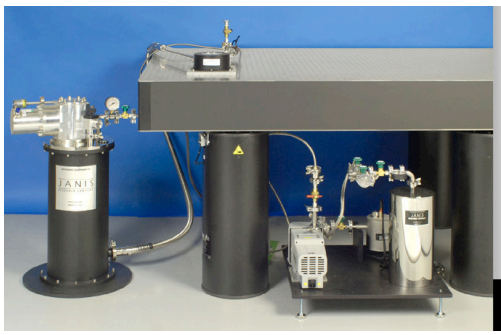
Review of Scientific Instruments

Design of multichannel potentiostat for remote and longtime monitoring of glucose concentration during yeast fermentation

Cite as: Rev. Sci. Instrum. **91**, 054104 (2020); https://doi.org/10.1063/1.5137789
Submitted: 13 November 2019 . Accepted: 09 April 2020 . Published Online: 05 May 2020

Saad Abdullah, Mauro Serpelloni, and Emilio Sardini



AIP Publishing

Review of Scientific Instruments ARTICLE scitation.org/journal/rsi

Design of multichannel potentiostat for remote and longtime monitoring of glucose concentration during yeast fermentation

Cite as: Rev. Sci. Instrum. 91, 054104 (2020); doi: 10.1063/1.5137789
Submitted: 13 November 2019 • Accepted: 9 April 2020 •
Published Online: 5 May 2020

Saad Abdullah,[a] Mauro Serpelloni, and Emilio Sardini

AFFILIATIONS

Department of Information Engineering, University of Brescia, Piazza del Mercato, 15-25121 Brescia, Italy

[a]Author to whom correspondence should be addressed: s.abdullah@unibs.it

ABSTRACT

This paper presents the design of a wireless portable and multichannel potentiostat for remote monitoring in enclosed environments for long-time applications. In this paper, the proposed potentiostat is tested for monitoring the glucose concentration during the fermentation of yeast in real time for more than 24 h. The potentiostat is powered by a USB-connected battery and operated through a Bluetooth using a LabVIEW designed data monitoring and control panel. The potentiostat is capable of performing cyclic voltammetry or chronoamperometry on six biosensors simultaneously and gives the real-time response using Bluetooth connection. The potentiostat has a common counter electrode and reference electrode connection to all biosensors and independent working electrodes for all biosensors. The potentiostat was tested and validated by comparing the results obtained by a commercial potentiostat. The tests performed for monitoring the glucose concentration during the fermentation process showed a current detection limit of 180 nA and reported a standard deviation of ±2% for anodic and cathodic current peaks for cyclic voltammetry measurements when compared with the commercially available device. This study enables the novel method of monitoring the fermentation process wirelessly for days.

I. INTRODUCTION

Monitoring of metabolites is of prime importance in medical diagnostics, and also in the industrial field for many purposes. In the medical field, the difficulty of sensing small quantities of containments present in biological fluids threatens the health of millions of people as they are associated with the causes of various dangerous diseases. In order to address the problem, many efforts have been directed in the domain of genomic research, electronics, and biomaterials and have discovered thousands of protein biomarkers for disease detection before the occurrence of symptoms via miniaturized biosensors.[1,2] Of the many techniques presently available for metabolite detection, the potentiostat offers the most promising solution without compromising the accuracy, sensitivity, and quality of the result. Instead, it overcomes the barriers and limitations offered by the conventional currently available options to run electrochemical analysis by enabling us to run tests on a small quantity of samples and also eliminates the need of highly trained laboratory professionals. Furthermore, unlike the traditional methods/approaches, such as laboratory assays, the use of a potentiostat has also been reported to yield results more rapidly without consuming an ample amount of time and requiring minimal sample preparation. Therefore, potentiostat design has a wide range of applications in long term monitoring of electrochemical processes[3,4] and analysis of various analytes present in minor quantities in biological fluids.[5]

Several potentiostats have been proposed in the literature with different features to overcome different issues in many applications. For example, in Ref. 6, the complexity of electrode arrangement employed in electrochemical analysis can be reduced by implementing computer controlled multichannel potentiostats. Moreover, multi-electrode, multi-array biosensor, and multichannel, hybrid-multiplexed potentiostat designs were proposed to improve the efficiency.[7–15] To further miniaturize the electrochemical systems on chip devices,[16] the design of a multichannel very large scale integrated (VLSI) potentiostat was presented.[17–24] Likewise, to meet the need of on-site diagnosis wireless data transmission, portable designs were demonstrated. Additionally, a

USB-controlled/USB-powered portable potentiostat[2,25–33] and a disposable device design[34] with printed batteries were also presented. However, each of these pioneering designs has different issues that lead to difficulties in a continuous real-time monitoring for a long time. For example, they have the capability to retrieve data on-site, yet only display one data point at a time, and therefore, later, they require the use of an external personal computer (PC) to view all data at once and perform analysis. Some designs store data without display and later upload the data to a PC through an RS-232 connection, whereas other designs restrict simultaneous analysis of electroactive enzymatic products.

Among the wide range of industrial applications of potentiostat design in long-term monitoring of electrochemical processes, the fermentation process is the most common and of prime economic importance as it produces vinegar, wines, lactic acid, and many others.[3,4] Some organic compounds are yielded as an end product of the catabolic process of incomplete oxidation called fermentation. This process is carried out in an anaerobic atmosphere and produces low molecular weight organic acids (acetic acid, lactic acid, butyric acid, etc.) or low molecular weight alcohols (propanol, methanol, or ethanol) depending on factors, such as the substrate, culture medium, and the type of microorganism.[35,36] The monitoring and control of this type of bioprocess are vigorously studied due to its economic importance in producing vinegar, wines, lactic acid, and many others.[3,4] The ethanolic fermentation processes involve the transformation of sugars (mainly glucose, fructose, and sucrose) into ethanol and carbon dioxide. Among several other types of microorganisms, yeast *Saccharomyces cerevisiae* is mostly used in many traditional biotechnological fermentation processes because of its tolerance to relatively high concentrations of ethanol and good performance. These types of fermentation processes are frequently used in bread making and the production of several alcoholic beverages,[37] where a continuous monitoring of the microorganism's activity is necessary to improve the quality of the final product and to avoid waste conditions.

Enzyme-mediated oxidation–reduction processes take place simultaneously during fermentation; this enhances the usage of the electrochemical analysis technique as a strong tool for characterization of fermentations and ethanolic fermentations in particular.[3,4,37,38] Amperometric detection is used for quantification of molecules, such as fructose and glucose, which are involved in the ethanolic fermentation. This method usually uses enzymes as recognition elements using high selectivity conferred by these macromolecules; in addition, it allows the possibility of monitoring molecules of non-electroactive species, such as fructose or glucose.[3,4,37–39] Different types of techniques, such as electrochemical CO_2 probes,[40] optical fiber refractometry, density determination using flexural oscillators, and ultrasound techniques,[41] are proposed to measure the amount of CO_2 released during fermentation in order to monitor sugar consumption by yeasts.

