA presented in this work is a *first-of-its-kind* development to improve the performance of EC sensing. Key research and development contributions presented in this work include:

1. The very first Multi-set DPV technique for EC sensing with the unique advantage of reduction in random error.
2. Accurate, portable and low-cost electronics to perform MS-DPV and on-board data-analysis. Our sensor exhibits excellent performance providing a novel, accurate and portable potentiostat where the total cost of a single unit is about $50.
3. Detection of SA using MS-DPV enabled by our portable sensing system. It was shown that the measurement error reduced by 3%–12% for the tested real plant/fruit samples and artificially prepared sample, by just using a "4-set-DPV-based" SA detection as compared to conventional DPV approach.

This paper has been divided into the seven sections including introduction, materials and equipment, multi-set DPV operation, sensing and algorithmic system for implementing MS-DPV, SA sensing using MS-DPV technique, results and discussion, and conclusion.

The key motivation behind this work is based on the fact that error is a vital parameter for the assessment and adoption of any portable EC sensing technique and this article addresses the need for reduction in random error through a novel methodology which leverages the unique capability of the developed portable EC sensing system to record multiples sets of differential voltamograms from a single input differential voltage sweep. Thus, gaining the advantage of error variance reduction through *averaging* without the need for repeating the experimental measurements.

2. Materials and equipment

C2000 Launchxl-F28379D (MCU Launchpad; manufactured by Texas instruments Inc.) and other electrical components 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. SA (in powder form), sodium hydroxide (NaOH), potassium ferricyanide ($K_3[Fe(CN)_6]$) and phospahte buffered saline (PBS) of pH 6.6 buffer was purchased from Millipore-Sigma, MO, USA. Ethanol (200 Proof) and potasssium chloride (KCl) were 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 spectro-photometer. Deionized (DI) water with a conductivity of 18.2 MΩ was used to prepare all the solutions.

3. Multi-set DPV operation

Fig. 1 shows the schematic of the MS-DPV technique compared with the conventional DPV method. In conventional DPV, an initial and final current samples (denoted by black dots in Fig. 1) are recorded within each pulse period and are then subtracted to obtain the differential current (δi) as:

$$\delta i = i(t_f) - i(t_i), \tag{2}$$

where $i(t_i)$ and $i(t_f)$ represent the initial (at t_i) and final (at t_f) current samples recorded within each pulse period, respectively. The samples are collected near the rising and falling edges of the differential pulse voltage signal.

Most commercially available potentiostats only have a single user-controlled parameter for selecting the sampling time that is the *sample width*. This may be because the differential current calculation is realised directly in the circuit design limiting the operation's flexibility. However, in the proposed work, a portable potentiostat-based sensing system is designed which allows for the precise control on the time instance at which a current sample is recorded. This, in turn, adds unique functionality to conventional DPV, by recording multiple current samples,

