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Towards the development of low-cost implantable sensors using open source and accessible fabrication equipment for pH sensing and IoT applications †

Antonio Ruiz-Gonzalez [1], Harriet Kempson [1] and Jim Haseloff [1,*]

[1] Department of Plant Sciences, University of Cambridge, Downing St., Cambridge, CB2 3EA
* Correspondence: jh295@cam.ac.uk;
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Abstract: The determination of optimal growth conditions for crops is crucial to avoid losses in agricultural production due to preventable factors. In particular, the design of implantable sensors represents a promising technology to enable the in-situ evaluation of key environmental conditions. However, current developments in the field require expensive equipment, either for the fabrication of sensors, or measurement processes, limiting their applications within real-world environments. This work presents for the first time a low-cost and accessible approach for the fabrication of miniaturised pH sensors, that can be fabricated using open-source and low-cost equipment. This device was developed by electrodepositing Ruthenium oxide nanoparticles onto thin copper films using a microcontroller-based potentiostat (>£50). A cellulose-based coating was then incorporated by an aerosol-based method, developed using off-the-shelf low-cost devices. The combination of these two low-cost deposition methods allowed the fabrication of nanometrically thick pH sensors. The final setup combined the pH sensing layer of ruthenium oxide and cellulose, with a microcontroller that could send the collected data wirelessly to online servers for Internet of Things applications. A proof-of-concept device was implanted inside a tomato plant, including multiple environmental sensors, and the changes in pH inside the stem could be measured continuously. These results represent a step forward towards the practical application of implantable sensors in crop production, offering a plethora of applications in smart farming and plant research within low-resource settings.

Keywords: pH sensor; precision agriculture; metal oxide.

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1. Introduction

The development of precision agricultural methods has become an essential field to address current challenges in food security. This technology has the potential to tackle the 70% increase in agricultural production needed to mitigate the demands of the growing population by 2050 [1, 2]. To achieve a high-quality monitoring, precision agriculture requires from the use of sensors that can provide information about crop health [3, 4], ideally at an individualised level [2]. However, the field of implantable sensors in crops have been dominated by spectral imaging techniques, often requiring the pre-implantation of nanomaterials such as carbon nanotubes, and determining the changes in fluorescence [5]. However, in most cases, these sensors are limited to the detection of simple reactive oxygen species (ROS), such as H_2O_2, or nitroaromatics [6], and require expensive optical equipment for the imaging of the implanted nanoparticles, hindering their application within real-world environments.

Electrochemical technologies for the monitoring of internal analytes in plants has been proven to be a promising alternative for the low-cost fabrication of implanted sensors, that can continuously monitor biomarkers. These methods could be used for a wide

range of analytes and applications, including the monitoring of hormone fluxes in roots through the use of carbon nanotube-based self-referenced microelectrodes [7]. Recently, a monitoring of the relative concentrations of certain leaf biomarkers such as glucose and fructose have been made possible through the incorporation of transistor-based devices [8]. This sensor evidenced for the first time an increase in fructose concentrations during the night-time. However, the determination of single ions such as H+ still represents a challenge in the field of implanted sensors in plants, due to the scarcity of suitable materials for their determination.

Within the present work, an implanted pH sensor based on ruthenium oxide nanoparticles has been developed. Thin RuO_x films were initially fabricated by a custom-made potentiostat device, involving a microcontroller and two operational amplifiers (>£50). The fabrication results were compared to the ones obtained using a laboratory-standard equipment (Metrohm, Autolab). To improve the stability of the films, and enable the monitoring of xylem pH in vivo, a cellulose:elastomer film was additionally incorporated onto the RuO_x electrodes. This layer was deposited by using an aerosol-based method, that incorporated off-the-shelf components, and allowed a control over the film dimensions within the nanometre range. Finally, the devices were tested implanted inside a 4-week-old tomato plant, and the results, along with the temperature, humidity and Volatile Organic Compounds (VOC) data collected by an environmental sensor, were wirelessly reported to an online server to simplify the data collection process.

2. Materials and methods

2.1. Materials

Reagents were purchased from Sigma Aldrich unless otherwise specified; Ruthenium (III) chloride, ethyl cellulose, conductive silver ink, and iron (III) chloride. All pH buffer solutions were purchased from Fisher Scientific (Fisher scientific Ltd, UK). Sylgard 184 silicone elastomer kit was purchased from Dow. A Wio Terminal microcontroller was purchased from Seeed Studio, MCP4725 and BME680 were purchased from pimoroni. Arduino pH-4502C pH meter was purchased from Morden Store. Finally, LM324 Operational amplifier was purchased from Texas Instruments.