Several electrochemical systems used for determination of glucose and electrochemical monitoring of ethanolic fermentation are reported in the literature;[1,42–46] these examples include commercial kits, which are used on a laboratory scale using screen-printed electrodes modified with a carbonaceous material. The detection depends on the electrochemical oxidation reaction of NADH, which occurs at a potential where the components of the kit do not generate current signals even in the presence of a fermentation medium.[47] In addition, Piermarini *et al.* discussed a procedure for regulating the consumption of fructose and glucose in real time.[4] However, the drawback of this technique is that it needs construction of a biosensor, which uses glucose oxidase as a bio-receptor. Impedance spectroscopy has also been employed to monitor the growth of yeast cell online.[48] In line with this, Perez *et al.*[49] discussed a method, which could measure changes in the resistance of yeast cells for real-time monitoring of fermentation by measuring the CO_2 produced during the procedure. The major drawback of this method is that it is an offline method, which means that it is mandatory to extract the medium from the fermentation tank. Additionally, this method needs temperature compensation as the temperature is uncontrollable during the assay. The time of measurements of the experiments conducted by Perez and co-workers was 200 h, which allowed the production of yeast by fermentation. They measured relatively high frequency in the medium resistance (Rm), which increases the signal-to-noise ratio. In addition, Zamora *et al.*[50] proposed work to follow the sugar consumption in yeast. This procedure is based on the change in medium resistance (Rm), which is induced by bubbles of CO_2 produced during the process of fermentation. However, considering that approximately 90 min is the duplication time of *Saccharomyces cerevisiae* in rich medium,[51] 80 min, which is nearly closer to 90 min, is the duration of experiments conducted, which indicates that, in their assay, the yeast cells do not grow significantly.

The proposed potentiostat allows overcoming the previously explained issues of the systems reported in the literature. The aim of this research work is a wireless, low-cost, multichannel potentiostat for continuous electrochemical analysis performance for long time using potentiodynamic electrochemical methods (chronoamperometric technique or cyclic voltammetry technique). Moreover, Bluetooth connection is used in replacement of RS-232 connection for data transfer for wireless communication. Additionally, the proposed design is portable and battery operated, and it can transfer data wirelessly up to 100 m providing comparable accuracy with those reported in the literature for this type of application.

II. POTENTIOSTAT DESIGN

The proposed multielectrode potentiostat is based on a classic three-electrode arrangement (Fig. 1). These three electrodes in a potentiostat are labeled working electrode (WE), reference electrode (RE), and counter electrode (CE).[52,53] Figure 1 shows a schematic representation of the voltammetric method of potentiostat, where Rf is used as a gain control resistance for current to voltage converter, and OP1 represents a control amplifier.

Figure 2 shows the block diagram representation of the proposed system. The system is divided into three major parts: (1) biosensors, (2) potentiostat unit, and (3) data acquisition unit. In order to make the system portable and to be able to place it inside the incubator, a USB-powered solution was implemented, which not only removes the use of additional circuitry used for battery charging but also minimizes the effect of noise generated because of the buck and boost circuits.

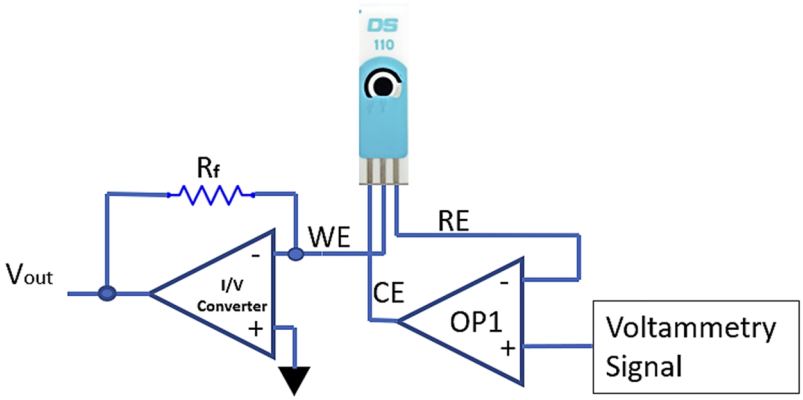


FIG. 1. Schematic representation of the potentiostat.

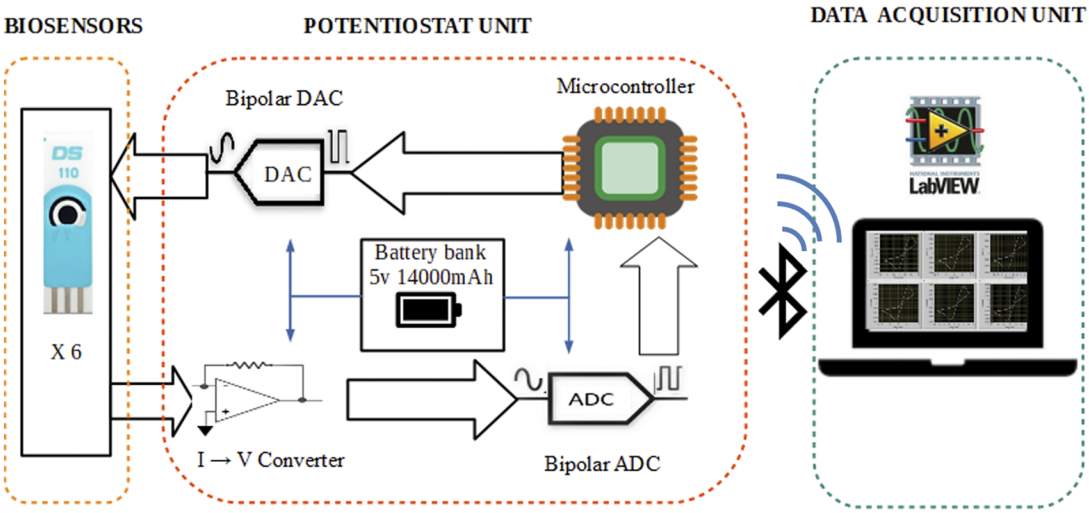


FIG. 2. Block diagram of the multichannel potentiostat.

A. Biosensor

The proposed system is capable of interfacing with most of the screen-printed biosensors in standard of 3-electrode configuration. The biosensors can be clamped directly to the potentiostat by means of an amphenol functional configuration identification Framatome Connectors International (FCI) clincher connector, and therefore, no soldering process is required. Furthermore, this solution permits us to reduce the noise generated by cables used to connect the sensors. In this research, two different commercial biosensors, (1) DS110 and (2) GLU10, both from DropSens have been connected and used without highlighting any problems.