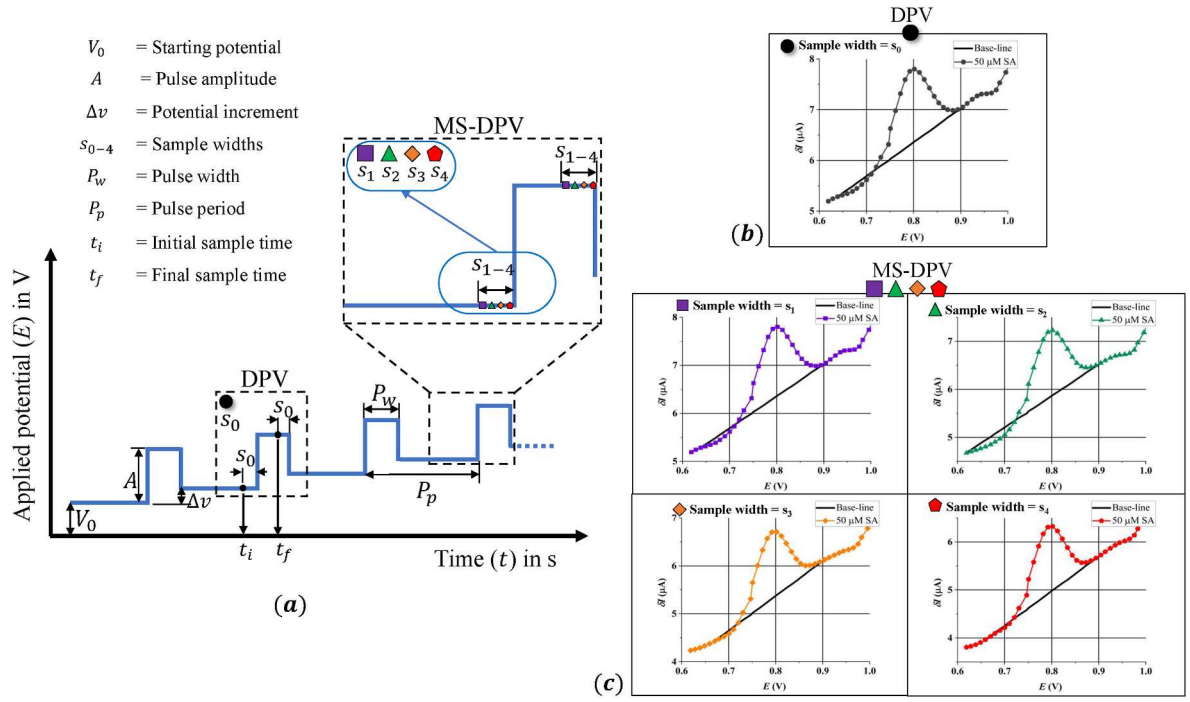


Fig. 1. The schematic of the proposed MS-DPV technique; (a) DPV input signal with a comparison between the sampling scheme in DPV and the proposed MS-DPV (shown here for 4-set DPV); (b) A voltammogram obtained from conventional DPV for a given input DPV signal; (c) 4-sets of voltammograms obtained using MS-DPV method (colors correspond to their specific sampling widths); All the data was experimentally obtained using the developed sensing electronics for 50 μM SA sample.

denoted by colored dot in Fig. 1) and storing in onboard memory, within the same sample widths, near the rising and falling edges of the applied potential signal. The stored current samples are subsequently algorithmically processed to get *multiple differential currents from a single voltage scan* resulting in multiple voltammograms forming the basis of MS-DPV. The novelty of the proposed approach is that it takes the same amount of time and resources to record multiple voltammograms as it takes to record one voltammogram in conventional DPV. Thereby, multiple datasets are available providing multiplicity in a measurement leading to reduction in error and improved precision as per (1), that shows that the error is reduced by a factor of $\sqrt{N}$ when N measurements are taken.

4. EC sensing electronics for MS-DPV

4.1. Sensing electronics design

Fig. 2 presents the schematic of the complete EC sensing electronics developed and used to implement MS-DPV. The main components of the EC sensing electronics include a low-cost disposable electrode, 3D-printed electrical interface for the electrode, application-specific sensing electronics and sensor data analysis. Commercially available planar screen-printed electrodes (as shown in Fig. 2) consisting of a carbon working electrode (WE), a carbon counter electrode (CE), and an Ag/AgCl reference electrode (RE), integrated together and arranged in a three-electrode configuration, were employed in this work. These electrodes offer economical and reliable operation, ideal for testing MS-DPV and evaluating the a low-cost EC sensing platform. The electrode holder was fabricated using a 3D polymer printer (using B9 creator v1.2 3D printer) and provided an easy-to-use, quick and reliable electrical interface between the planar electrodes and the sensing electronics. The developed sensing electronics additionally consisted of two main components:

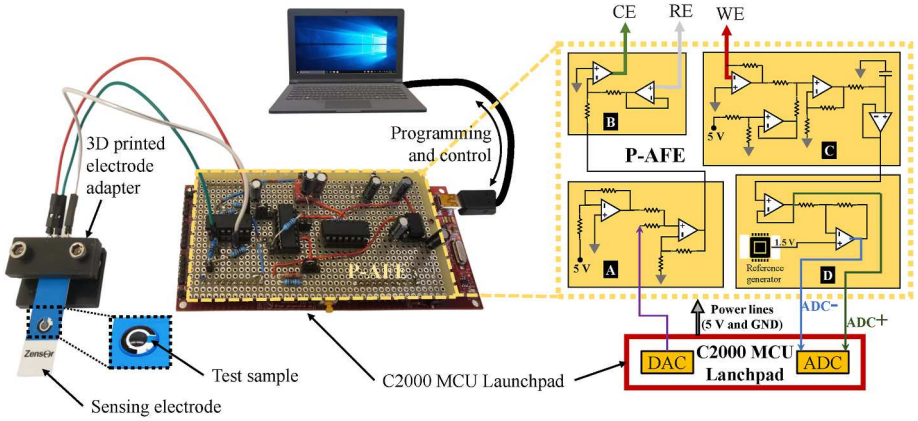


Fig. 2. Schematic of the developed portable EC MS-DPV sensing system. (A) Input signal conditioning circuit; (B) Core potentiostat circuit; (C) Output signal detecting circuit; (D) Single-ended-to-differential converter circuit.

1. C2000-Launchpad microcontroller (MCU) from TI. The C2000 MCU was selected for developing the sensing system as it comes with 12 bit digital-to-analog converter (DAC) and a 16 bit analog-to-digital converter (ADC; with upto 1 MHz sampling rate), 200 MHz dual-CPUs and sufficient onboard memory, all integrated on a single IC which was well-suited for our application.
2. A specially-developed potentiostat analog-front-end (P-AFE). The P-AFE module was fabricated on a perfboard such that it can be conveniently mounted on the MCU platform with the desired communication and power channels connected between the two. The developed P-AFE comprised of four main sub-circuits (refer Fig. 2): (a) the input signal conditioning circuit, (b) the three-electrode potentiostat system, (c) the output current-to-voltage converter and voltage level adjuster, and (d) the single-ended to differential signal converter, required specifically for sampling the signal using the differential 16 bit ADC integrated in the C2000 MCU platform.

The complete sensor circuit system is operable by a PC which triggers the measurement, and collects the recorded MS-DPV analyzed data. The details of operation of the portable sensing system were described in our recent work Kashyap and Kumar (2021b), where the operation of the sensing system was limited to conventional DPV. Below, the EC sensing system's operation is presented focusing on its implementation of the proposed MS-DPV technique.

The measurement procedure begins with DPV input signal generation using the 12 bit DAC, which is then followed by any DC offset adjustment using a voltage adder circuit. The final DPV input signal is then routed to the core potentiostat sub-circuit, developed based on a *potential control amplifier in adder configuration* as described in Bard and Faulkner (2000). The current through the WE is then measured by converting the current signal to an output voltage signal which is then sampled using the differential 16 bit ADC. The overall circuit formed a compact sensing device (refer Fig. 2) and was optimized for MS-DPV-based electrochemical detection. The sampling scheme was designed such that four different differential currents are recorded, resulting in "4-set-DPV", and transferred via serial communication to a PC.

4.2. Sensing system validation

In order to evaluate the operation of the developed sensing system, a well-known redox reaction was characterized using cyclic voltammetry (CV). The reversible conversion between potassium ferricyanide ($K_3[Fe(CN)_6]$) and potassium ferrocyanide ($K_4[Fe(CN)_6]$) was used as the redox probe where the chemical reaction is given by:

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

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 on the disposable screen-printed electrode. The following parameters were selected for recording the CV responses: initial potential $= -0.2$ V, final potential $= 0.8$ V, scan rate $= 0.1$ V/s, and sampling rate $= 100$ Hz.

The CV voltammograms obtained from a bench-top potentiostat (CHI 660E; CHI Instruments Inc., Austin, Texas, USA) and the developed system were compared as shown in the Fig. 3. From this figure it can be observed that the CV voltammogram obtained using the developed sensing system corresponds well to the one recorded using the commercial benchtop potentiostat.

5. Sensing using MS-DPV technique

This section describes the use of the proposed MS-DPV method by demonstrating the EC detection of the analyte SA (salisylic acid). The proposed MS-DPV procedure exhibits selectivity for determining an analyte in form of its differential current peak in a given voltammogram,