2.2. Assembly of Low-cost potentiostat

The pH sensing electrodes were fabricated by electrodeposition, using a custom-made and low-cost potentiostat. This potentiostat was assembled by following reported circuits within the literature [21-23]. Briefly, a LM324 Op amp was used combined with a MCP4725 Digital-to-Analog converter (DAC), that allowed the user to set a specific voltage output. This MCP4725 was connected to the non-inversing input of an Op Amp, while the counter and reference electrodes were connected to output and inverting electrodes respectively. On a different Op Amp, the working electrode was connected to the inverting input, and a current-to-voltage converter circuit was designed by a closed-loop configuration, using a 15 kOhm between the inverting input and the output. This circuit was connected to the analog pin of a Wio Terminal microcontroller, which could be used to set the potentiostat parameters by the user. This circuit has been schematised on Figure A.1.

2.3. Electrodeposition and characterisation of Ruthenium oxide films

Within the present work, a thin RuO_x film was used for the pH sensing. Thin RuO_x films were fabricated onto copper electrodes by using electrodeposition as reported elsewhere [12]. Briefly, copper electrodes were immersed onto a solution containing 0.1 M Ru, and an increasing voltage was applied. This electrodeposition process was conducted initially by using a benchmark laboratory equipment (Metrohm, Autolab BV, The

Netherlands) employing a Ag/AgCl reference and a platinum film as counter electrodes. A voltage comprised between 0 – 0.8 V was applied at a rate of 10 mV/s, and the current was measured to make a Cyclic voltammogram. The cyclic voltammetry process was repeated 10 times to develop the metal oxide films. This deposition method was replicated using our custom-made potentiostat, applying the same conditions in the case of the benchmark laboratory equipment, and the analog response recorded by the microcontroller was recorded.

After the fabrication of RuOx, the films were visualised by scanning electron microscopy (EVO LS15, ZEISS, Jena, Germany), using an acceleration voltage of 20 kV. This method allowed the characterisation of the surface structure of the sensing films. The morphology of RuOx films fabricated by standardised laboratory equipment and our custom-made potentiostat under abovementioned conditions were then compared. The chemical structure of the RuO_x sensing film was additionally studied by using FTIR (L160000A Perkin Elmer, Waltham, MA, USA). This method allowed the determination of the presence of the stretches corresponding to the Ru-O bonds, and presence of surface hydroxyl groups that are necessary for the sensing. In this case, the transmittance of the deposited films was measured between 400-4000 cm^{-1} using an ATR configuration. Finally, the sensing performance of the developed devices in terms of sensitivity and electrochemical noise was determined by calibrating the electrodes using multiple pH buffers ranging from 4-11. In this case, a Ag/AgCl reference electrode was designed by coating a copper electrode with silver paint. This silver paint was further oxidised by leaving the electrodes in contact with a 0.1 M solution of FeCl3 for 1 min.

2.4. Incorporation of cellulose-based thin films

To improve the performance of the sensing films, a cellulose:PDMS film was deposited onto the RuO_x film. This deposition was carried out by using a custom-made aerosol deposition method. The deposition system consisted of an ultrasonic atomiser operating at a frequency of 110 kHz, and a low-cost air pump. A solution containing 40 mg cellulose and 60 mg PDMS diluted in 10 mL ethyl acetate was then aerolised and directed towards the desired substrate. Initially, the thickness obtained by this method was characterised by fabricating films using different deposition times. To do so, the films were deposited onto glass substrates, and the obtained thicknesses were determined by using a stylus profilometer (Dektakxt, Bruker, UK).

The final devices, containing the RuO_x films fabricated by our custom-made potentiostat onto the copper electrodes, were modified by deposition of 80 nm thin films. The sensitivity of these sensors was characterised by subjecting the electrodes to different pH buffers, and the voltage was monitored.

2.5. In vivo testing of electrodes

To test the feasibility of the devices within an in vivo environment, the sensing devices were implanted inside 4-week-old tomato plants (Moneymaker variety). Sensing devices containing the electrodeposited RuO_x sensing films and Ag/AgCl reference electrodes were fabricated using the low-cost potentiostat reported here. Initially, electrodes where no cellulose-based film had been incorporated were tested, and the voltage was monitored for 5 hours. This experiment was conducted using a Wio Terminal device as the microcontroller, enabling the wireless reporting of results to Adafruit IO server. Devices containing both the RuO_x and the cellulose-based coating were also produced and tested. In this case, the sensors were also implanted in 4-week-old tomato plants, and the voltage was monitored using a Wio Terminal device. In addition, a BME680

environmental sensor was incorporated to prove additional information about the environmental conditions of the plant.