B. Potentiostat unit

The system uses ATmega 2560 as a core microcontroller, controlling all the functionality of the potentiostat. The microcontroller is an 8-bit AVR device with high-performance and low-power requirement, and it operates with the supply voltage of 4.5–5.5 V. The microcontroller is responsible for operating DAC (Digital to Analog Converter), bipolar ADC (Analog to Digital Converter), and Bluetooth for communicating with LabVIEW. The opamps used for are TLC2264 (Texas instrument) in dual power supply mode; they have a low offset voltage, typically 950 μV Max at 25 °C and low input bias current typically 1 pA, and also the output current of opamp is ±50 mA, making it a great choice for interfacing with ADC and used to design the potentiostat circuit. The opamp used for I–V was LF356N from Texas instrument, powered with dual power supply with adjustable gain. This opamp has input noise of 12 nV/$\sqrt{}$Hz and input current noise of 0.01 pA/$\sqrt{}$Hz. It offers a low input bias current (30 pA) with low offset current (3 pA), it also has a high input impedance (1×10^{12} Ω) with high CMRR (100 dB), and the IC has a fast settling time (1.5 μs) with a slew rate of (12 V/μs) making it the best choice for current to voltage converter.

Figure 3 shows the printed circuit board (PCB) layout of the multichannel potentiostat system, where each portion of circuit is represented separately. The DAC integrated in the potentiostat as the main signal generator unit is AD5752, commercialized by

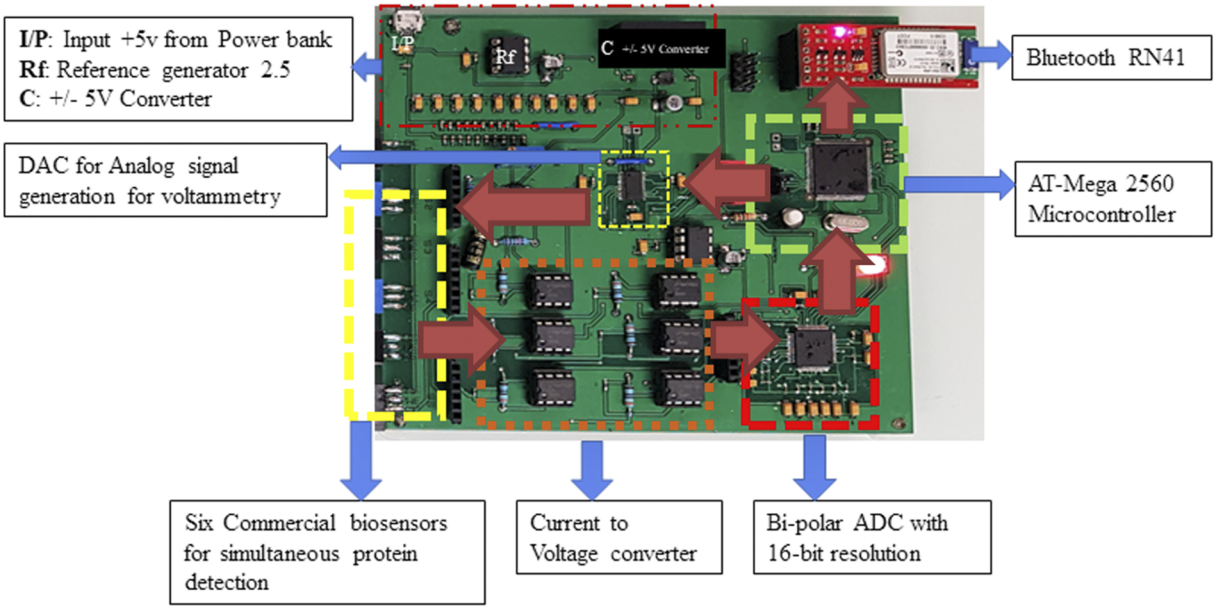


FIG. 3. PCB system layout of the multichannel potentiostat. Red arrows show the direction of data flow.

Analog Devices. This DAC is 16 bit with dual supply; it has an output range of ±5 V with integrated reference buffer and a maximum settling time of 10 μs. The DAC can be programmed by LabVIEW interface to generate an output ramp voltage with the scan rate range defined by the user. The output generated by DAC leads to the redox reaction on the biosensors, and the output currents can be measured through six independent current to voltage converter channels by means of six LF356N ICs. The voltage generated by

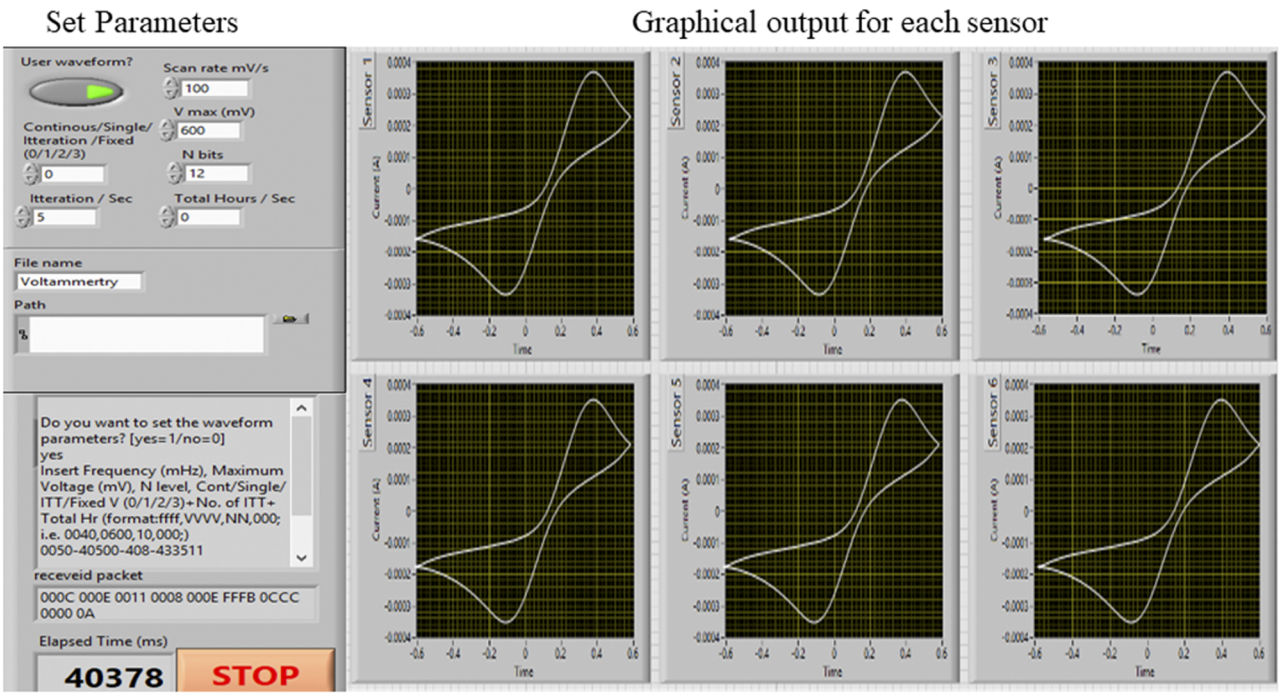


FIG. 4. LabVIEW data acquisition platform.