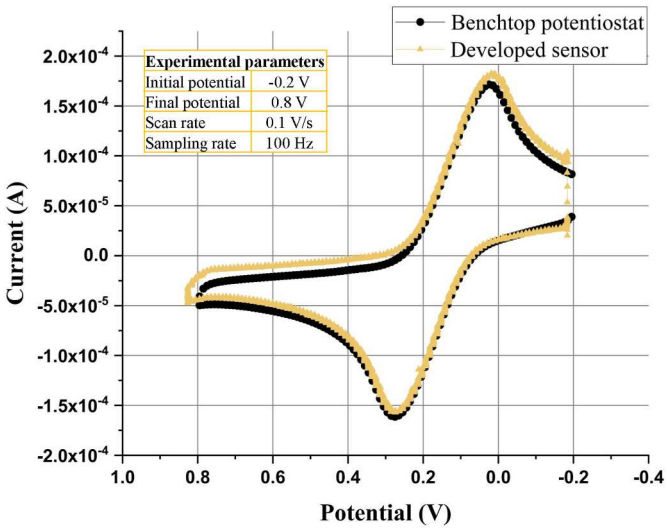


Fig. 3. Comparison between the CV plots obtained using a bench-top potentiostat and the developed portable EC MS-DPV sensing system; For 10 mM $K_3[Fe(CN)_6]$ in 0.1 M KCl aqueous solution.

that occurs at the experimentally established SA-oxidation-specific potential. Also, depending on the conductivity of the analyte solution, the base-line (or the background) may shift but our algorithm for determining I_{SA} (final measured current) is independent of any such changes making the procedure robust.

5.1. MS-DPV data analysis

The data analysis procedure for MS-DPV-based analyte sensing consists of two main steps: (a) Determination of SA-specific differential current (or the differential current peak) from an experimentally recorded DPV voltammogram, and (b) Determination of SA from the *multi-set* calibration functions (four distinct calibration were obtained using four voltammograms from a single DPV scan).

During the first step, an automated current peak (corresponding to analyte oxidation reaction) determining algorithm is implemented as enumerated below:

1. Detect the current peak (δI_{peak}). First the value of the voltage where the current peak within the SA-oxidation specific DPV response occurs is determined, and next the value of the current at that voltage is noted (see Fig. 4 for a visual):

$$E_{peak} = \arg\min_E \left| \frac{d(\delta I(E))}{dE} \right|, \tag{3}$$

$$\text{s.t.} \quad 0.75 < E < 0.85 \quad \text{and} \quad \frac{d^2(\delta I(E))}{dE^2} < 0, \qquad \delta I_{peak} = I(E_{peak}) \tag{4}$$

where E_{peak} is the potential at which the differential current maximum occurs within the SA-oxidation specific DPV response, and δI and E represent the differential current and voltage variables, respectively.

2. Calculate the SA-specific current (I_{SA}) as the distance of δI_{peak} from the base-line (see Fig. 4). For this, a base-line is first formed by noting a left and a right minima (where slopes are again the smallest) and connecting the two via a straight line and noting the current value $\delta I_{base} = I(E_{peak})$ on that line at the potential of E_{peak}. The distance of the differential current peak from the base-line is calculated to produce the measured SA-oxidation-specific current ($I_{SA} = \delta I_{peak} - \delta I_{base}$), as in Fig. 4.

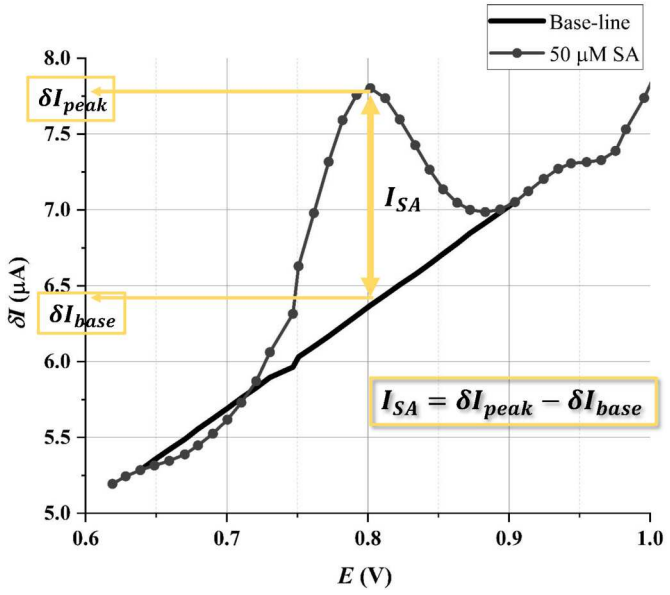


Fig. 4. EC sensor data analysis method using experimentally obtained DPV voltammogram.