3. 3. Results and discussion

3.1. Deposition of pH sensing films

One of the key steps in the fabrication of the pH sensors is the deposition of a sensitive film. Within this work, ruthenium oxide was employed as the active layer, given its ability to reversibly reduce the surface RuO_2 using H^+ groups according to the formula below [13]:

$$RuO_2 \cdot H_2O + H^+ + e^- \rightarrow H_2O + Ru(OH)_3$$

The RuO_2 sensing films were deposited by electrodeposition, using a copper substrate as the working electrode, a Ag/AgCl reference and a carbon-based counter. In this case, a voltage comprised between 0-0.8 V was applied at a rate of 100 mV/s, and the resulting current was determined. Up to 10 cycles were applied, and the results using a standardised laboratory equipment (AUTOLAB, Metrohm), and low-cost potentiostat device reported here were compared (Figure 1.a. and Figure 1.b.).

To test the initial sensitivity of the films after deposition using the lab-proof potentiostat, a two-electrode cell was prepared, by coating a copper electrode using a silver ink, and oxidising it by using $FeCl_3$ for 1 min. The full device was immersed in different pH buffers, and the voltage of the cells was recorded (Figure 1.c. and Figure 1.d.). In the case of the low-cost Arduino device calibration, an off-the-shelf device was employed for the voltage measurements.

When the sensing devices were characterised using laboratory equipment, a Nernst sensitivity of 53.7 mV/pH was achieved. This value demonstrated the suitability of our potentiostat in the fabrication of pH-sensitive electrodes. When the Arduino-based device was employed instead, a good linearity was observed within the measured pH range ($R^2 = 0.987$), with a sensitivity of 30.4 Points/pH. This performance allowed an accurate determination of the pH of solutions within biological environments.

The low-cost approach described within the present work for the fabrication of the sensing films comprised a Wio Terminal device, that allowed a control of the components involved, and an interactive interface for the selection of the desired voltage range and speed by the user. This system could be complemented with multiple environmental sensors of interest such as the BME680 for temperature, humidity and gas measurements, and could additionally analyse the results in real-time. The whole circuit was enclosed within a plastic embodiment, and the three electrode cells were connected to the potentiostat (Figure 1.e. and Figure 1.f.). A schematical representation of the device circuit is shown in Figure A.1. In addition, the necessary codes have been made available on XOD.io, for object-oriented programming (Figure A.2.).

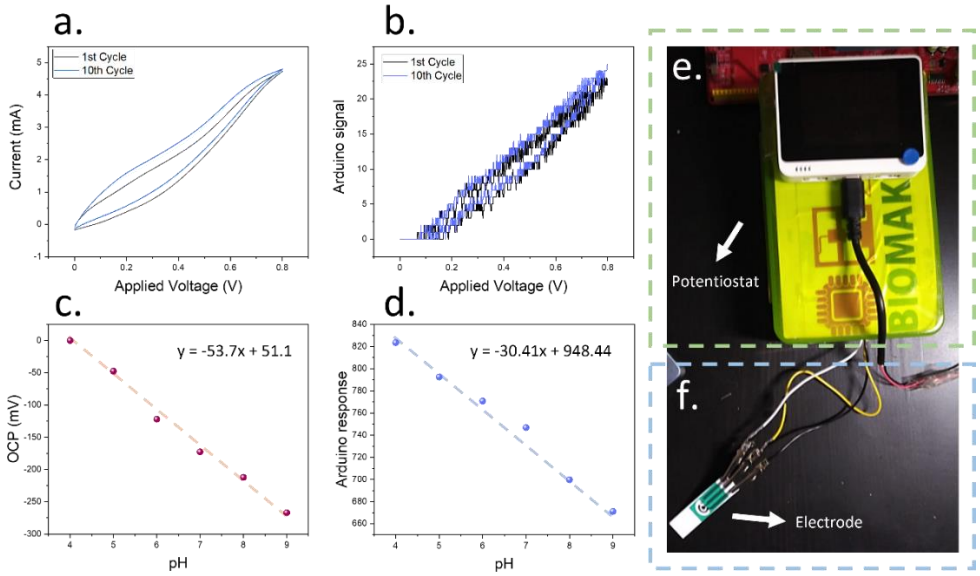

Figure 1. a. Cyclic voltammogram obtained during the electrodeposition of ruthenium oxide films onto copper electrodes using laboratory equipment. The differences between the first and tenth cycles are shown. **b.** Comparison using a cyclic voltammogram obtained using the low-cost potentiostat reported in the present work. **c.** Calibration plot of the ruthenium oxide sensing films obtained using the low-cost Arduino device reported here using laboratory equipment. The obtained calibration plot is shown. **d.** Comparison of the calibration results using an off-the-shelf low-cost device. **e.** Embodiment of the low-cost potentiostat employing the Wio Terminal device for the fabrication of pH sensing films. **f.** This potentiostat could be connected to a three electrode cell incorporating a Ag/AgCl reference, a carbon-based counter and working electrodes.