I–V is bipolar, and therefore, a bipolar ADC is used (AD7656); this ADC has six independent bipolar channels with 16 bit resolution and throughput rates up to 250 kbps, and the selection of ADC was thoroughly carried out by considering the requirement of the current study, which is to independently read all six analog channels at a higher speed (250 kbps) with a higher bit rate (16 bits) and using the selection criteria evaluated in the previous study.[53] The microcontroller controls the data conversion from ADC and simultaneously transfers the received data to the readout unit via Bluetooth. The compact system can perform simultaneous cyclic voltammetry on all six channels and transfer the data to the data acquisition platform in real time. The selection criteria of each component are thoroughly evaluated and explained in greater detail in our pre-requisite study.[53]

C. Data acquisition unit

The portable system uses Bluetooth RN41 from Microchip Technology, which serves as a main communication platform, where real-time data are transmitted over the range of up to 100 m to the receiving unit. The data baud rate of the RN41 Bluetooth module is 115 200, and the data transfer rate is 300 kbps. The receiver unit is equipped with the LabVIEW data acquisition platform. LabVIEW receives the data from Bluetooth in HEX format for all the channels in a single stream, which are further separated and converted back into current data generated by each biosensor; LabVIEW also records and plots the current to voltage graph of each channel. Figure 4 shows the front panel of the LabVIEW data acquisition platform during the experimental session.

III. OPERATION ANALYSIS

To validate the operations of this multichannel, portable potentiostat system, several tests were performed using fixed resistance (3.5 kΩ) and fixed supply voltage to obtain quantitative results related the current detection limits and noise of the system. These tests also validated the accuracy over time and response time. A constant voltage of 0.6 V, which is the operating range of our cyclic voltammetry, was applied for 120 s to six fixed resistances representing the sensors, and the currents were measured through the readout unit simultaneously. Figure 5(a) shows the comparison results between the actual resistance and the measured resistance, which shows 99% significance among the values with the maximum standard deviation of 2.7%.

Another test was carried out measuring the current on a fixed resistance (3.5 kΩ) with a constant applied voltage (0.5 V) over a period of 1 h. The experimental results showed no drift and a standard deviation of about 0.053 kΩ. The experimental results of these two tests demonstrate that the system is able to correctly measure currents through resistance values, which are within the limits of sensor chip resistance (0.34–6 kΩ), with an accuracy of about 99%. Furthermore, in Fig. 5(b), the signal to noise ratio, when tested in the operating frequency range of the system (10 mHz to 50 Hz), is reported. The tests showed a signal to noise ratio between 180 dB and 145 dB, which have been computed using TINA software regardless of the input sensor chip [Fig. 5(b)]. These tests also gave information about the current detection limits of the system, which is of about 180 nA.

A. Electrochemical measurements: Cyclic voltammetry and chronoamperometry

Figure 6 shows the cyclic voltammetric studies carried out on the proposed potentiostat when compared with a commercial potentiostat (Palmsens3, commercialized by Palmsens BV) using potassium ferrocyanide solution as a redox reference solution. To compare the results of cyclic voltammetry, both potentiostats were operated under the same conditions. DropSense sensors (DS-110) were used as electrodes, and each sensor was introduced with 50 μl of 100 mM potassium ferrocyanide solution at 50 mV/s in the potential range of −0.6 V to 0.6 V. Figure 6 shows the cyclic

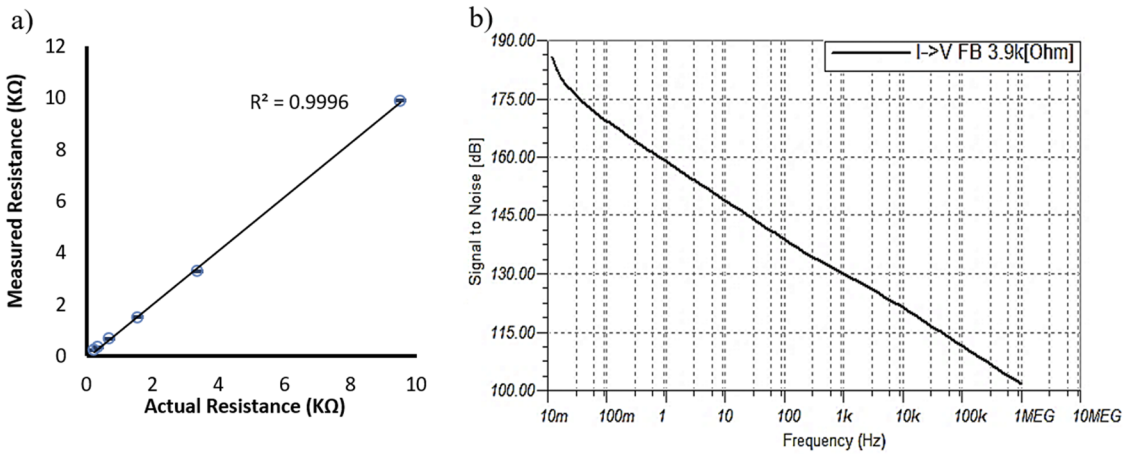


FIG. 5. (a) Testing of the multichannel potentiostat with simultaneous current measurement with different resistances at fixed voltage and (b) signal to noise ratio of the I/V converter with a FB (feedback) resistance of 3.9 kΩ.

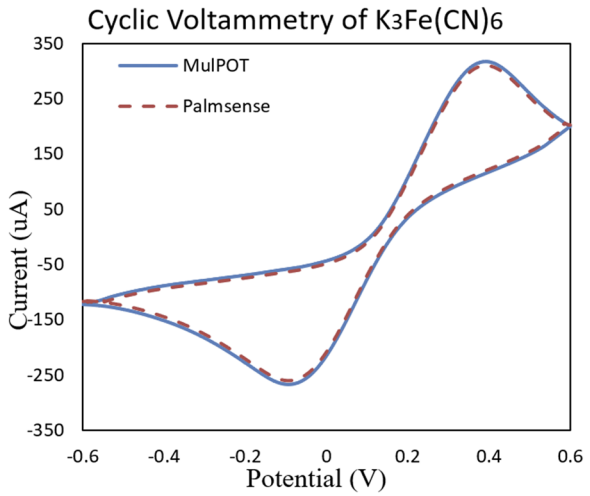


FIG. 6. Cyclic voltammetry comparison of the portable and Palmsens potentiostats. MulPOT (blue) shows the cyclic voltammetry of $K_3Fe(CN)_6$ on the multichannel portable potentiostat, whereas Palmsens (orange) shows the cyclic voltammetry of $K_3Fe(CN)_6$ on the Palmsens potentiostat.

voltammetry results of the proposed potentiostat and Palmsens potentiostat. To avoid variations in voltammetry results, the third cycle of cyclic voltammetry results is reported for both platforms. The anodic and cathodic peak current for the Palmsens system is 174 μA and 155 μA, whereas the anodic and cathodic peak current for the proposed system is 176 μA and 157 μA, showing the overall deviation of 2 μA.