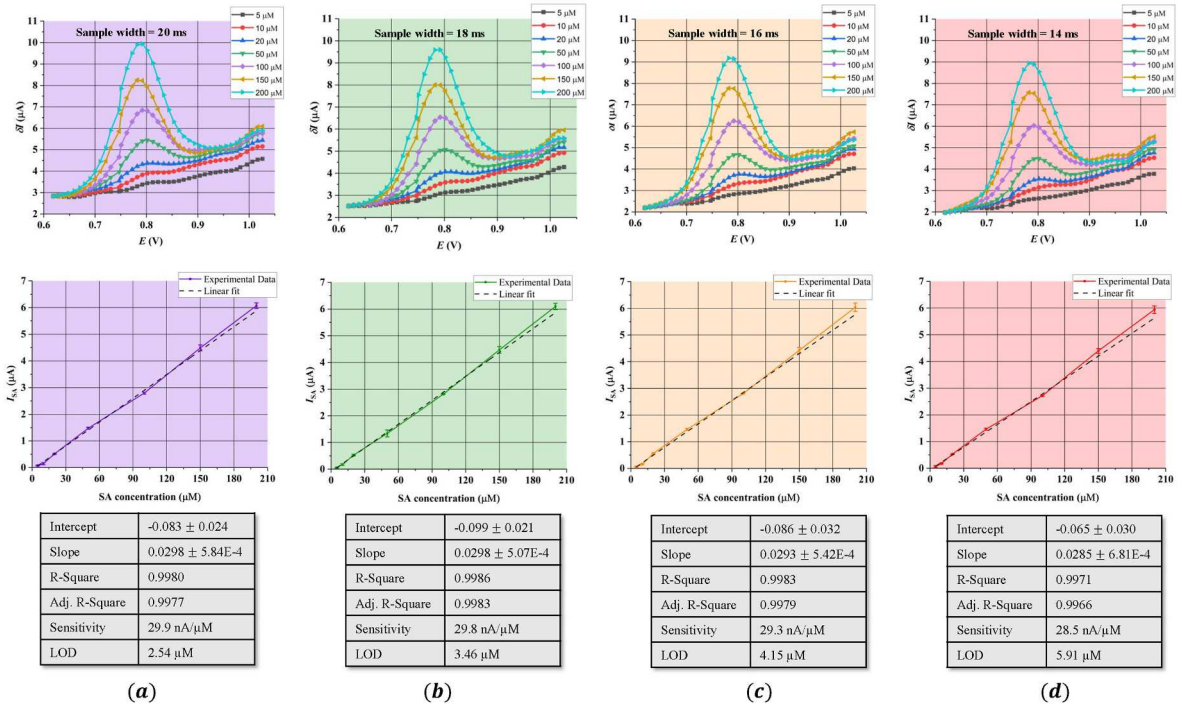
The aforementioned procedure is carried out on all the four experimentally obtained voltammograms from the "4-set-DPV" (refer Fig. 1) and the corresponding 4 I_{SA} values (all obtained from the single run of DPV) are recorded. During the second step, the estimates of the analyte concentration are obtained using the four different linear calibration functions (described in the next section below) obtained from the MS-DPV approach, and the mean of the calculated analyte concentration estimates is taken as the final estimated analyte level in the test sample.

5.2. MS-DPV sensor response and calibration

Fig. 5 presents the experimentally obtained MS-DPV responses ("4-set-DPV" in this example) and calibration functions, namely, the four sets of voltammograms, simultaneously obtained from single DPV scans, for SA test solutions of concentrations between 5 μM and 200 μM. 4 sample widths were used as $s1 = 20$ ms, $s2 = 18$ ms, $s3 = 16$ ms and $s4 = 14$ ms (depicted in Fig. 1), providing the 4 responses (a) purple, (b) green, (c) orange, and (d) pink in Fig. 5, respectively. Other MS-DPV experimental parameters are shown in the caption of Fig. 5 and are also presented in the Table S1. SA test solutions were prepared by dissolving SA (in powder form) in ethanol (SA is highly soluble in ethanol) to obtain a concentrate of 100 mM (stock solution) followed by dilution using aqueous 0.1 M KCl in 0.2 M 6.6 pH PBS buffer solution to obtain the desired SA concentration. 60 μl of the SA test solutions were drop-casted on to the electrode surface using a pipette covering all the three screen printed planar electrodes.