Our results evidence that the Arduino devices reported in the present work could lead to similar results when compared to laboratory equipment. The RuO_x films showed a Nernst response when used in the presence of different pH buffers, and a good linearity was observed within the measured range (4-9). This performance will be advantageous for the development of implanted devices for plant monitoring. However, one of the limitations of the devices is the high noise rates achieved, being in the range of 0.16 mV/min, and 0.24 Point/min in the case of the Arduino-based devices. These noise rates could hinder the application of the sensors within biologically relevant environments. As such, a further modification using a cellulose-based coating will be conducted within the following sections to improve the performance of the sensors.

3.2. Characterisation of ruthenium oxide films

After the fabrication of RuO_x films through electrodeposition using laboratory-standard equipment and our low-cost microcontroller-based solution, the electrodes were characterised. Initially, the chemical composition was studied using FTIR. This method evidenced the presence of the Ru-OH stretches at 821 cm^{-1} [14] in both cases, which are essential for the sensing of H^+ [13]. In addition, the stretch corresponding to the peroxo groups was observed at 1014 cm^{-1} [15], along with the H2O stretches at 1600 cm^{-1} [16], and the ones from hydroxyl groups at 3400 cm^{-1} [17]. These stretches were also present within both laboratory- and Arduino-based samples, proving the suitability of the low-cost method for the fabrication of pH sensing films (Figure 2.a.).

The morphology of the final sensing films was additionally evaluated by using SEM. Initially, pristine copper electrodes prior the deposition of films were studied. In this case, a homogeneous surface was obtained, with no presence of nanoparticles (Figure 2.b.). After electrodeposition, a film of RuO_x nanoparticles was observed onto the copper

electrodes, evidencing the successful deposition of the sensing material (Figure 2.c.). Similar structures have been observed for the determination of pH changes in Lab-on-a-Chip devices [18], and water quality monitoring [19]. A similar morphology than the one obtained using laboratory equipment was observed in the case of low-cost electrodeposition with the Arduino-based potentiostat, showing the presence of nanoparticle film onto the surface of the copper-based electrodes (Figure 2.d.).

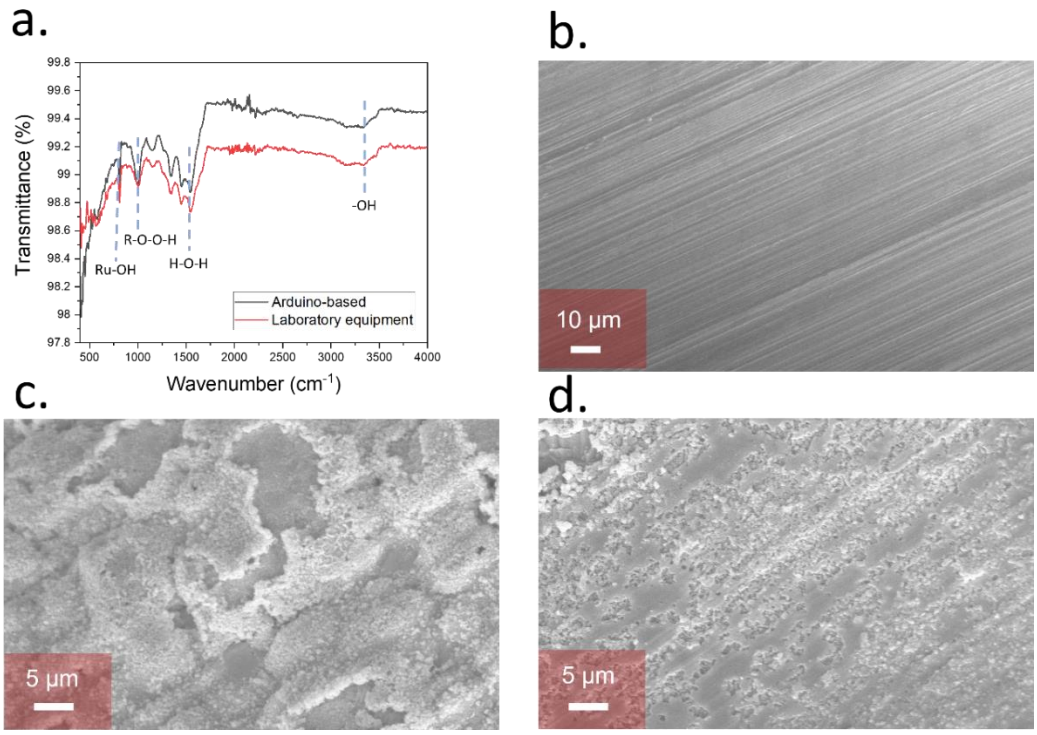

Figure 2. a. FTIR spectrum of the Ruthenium oxide films deposited onto the copper substrates and using laboratory equipment (red), and the arduino-based device reported in this work (black). The main stretches that indicate the successful deposition of RuO_x are highlighted. **b.** SEM imaging of copper electrodes before the modification through electrodeposition. **c.** Morphology of the ruthenium oxide-based pH sensing films after electrodeposition using laboratory equipment. d. Results comparison using an Arduino-based potentiostat.