To further investigate the operating performance of the proposed potentiostat, 50 μl of 5 mM ferrocyanide electrolytic solution was used on DropSense (DS-110) sensors, and the cyclic voltammetry results (third cycle) were recorded when a voltammetry input of different scan rates was applied on the solution. Figure 7 shows the cyclic voltammetry results of ferrocyanide solution obtained at different scan rates (16 mV/s, 40 mV/s, 150 mV/s, 200 mV/s, and 250 mV/s). The inset of Fig. 7 shows the linearity of the anodic peak current, which increases with increase of scan rates with 99% significance and an overall standard deviation of 1.75% for all the scan rates.

In order to investigate further the performance of the proposed potentiostat, tests on chronoamperometric quantification of different concentrations of glucose (25–500 mM) were conducted simultaneously on six different electrodes. Distilled water is used as reference/blank. A 50 μl solution was dropped directly on the sensor, and so no stirring is required during the test. In these tests, DropSens screen-printed electrodes modified with enzyme glucose oxidase (GLU10) were used with a fixed potential of 0.1 V, which is similar to the potential proposed in the sensor (GLU10) data sheet applied on the counter electrode. Figure 8 shows that the stationary current was obtained after 50 s of the applied signal as reported in the literature. Each point in the graph is an average of 100 stationary current points. The log of the current in chronoamperometric is plotted for precise and better understanding of the current behavior. No passivation or fouling was observed. The results confirm that the current is a function of increasing glucose concentration governed by the Cottrell equation,[54] $Current = 0.0042^{*}(Glucose\ Conc.) + 1.9735$ with $R^2 = 0.9819$ showing 98% significance and an overall standard deviation of 2% of the obtained current against the glucose concentration with 0.71 μM of limit of detection.

IV. CASE STUDY: MONITORING GLUCOSE CONCENTRATION DURING FERMENTATION PROCESS

To measure the glucose concentration during the fermentation process for a long time without altering the temperature of the experiment, a lab-based study was conducted in an incubator using the proposed potentiostat. In these tests, screen-printed sensors containing glucose oxidase as enzyme were used to react with glucose molecules.

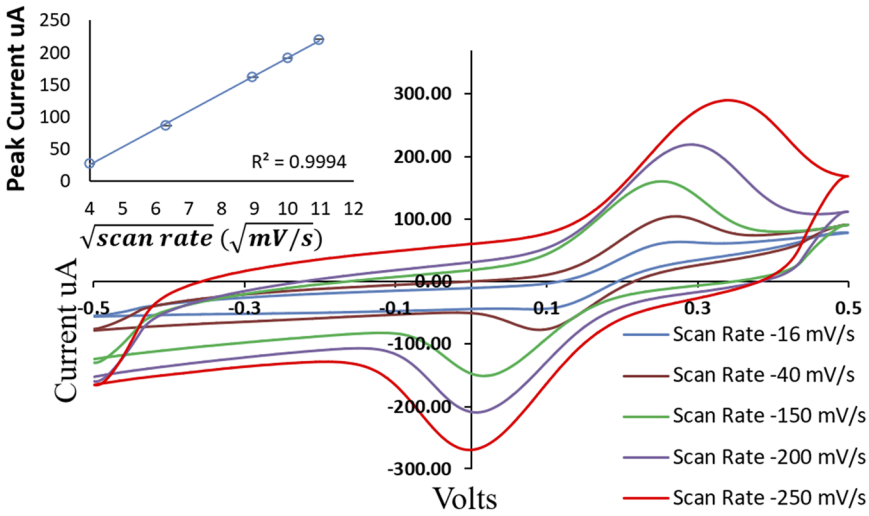


FIG. 7. Cyclic voltammogram of 5 mM ferricyanide at different scan rates. The inset shows the theoretically expected linear relationship of peak current and square root of scan rate.

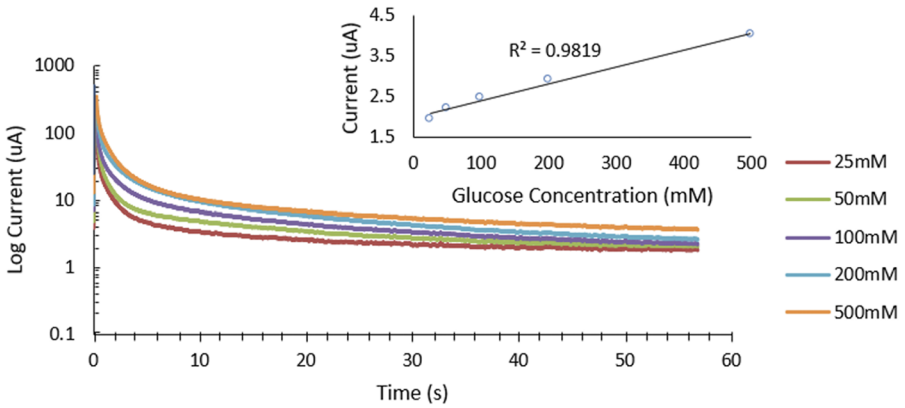


FIG. 8. Analysis of glucose concentration over time with a constant applied voltage of 0.1 V.

A. Materials and methods

Disposable screen-printed electrodes modified with the enzyme glucose oxidase (ref. GLU10) intended for the determination of glucose in liquid samples were used. Each electrode was extended to the sensor chip by a standard size male to female metal (silver) connector to which an Amphenol FCI clincher connector is attached. Seven solutions were prepared, out of which one was the control solution. Six different solutions were prepared with different concentrations of yeast inside each solution. The total volume of each solution is 6 ml containing 2 ml of glucose (500 mM concentration) and 4 ml, 3 ml, 2 ml, 1 ml, 0.5 ml, and 0.1 ml of yeast (commercially available yeast used for alcohol fermentation), and distilled water having w/v % = 50 g/100 ml, whereas the control solution contains 2 ml of glucose (500 mM) and distilled water with a total volume of 6 ml. This glucose oxidase enzyme reacts with glucose molecules resulting in generation of electrolytes, which then reacts with potassium ferrocyanide, i.e., the first layer of sensor resulting in generation of current equivalent to the concentration of glucose.