The recorded MS-DPV (4-set-DPV in our case) data was then analyzed according to the procedure of the previous subsection to calculate I_{SA} values for different SA solutions of known concentrations. Linear models were fitted to the experimentally recorded data to estimate the calibration functions exhibiting excellent linear response, where R-square values (also known as the coefficient of determination) of over 0.99 were observed. Although the DPV graphs are shown for a single set of data, 3 measurements were at each data point that were used to calculate standard error and add error bars on the calibration graphs. From each calibration graph, sensitivity and limit of detection (LOD; $3 \times SD_y$/slope) were calculated and are shown in Fig. 5.

Additionally, reproducibility (multiple measurements on same sensor surface) and repeatability (measurements on multiple sensor surfaces) were evaluated by means of relative standard deviation (RSD) calculation of the slope of calibration graphs. Based on the reproducibility and repeatability study, RSD of calibration slopes was calculated to be as 0.0415 and 0.052, respectively. The detailed measurements and calculations are present in the Tables S2–S3 and Figs. S1–S2.



	(a)	(b)	(c)	(d)
Intercept	-0.083 ± 0.024	-0.099 ± 0.021	-0.086 ± 0.032	-0.065 ± 0.030
Slope	0.0298 ± 5.84E-4	0.0298 ± 5.07E-4	0.0293 ± 5.42E-4	0.0285 ± 6.81E-4
R-Square	0.9980	0.9986	0.9983	0.9971
Adj. R-Square	0.9977	0.9983	0.9979	0.9966
Sensitivity	29.9 nA/μM	29.8 nA/μM	29.3 nA/μM	28.5 nA/μM
LOD	2.54 μM	3.46 μM	4.15 μM	5.91 μM

Fig. 5. Experimental MS-DPV response obtained for different SA concentrations using the developed portable SA sensing system; (a), (b), (c) and (d) show the datasets and respective calibration models at different sample widths of 20 ms, 18 ms, 16 ms and 14 ms, respectively. Additionally, other experimental parameters were used as: Pulse amplitude 50 mV, potential increment 10 mV, pulse width 50 ms, and pulse period 500 ms; all SA solutions were prepared from dilution of 100 mM stock (dissolved in ethanol) using aqueous 0.1 M KCl in 0.2 M 6.6 pH PBS buffer; LOD refers to Limit of detection.

6. Results and discussion

As shown in Fig. 5, the analyte specific current I_{SA} at the analyte specific redox-potential peaking location as a function of the analyte concentration can be computed and used to generate concentration versus the current plots, one for each sample width of the proposed MS-DPV. Linear models were then used to form calibration graphs with excellent linearity (R-squared over 0.99). Based on these plots, performance metrics of sensitivity and LOD for the 4 individual data-sets recorded using the low-cost portable EC sensor with integrated MS-DPV were calculated. The sensitivity and LOD of the developed sensor is among the best as compared to recent prior works such as Kashyap and Kumar (2021b) where a sensitivity of 30 nA/μM and LOD of 2.5 μM is reported, Rawlinson et al. (2018) where a sensitivity of 1.2 nA/μM and LOD of 5.6 μM is reported, Park and Eun (2016) where a sensitivity of 0.21 nA/μM and LOD of 1.7 μM is reported but with larger range of operation (up to 3000 μM), and Xiong et al. (2020) where sensitivity is not mentioned and LOD of $3.9 \times 10^{--8}$ M is reported but with significantly smaller range of operation. Moreover, RSD of the slope of calibration graphs provided an estimate of reproducibility and repeatability and was calculated to be about 5% which indicates that our sensing system provide good reproducibility and repeatability. To the best of our knowledge, RSD estimates are not available/reported in literature for SA sensors.

In practice, any of the 4-set DPV data with different sample widths can be considered as a single run of DPV by itself. Therefore, the sensitivity and LOD of the data obtained from conventional DPV and MS-DPV may be similar. However, the goal of the MS-DPV method is to improve precision in sensing by reducing the random error. In other words, it improves the closeness of the measured value to a standard or true value. This was demonstrated as follows where unknown samples were tested to evaluate the performance of the MS-DPV approach by comparing the SA levels obtained using the conventional DPV and the proposed MS-DPV methods. For the MS-DPV measurement, the mean of the individual SA measurements from the 4 calibrations of Fig. 5 were taken as the final SA concentration value.