As such, the incorporation of our Arduino-based approach could lead to the successful deposition of sensing films onto the copper substrates. As studied within the previous section, these films could also be used to determine the pH of solutions using a low-cost device. However, the electrochemical noise obtained was relatively high, hindering its incorporation during in vivo studies.

3.3. Deposition of cellulose-based film on sensing device

As mentioned within previous sections, the electrodeposition of ruthenium oxide-based films onto copper electrodes allowed the fabrication of nanoparticulated films, that could successfully determine the pH in solution using an Arduino-based device. The deposition using laboratory equipment and microcontroller-based devices led to similar morphologies and sensing performances, showing promise for the incorporation of these low-cost methods in the fabrication of implantable devices. However, the noise rates of the films were relatively high, which could lead to large uncertainties on the measured pH, especially given the logarithmic nature of this value [20]. To improve the performance of the sensing films by reducing the electrochemical noise, a cellulose-based coating containing PDMS elastomer at a ratio of 60:40 was developed. This coating

composition was selected following previous reported work that indicated an improvement in sensing stability of ion-selective electrodes using elastomer coatings [21], and a potential decrease in biomolecule adsorption when PDMS is combined with ethyl cellulose [22].

Thin films were deposited onto the RuO_x films using an aerosol-based method (Figure 3.a.). The aerosol method developed in this work consisted of a piezoelectric atomiser, that could operate at a frequency of 110 kHz, and a low-cost air pump that could be connected to a microcontroller (Figure 3.a.). The use of an air pump allowed the displacement of the generated aerosol from the precursor solution reservoir onto the electrodes, generating a uniform film with a roughness in the range of 3 nm. Initially, this deposition method was applied to copper wires to compare the performance with the drop casting method (Figures 3.b. and Figure 3.c.). A higher surface roughness was observed in the case of drop casted samples compared to the aerosol deposited films, evidencing a higher surface homogeneity of the case of aerosol deposited films. In addition, the thickness of the films fabricated by aerosol deposition could be controlled by changing the deposition time, which allowed a good control of the dimensions, with an estimated growth of 0.77 nm/s (Figure 3.d.).

The presence of a cellulose-based coating could reduce the measured electrochemical noise, from 0.24 Point/min, obtained in the case of uncoated electrodes, up to 0.19 Point/min (Figure 3.e.). In addition, the electrodes showed a similar sensitivity compared to the pristine RuO_x electrodes, with 35 point/pH, and a linear response within the same pH range as the uncoated electrodes (Figure 3.f.).