Since the multichannel potentiostat supports six channels for simultaneous monitoring of the solution, the experiment was conducted in two phases, the first phase had four solutions with yeast concentrations of 4 ml, 3 ml, 2 ml, and control solution, and the second phase also had four solutions with yeast concentrations of 1 ml, 0.5 ml, 0.1 ml, and control solution. Figure 9 shows the experimental setup, where a Panasonic incubator (MCO-170AIC-PE) was used with a set temperature of 28 °C, each test tube was mounted horizontally on the shaker bed (IKA-VIBRAX-VX9) with 250 rpm, and the glucose sensor was mounted through the cap of the test tube and thoroughly sealed. The whole system was placed inside the

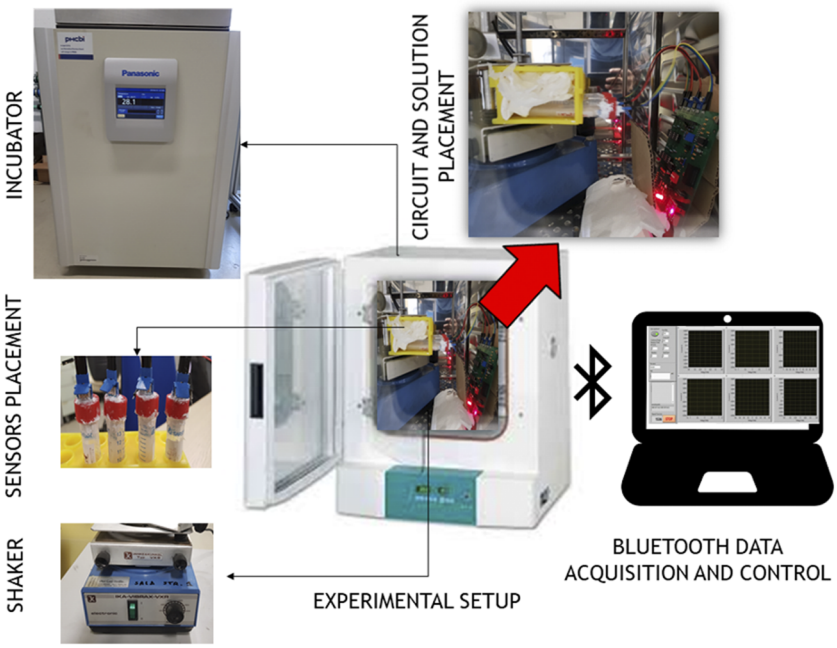


FIG. 9. Experimental setup, which contains an incubator, setup of test tubes, shaker bed with test tubes fixed on it, and LabVIEW environment for wireless data monitoring and control of the potentiostat system.

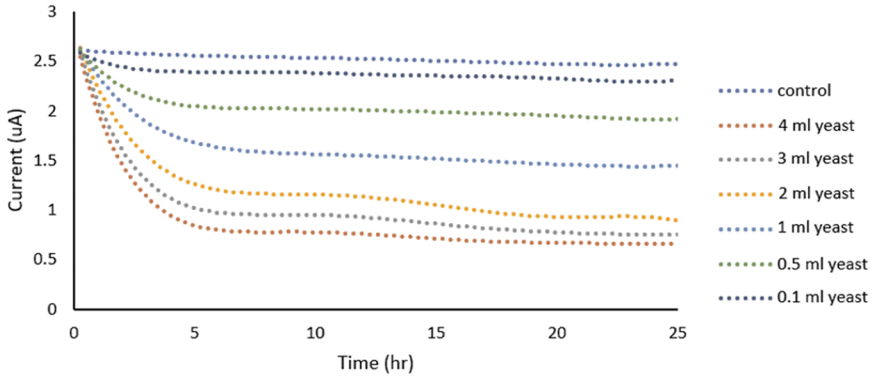


FIG. 10. Measurement of the glucose concentration over time during fermentation of yeast.

incubator along with the incubator circuit equipped with long range Bluetooth and high capacity battery bank (14 000 mA h) to power the circuit for more than 30 h on a continuous cyclic voltammetry assessment.

B. Measurement of glucose concentration over time

The goal of the designed device is to operate autonomously with wireless data transmission for a period of 24 h. Therefore, the test regarding the monitoring of the fermentation process aiming at verifying the capability to operate autonomously with wireless data transmission for a period of 24 h. In this regard, the current study monitors the glucose concentration via chronoamperometry, which has been adopted as a preferred method for glucose concentration monitoring as reported in prior studies.[55–57] Figure 10 shows the results obtained during the period of 25 h of continuous monitoring. The electrodes were left untouched during the complete course of experiment, i.e., 25 h. The graph trends in Fig. 10 show the behavior of glucose concentration consumed by yeast over 25 h measured by chronoamperometry. Every measurement was carried out over a different electrode with continuous stirring for 25 h. In Fig. 10, an abrupt decreasing behavior of glucose concentration can be observed in the first 5 h, which is due to the increased growth of yeast under favorable conditions of temperature and glucose. For the remaining 20 h, the graph trends show low growth rates and almost linear behavior. According to the experiment, 4 ml yeast solution shows a substantial decrease of 70 mM/h (0.348 μA/h) in the concentration of glucose during first 5 h, which gives the total growth rate of yeast as 0.251 ml/h. Similarly, for the remaining samples, growth rates are 0.235 ml/h, 0.192 ml/h, 0.132 ml/h, 0.0816 ml/h, and 0.019 ml/h for 3 ml, 2 ml, 1 ml, 0.5 ml, and 0.1 ml of yeast, respectively.

V. CONCLUSION

In this paper, we proposed a multichannel, portable potentiostat for biomolecule detection, capable of performing cyclic voltammetry and chronoamperometry for a long time. The proposed system can operate all six channels simultaneously, and it is capable of performing cyclic voltammetry and chronoamperometry in the range of ±5 V with variable scan rates ranging from 1 mV/s until 250 mV/s with the minimum current detection limit of ±180 nA. Furthermore, we successfully verified the performance of the proposed system by comparing the proposed potentiostat with a commercially available potentiostat. The comparison of the proposed device with the gold standard device has shown an accuracy above 98%. Furthermore, the system has therefore been tested in various operating situations, and all the experiments were carried out in triplets and have shown a standard deviation of less than 2%. Therefore, the experimental results show the performance and accuracy of the proposed potentiostat comparable to the commercial ones. In addition, the proposed potentiostat is a low-cost solution with high portability, and it has an advantage of interfacing multiple biosensors, with a large range of Bluetooth operability (100 m). The portable system has been used to effectively monitor the glucose concentration during the fermentation process for a long time under constant temperature conditions. The obtained results show the behavior of glucose concentration during the fermentation process demonstrating the feasibility of a multichannel analysis and remote monitoring for a long time.