Table 1 presents the performance comparison between SA determination using conventional DPV vs, MS-DPV. SA measurement and estimation was performed for the real plant/fruit as well as prepared SA samples. The orange juice and tomato juice 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, where the samples were diluted with the ratio 1:3 and 1:4, respectively. For knowing the ground truth values of the SA levels in the real plant/fruit samples, a commercially available enzyme kit (Salicylate liqui-UV test kit; refer Section 2) was used. The working principle is based on the enzymatic reaction:

$$SA + NADH + O_2 + 2H^+ \xrightarrow{SH} Catechol + NAD^+ + H_2O + CO_2,$$

where the amount of Nicotinamide adenine dinucleotide (NADH) consumed is proportional to the concentration of SA in the solution. NADH exhibits an absorption peak at 320 nm therefore by measuring the changes in absorbance at 320 nm, the amount NADH (and SA) can be determined. The method was calibrated by first measuring the intensity change for a known SA concentration solution followed by real sample testing.

As can be seen from Table 1 the error improved between 3% and 12% by just using "4-set-DPV". Our measurement principle allows for higher number of sampling widths, but 4 were chosen to account for the current MCU's memory limit. Even the current design provides the proof-of-concept of accuracy improvement due to the use of MS-DPV approach. Moreover, testing the real samples demonstrates the applicability of the developed portable sensor for practical in-field applications such as for plant health monitoring.

Additionally, an interference study involving the evaluation of the sensor responses towards common interfering chemical species such as glucose, citric acid, uric acid, malic acid, abscisic acid (ABA), succinic acid, methyl-jasmonate (MeJA) and indole-3-acetic acid (IAA) in plant/food samples were observed in our prior work Kashyap and Kumar (2021b), where it was concluded that there are no detectable differential current peaks from the above potential interferrants in the SA-oxidation-specific potential. The interference study is presented in Figs. S3–S4 where SA concentration was measured with over 90% accuracy in the presence of interfering chemical species.

Table 1
SA level testing in real samples.

Sample	Actual SA level	SA level measured using DPV, % error	SA level measured using MS-DPV, % error	Percentage error improvement[a]
Fresh orange juice	45.2[b] μM	51.6 μM, 14.1%	44.2 μM, 2.3%	11.8%
Fresh tomato juice	22.8[b] μM	25.2 μM, 10.5%	23.7 μM, 4.0%	6.5%
Test solution (15 μM SA)	15 μM	17.13 μM, 14.2%	16.54 μM, 10.3%	3.9%

[a] Percentage error improvement = % error (MS-DPV) - % error (DPV).
[b] Obtained using the Salicylate UV test kit.

7. Conclusions

In this article, a novel electrochemical method termed MS-DPV was presented with the goal of improving precision through reduction in random error in any differential pulse voltammetry-based sensor. MS-DPV offers a distinctive advantage of recording multiple readings in a single measurement, offering the same advantage that multiple measurements and averaging offer for error variance reduction, thus saving the cost of energy, time, or materials, required for additional rounds of measurements. In particular, a "4-set-DPV" was implemented to demonstrate the efficacy of MS-DPV approach where an error reduction of up to 12% was observed in real samples. The sensitivity and the LOD of the sensing system is also among the best for the given range of operation (up to 200 μM). The overall cost of the developed system for a single unit was around $50 making it ideal for various applications spanning agriculture, healthcare and pharmaceutical.

Future works may focus on modifying the sensor surface with unique materials which may have higher conductivity and high effective surface area for enhancements in performance metrics. Additionally, the 4-set DPV method presented in this works can be applied to N-set DPV measurements employing MCUs with larger memory or external memory integration for higher precision. However, as N increases, the improvement in precision will exhibit diminishing returns due to inverse square relationship of standard deviation and N (number of measurements) as indicated in (1).

CRediT authorship contribution statement

Bhuwan Kashyap: Conceptualization of this study, Methodology, Software, Experimentation, Investigation, Data curation, Writing – original draft. **Ratnesh Kumar:** Supervision, Validation, Writing - review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bios.2022.114628.

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