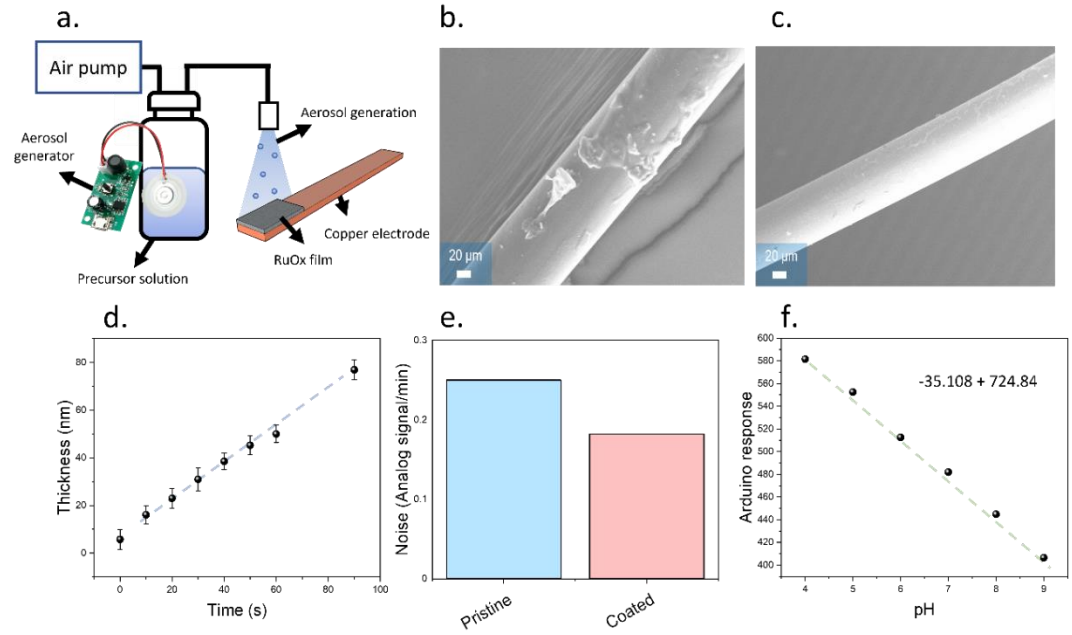

Figure 3. a. Schematical representation of the aerosol system employed within the present work for the deposition of cellulose-based coatings. The ultrasonic atomiser could be used to generate an aerosol which could be directed towards the sample by using an air pump. **b.** SEM imaging of drop casted substrates, evidencing the presence of a high surface roughness. **c.** The deposition of the cellulose-based coating using the aerosol method led to homogeneous films with controllable thicknesses. **d.** Calibration plot obtained after fabricating cellulose-based films onto the RuO_x films using different deposition times. **e.** Comparison graph of the noise rates obtained using the pristine sensors, only containing the RuO_x films, and the cellulose-based electrodes. **f.** Calibration plot of the final devices containing RuO_x and a cellulose-based coating. The sensitivity achieved increased compared to the one achieved in the case of pristine RuO_x.

One of the advantages of the incorporation of this cellulose-based coating within the electrode surface is the improvement of the stability when incorporated during in vivo studies as shown in the next section. Such improvement in the noise rates of sensors were a consequence of the lowest adsorption of biomolecules, as described in previous reported work [22].

3.4. Testing of final device for in vivo plant pH monitoring

After the fabrication and optimisation of the sensing devices through the incorporation of a cellulose-based coating, the electrodes were implanted inside tomato plants. The working and reference electrodes (1 mm wide) were glued onto a PP substrate to facilitate the implantation (Figure 4.a. and Figure 4.b.), and they were directly inserted onto the tomato stem (Figure 4.c.). A Wio Terminal-based device was assembled, incorporating a low-cost voltage meter, and a BME680 sensor, able to measure environmental humidity, temperature, pressure and VOC concentrations. The device was also programmed to send data wirelessly to an online server for data analysis and could be directly powered using an inductive charger (Figure 4.d. and Figure 4.e.). All the necessary components for the environmental measurements were enclosed inside a portable box, that enabled an easy handling of the devices. Finally, the results were downloaded from an online server, enabling a wireless reporting of results.

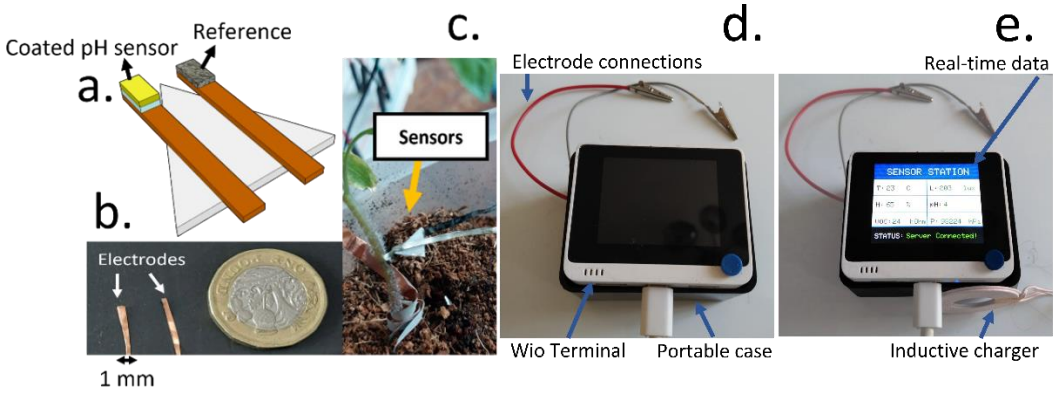

Figure 4. a. Schematical representation of the implantable probe that was inserted inside tomato stems. To improve the implantation, the 1 mm wide electrodes were glued onto a propylene substrate. **b.** Picture of the pristine copper electrodes prior implantation. **c.** Final device configuration involving the implanted electrodes inside tomato stems. **d.** Picture of the final device involving a Wio Terminal device, connected to an inductive charger as a power supply, as well as the voltage meter and BME680 environmental sensor (enclosed inside a box). **e.** Upon connecting the inductive chargers to the Wio Terminal device (which could also be achieved using a mobile phone), the Wio Terminal can be used without requiring any battery.

After the assembly of the low-cost system, the electrodes were implanted inside tomato plants. Initially, electrodes where no cellulose coating had been deposited were tested. The initial baseline was first recorded for 1 h, stabilizing at a pH of 2.42±0.84. The plant was then watered using 20 mL DI water, increasing the pH to 3.44±1.52 (Figure 5.a.). However, given the increasing noise rates obtained in this case, an objective study of the plant response became difficult. Such high electrochemical noise was attributed to a protein adsorption and biofouling, which commonly takes place within implantable devices that incorporate similar materials such as iridium oxide [23].