ACKNOWLEDGMENTS

The authors have no conflict of interest.

REFERENCES

[1] M. Famulok, "Bringing picomolar protein detection into proximity," Nat. Biotechnol. **20**(5), 448–449 (2002).
[2] C. Loncaric, Y. Tang, C. Ho, M. A. Parameswaran, and H.-Z. Yu, "A USB-based electrochemical biosensor prototype for point-of-care diagnosis," Sens. Actuators, B **161**(1), 908–913 (2012).
[3] P. Giménez-Gómez, M. Gutiérrez-Capitán, F. Capdevila, A. Puig-Pujol, C. Fernández-Sánchez, and C. Jiménez-Jorquera, "Monitoring of malolactic fermentation in wine using an electrochemical bienzymatic biosensor for L-lactate with long term stability," Anal. Chim. Acta **905**, 126–133 (2016).
[4] S. Piermarini, G. Volpe, M. Esti, M. Simonetti, and G. Palleschi, "Real time monitoring of alcoholic fermentation with low-cost amperometric biosensors," Food Chem. **127**(2), 749–754 (2011).
[5] A. Hickling, "A simple potentiostat for general laboratory use," Electrochim. Acta **5**(3), 161–168 (1961).
[6] T. Fang, M. McGrath, D. Diamond, and M. R. Smyth, "Development of a computer controlled multichannel potentiostat for applications with flowing solution analysis," Anal. Chim. Acta **305**(1-3), 347–358 (1995).

[7]Y. Liu, A. Gore, S. Chakrabartty, and E. Alocilja, "A molecular bio-wire based multi-array biosensor with integrated potentiostat," in *IEEE Biomedical Circuits and Systems Conference Healthcare Technology, BiOCAS2007* (IEEE, 2007), pp. 29–32.
[8]I. Ramfos *et al.*, "A compact hybrid-multiplexed potentiostat for real-time electrochemical biosensing applications," Biosens. Bioelectron. **47**, 482–489 (2013).
[9]M. Naware, A. Rege, R. Genov, M. Stanacevic, G. Cauwenberghs, and N. Thakor, "Integrated multi-electrode fluidic nitric-oxide sensor and VLSI potentiostat array," in *2004 IEEE International Symposium on Circuits and Systems (IEEE Cat. No.04CH37512)* (IEEE, 2004), Vol. 4.
[10]R. Hintsche, J. Albers, H. Bernt, and A. Eder, "Multiplexing of microelectrode arrays in voltammetric measurements," Electroanalysis **12**(9), 660–665 (2000).
[11]T.-C. Tang, A. Deng, and H.-J. Huang, "Immunoassay with a microtiter plate incorporated multichannel electrochemical detection system," Anal. Chem. **74**(11), 2617–2621 (2002).
[12]R. S. Freire, M. M. C. Ferreira, N. Durán, and L. T. Kubota, "Dual amperometric biosensor device for analysis of binary mixtures of phenols by multivariate calibration using partial least squares," Anal. Chim. Acta **485**(2), 263–269 (2003).
[13]M. Vergani *et al.*, "Compact potentiostat for cellular electrochemical imaging with 54 parallel channels," in *2012 IEEE Biomedical Circuits and Systems Conference: Intelligent Biomedical Electronics and Systems for Better Life and Better Environment, BioCAS 2012-Conference Publications* (IEEE, 2012), pp. 136–139.
[14]K.-S. Sohn *et al.*, "A unified potentiostat for electrochemical glucose sensors," Trans. Electr. Electron. Mater. **14**(5), 273–277 (2013).
[15]E. Salman, M. H. Asgari, and M. Stanaćević, "Signal integrity analysis of a 2-D and 3-D integrated potentiostat for neurotransmitter sensing," in *2011 IEEE Biomedical Circuits and Systems Conference (BioCAS)* (IEEE, 2011), pp. 17–20.
[16]D. Quinton *et al.*, "On-chip multi-electrochemical sensor array platform for simultaneous screening of nitric oxide and peroxynitrite," Lab Chip **11**(7), 1342–1350 (2011).
[17]M. Mollazadeh, K. Murari, C. Sauer, M. Stanacevic, N. Thakor, and G. Cauwenberghs, "Wireless integrated voltametric and amperometric biosensing," in *2006 IEEE/NLM Life Science Systems and Applications Workshop, LiSA* (IEEE, 2006).
[18]A. Bandyopadhyay, G. Mulliken, G. Cauwenberghs, and N. Thakor, "VLSI potentiostat array for distributed electrochemical neural recording," in *2002 IEEE International Symposium on Circuits and Systems* (IEEE, 2002), Vol. 2, pp. 740–743.
[19]K. Murari, N. Thakor, M. Stanacevic, and G. Cauwenberghs, "Wide-range, picoampere-sensitivity multichannel VLSI potentiostat for neurotransmitter sensing," in *IEEE Engineering in Medicine and Biology Society Conference* (IEEE, 2004), Vol. 6, pp. 4063–4066.
[20]M. Stanacevic, K. Murari, A. Rege, G. Cauwenberghs, and N. V. Thakor, "VLSI potentiostat array with oversampling gain modulation for wide-range neurotransmitter sensing," IEEE Trans. Biomed. Circuits Syst. **1**(1), 63–72 (2007).
[21]K. Murari, C. Sauer, M. Stanacevic, G. Cauwenberghs, and N. Thakor, "Wireless multichannel integrated potentiostat for distributed neurotransmitter sensing," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (IEEE, 2005), Vol. 7, pp. 7329–7332.
[22]K. Murari, M. Stanaćević, G. Cauwenberghs, and N. V. Thakor, "Integrated potentiostat for neurotransmitter sensing: A high sensitivity, wide range VLSI design and chip," IEEE Eng. Med. Biol. Mag. **24**(6), 23–29 (2004).
[23]R. Genov, M. Stanacevic, M. Naware, G. Cauwenberghs, and N. V. Thakor, "16-channel integrated potentiostat for distributed neurochemical sensing," IEEE Trans. Circuits Syst. I **53**(11), 2371–2376 (2006).
[24]M. Stanacevic, M. Naware, G. Cauwenberghs, and N. Thakor, "VLSI multichannel track-and-hold potentiostat," Proc. SPIE **5119**, 117–128 (2003).
[25]A. Muid, M. Djamal, and R. Wirawan, "Development of a low cost potentiostat using ATXMEGA32," AIP Conf. Proc. **1589**, 124–128 (2014).
[26]T. Dobbelaere, P. M. Vereecken, and C. Detavernier, "A USB-controlled potentiostat/galvanostat for thin-film battery characterization," HardwareX **2**, 34–49 (2017).
[27]P. Wu, G. Vazquez, N. Mikstas, S. Krishnan, and U. Kim, "Aquasift: A low-cost, hand-held potentiostat for point-of-use electrochemical detection of contaminants in drinking water," in *GHTC 2017-IEEE Global Humanitarian Technology Conference* (IEEE, 2017), Vol. 2017, pp. 1–4.
[28]C.-Y. Huang, Y.-C. Wang, H.-C. Chen, and K.-C. Ho, "Design of a portable potentiostat for electrochemical sensors," in *Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference* (IEEE, 2004), pp. 331–336.
[29]M. D. Steinberg, P. Kassal, I. Kereković, and I. M. Steinberg, "A wireless potentiostat for mobile chemical sensing and biosensing," Talanta **143**, 178–183 (2015).
[30]S. D. Adams, E. H. Doeven, K. Quayle, and A. Z. Kouzani, "MiniStat: Development and evaluation of a mini-potentiostat for electrochemical measurements," IEEE Access **7**, 31903–31912 (2019).
[31]P. S. Joshi and D. S. Sutrave, "Building an arduino based potentiostat and instrumentation for cyclic voltammetry," J. Appl. Sci. Comput. **5**(12), 163–167 (2018).
[32]Y. C. Li *et al.*, "An easily fabricated low-cost potentiostat coupled with user-friendly software for introducing students to electrochemical reactions and electroanalytical techniques," J. Chem. Educ. **95**, 1658–1661 (2018).
[33]C.-Y. Huang, "Design and implementation of potentiostat with standalone signal generator for vanillylmandelic acid biosensors," Sensors Mater. **29**(6), 619–628 (2017).
[34]J. Punter-Villagrasa *et al.*, "A low-power electronic instrumentation for multiparametric diabetes mellitus analysis," in *42nd Annual Conference of the IEEE Industrial Electronics Society* (IEEE, 2016), pp. 5211–5215.
[35]R. Kumar, J. Sharma, and R. Singh, "Production of tannase from *Aspergillus ruber* under solid-state fermentation using jamun (*Syzygium cumini*) leaves," Microbiol. Res. **162**(4), 384–390 (2007).
[36]*Wine Chemistry and Biochemistry*, edited by M. V. Moreno-Arribas and M. C. Polo (Springer, New York, NY, 2009).
[37]F. Badotti *et al.*, "Switching the mode of sucrose utilization by *Saccharomyces cerevisiae*," Microb. Cell Fact. **7**(1), 4 (2008).
[38]M. Florescu and C. M. A. brett, "Development and evaluation of electrochemical glucose enzyme biosensors based on carbon film electrodes," Talanta **65**, 306–312 (2005).
[39]M. Esti, V. Giulia, D. Compagnone, G. Mariotti, D. Moscone, and G. Palleschi, "Monitoring alcoholic fermentation of red wine by electrochemical biosensors," Am. J. Enol. Vitic. **54**(1), 39–45 (2003).
[40]J. Zosel, W. Oelßner, M. Decker, G. Gerlach, and U. Guth, "The measurement of dissolved and gaseous carbon dioxide concentration," Meas. Sci. Technol. **22**(7), 072001 (2011).
[41]F. Jimenez, J. Vazquez, J. L. Sanchez-Rojas, N. Barrajon, and J. Ubeda, "Multi-purpose optoelectronic instrument for monitoring the alcoholic fermentation of wine," in *2011 IEEE Sensors Proceedings* (IEEE, 2011), pp. 390–393.
[42]E. M. Avdikos, M. I. Prodromidis, and C. E. Efstathiou, "Construction and analytical applications of a palm-sized microcontroller-based amperometric analyzer," Sens. Actuators, B **107**(1), 372–378 (2005).
[43]J. R. Blanco *et al.*, "Design of a low-cost portable potentiostat for amperometric biosensors," in *IEEE Instrumentation and Measurement Technology Conference* (IEEE, 2006), pp. 690–694.
[44]D. Desmond, B. Lane, J. C. Alderman, M. Hill, D. W. M. Arrigan, and J. D. Glennon, "An environmental monitoring system for trace metals using stripping voltammetry," Sens. Actuators, B **48**(1-3), 409–414 (1998).
[45]M. D. Steinberg, "A micropower amperometric potentiostat," Sens. Actuators, B **97**(2-3), 284–289 (2004).
[46]A. Economou, S. D. Bolis, C. E. Efstathiou, and G. J. Volikakis, "A "virtual" electroanalytical instrument for square wave voltammetry," Anal. Chim. Acta **467**(1-2), 179–188 (2002).
[47]I. Acevedo-Restrepo, L. Blandón-Naranjo, J. Hoyos-Arbeláez, F. Della Pelle, and M. Vázquez, "Electrochemical glucose quantification as a strategy for ethanolic fermentation monitoring," Chemosensors **7**(1), 14 (2019).
[48]A. Soley *et al.*, "On-line monitoring of yeast cell growth by impedance spectroscopy," J. Biotechnol. **118**(4), 398–405 (2005).