When the RuO_x sensing film was coated using a cellulose/elastomer film, the noise rates of the measured signal improved significantly compared with the pristine pH sensors. A pH baseline of 4.17±0.03 was initially recorded when the devices were first implanted. This value resulted similar to previous measurements of xylem sap pH in tomatoes, that

reported a slightly acidic value [24]. Upon watering the plant, an initial increase in pH was observed, followed by a stabilisation of the value at 4.37±0.07 (Figure 5.b.). Changes in pH values have been observed in vascular plants due to an increase in transpiration [24], change of season [25], presence of light [26], or fertilisation using nitrates [27]. As such, the increase of pH was attributed to a higher water availability by the plant, evidencing the application of the developed device for the continuous monitoring of pH in vivo. This low-cost system could also potentially be employed in smart agriculture, enabling the study of plant infections [28], and wound response [29], which could save costs and enhance productivity.

To complement the information obtained by the in vivo devices, we incorporated a BME680 environmental sensor, which recorded information about the temperature, humidity and VOCs concentrations (Figure 5.c-e.). The built-in light sensor from the Wio Terminal Device was additionally used, to study the day-night cycles of plants (Figure 5.f.).

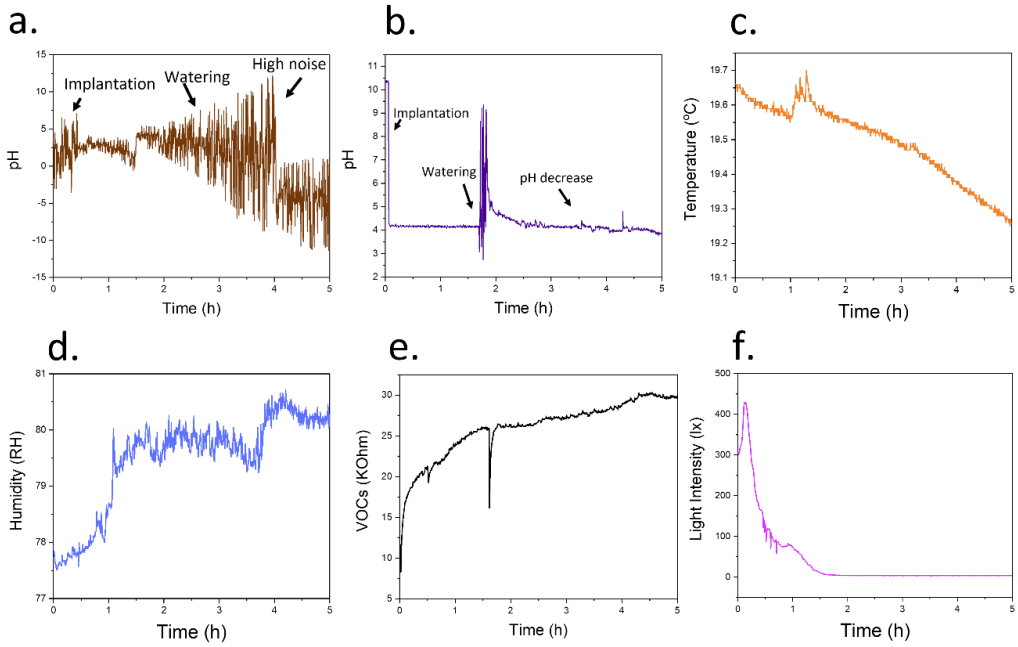

Figure 5. a. Measurement of pH inside the tomato stems using a pristine electrode without the incorporation of a cellulose-based coating. An increasing noise was recorded, with a change upon watering the plants. **b.** Plot obtained after the recording of pH in a tomato stem using cellulose-based device. The changes in pH upon watering the tomato plant could also be determined. **c.** The use of a BME680 sensor allowed the determination of environmental temperature. **d.** The humidity of the devices was additionally measured, evidencing an increase after watering the plant with DI water. **e.** The concentration of VOCs could additionally be assessed through the determination of the resistance of a metal oxide-based gas sensor. In this case, lower values of resistance represents a higher concentration of VOCs**. f.** The Wio Terminal device used within the present work incorporated a light sensor that could be used for the study of day/night cycles in plants.

As expected, the decrease in daylight led to a decrease in environmental temperature and an increase in humidity. In addition, the pH inside the stem increased after the stabilisation due to watering increased, with a value of 4.37±0.07 compared to the original baseline. Such slight increase in the pH values of tomatoes during night-time has been previously described in tomato plants. Such increase has been shown to be a consequence of to the differences in transpiration between day and night rather than changes in electrolytes concentrations in xylem [30].