[49]M. A. Pérez *et al.*, "Impedance spectrometry for monitoring alcoholic fermentation kinetics under wine-making industrial conditions," in *XIX IMEKO World Congress Fundamental and Applied Metrology, September 6-11, 2009, Lisbon, Portugal* (IMEKO, 2009), Vol. 4, pp. 2508–2512.
[50]M. L. Zamora, G. A. Ruiz, and C. J. Felice, "Evaluation of sugar yeast consumption by measuring electrical medium resistance," J. Electr. Bioimpedance **4**(1), 51–56 (2013).
[51]L. W. Bergman, "Growth and maintenance of yeast," in *Two-Hybrid Systems* (Humana Press, New Jersey, 2001), pp. 009–014.
[52]A. B. Islam *et al.*, "A potentiostat circuit for multiple implantable electrochemical sensors," in *ICECE 2010-6th International Conference on Electrical and Computer Engineering* (IEEE, 2010), pp. 314–317.
[53]S. Abdullah, S. Tonello, M. Borghetti, E. Sardini, and M. Serpelloni, "Potentiostats for protein biosensing: Design considerations and analysis on measurement characteristics," J. Sensors **2019**, 1–20.
[54]J. Wang, *Analytical Electrochemistry* (Wiley-VCH, 2006).
[55]E.-H. Yoo and S.-Y. Lee, "Glucose biosensors: An overview of use in clinical practice," Sensors **10**(5), 4558–4576 (2010).
[56]M. Artigues, J. Abellà, and S. Colominas, "Analytical parameters of an amperometric glucose biosensor for fast analysis in food samples," Sensors **17**(11), 2620 (2017).
[57]P. Krzyczmonik, E. Socha, and S. Skrzypek, "Electrochemical detection of glucose in beverage samples using Poly(3,4-ethylenedioxythiophene)-modified electrodes with immobilized glucose oxidase," Electrocatalysis **9**(3), 380–387 (2018).