4. Conclusions

Within the present work, a low-cost miniaturised device based on ruthenium oxide coated with a cellulose-based film has been developed to enable the in vivo monitoring of sap pH in tomato plants. Initially, a RuOx film was fabricated onto copper electrodes by electrodeposition. An Autolab potentiostat/galvanostat was used as a benchmark equipment for the fabrication, and the results were compared to the ones obtained by using a microcontroller-based low-cost approach. Nanoparticulate films were obtained in both cases, with a similar morphology and chemical compositions that allowed the sensing of pH with a Nernstian slope. However, the electrochemical noise rates of the devices were relatively high, in the range of 0.24 point/min, hindering the applicability of this system for the direct determination in vivo.

To improve the stability of the sensing devices, and allow the implantation of the films, a cellulose-based coating was incorporated onto the electrodes. This film was deposited by using an aerosol-based method, which included an ultrasonic sonicator and an air pump. The final low-cost system (>30$) allowed the deposition of nanometrically thin films on multiple substrates. A growth of 0.77 nm/s was measured by a stylus profilometer, with a roughness below 3 nm. Films within a thickness of 80 nm were then deposited, and the final device was calibrated using different pH buffers. A significative reduction in the noise rates was obtained, in the range of 0.19 point/min, while the measured sensitivity resulted similar to the one measured by the pristine electrodes, with no cellulose-based coating.

Finally, the devices were implanted inside tomato stems, and the pH was continuously monitored for 5 h. When no coating was incorporated, an increasing electrochemical noise was measured, which did not allow the determination of plant pH. On the contrary, the final device incorporating the cellulose-based coating could monitor the pH in the sap continuously for at least 5 h, with a low noise in the range of 0.07 pH/min. Initially, a stable pH of 4.17±0.03 was measured. Upon watering the plant using DI water, a sudden increase in this value followed by a stabilisation around 4.37±0.07 was measured. This slight increase in sap pH due to the transpiration mechanisms of plants was consistent with the previously reported work in the field. The low-cost measurement system also incorporated a bme680 sensor that allowed the measurement of environmental parameters such as temperature, humidity and VOC concentrations, and could send the obtained data wirelessly via an online server.

To simplify the incorporation of this technology within a real-world environment, and allow the use by the widest community of farmers, the codes needed for the operation of the final device were translated to XOD, an object-oriented programming tool to allow an easy operation by the final user. Thus, the results presented in this work represent a step forward for the incorporation of plant biosensors within low resource settings, with a plethora of applications in smart farming and Tnternet of Things (IoT) applied to agriculture.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1, Figure S2.

Author Contributions: Conceptualization, A.R, and H.K..; methodology, A.R.; software, A.R.; validation, A.R., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, J.H.; writing—original draft preparation, A.R.; writing—review and editing, A.R.; supervision, J.H. All authors have read and agreed to the published version of the manuscript.

Appendix A

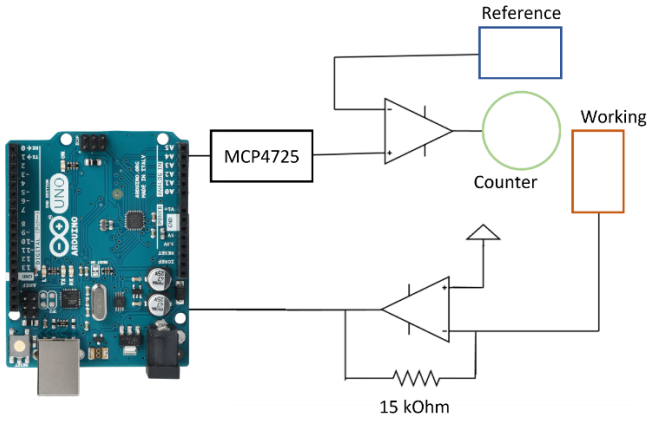

Figure A1. Schematical representation of the circuit employed within the present work for the development of a low-cost potentiostat.

Appendix B

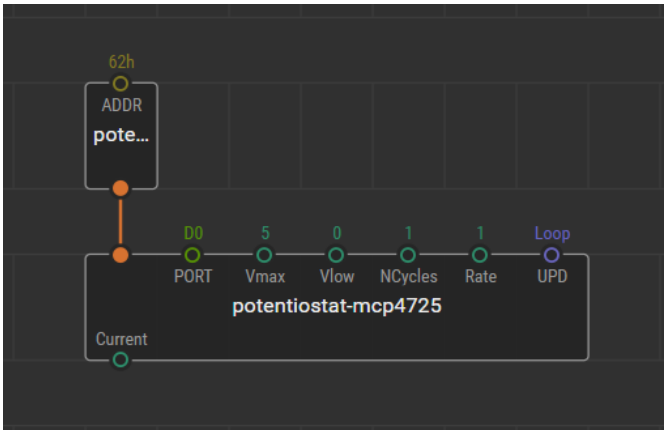

Figure A.2. Example of the program for the potentiostat developed for XOD, visual programming for the easy application of the device.

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