Biosensors and Bioelectronics: X 29 (2026) 100758

Contents lists available at ScienceDirect

Biosensors and Bioelectronics: X

journal homepage: www.journals.elsevier.com/biosensors-and-bioelectronics-x

Biodegradable wearable sensors for rapid non-destructive analysis of pesticides on plants and foods

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ARTICLE INFO

Keywords:
Plant-wearable sensor
Precision agriculture
Carbendazim
Diphenylamine
Diquat
Food safety

ABSTRACT

Wearable sensors technology in plant monitoring is emerging, disruptive and innovative tools offering new opportunities to enhance agricultural productivity and environmental sustainability as highlighted by World Economic Forum in Top 10 Emerging Technologies of 2023. On-site and nondestructive decentralized analysis of pesticides is essential for the effective management of agrochemicals on crops and foodstuff in precision agriculture and food safety that is not achievable with gold standard methods. Here, we develop eco-friendly substrates/support of biodegradable cellulose acetate (CA) films plasticized with diverse amounts of glycerol (GLY) or triethyl citrate (TEC) fabricated by casting method as a sustainable choice for portable sensing devices applications. The wearable devices containing full electrochemical sensing system were produced by screen-printing technology on green plasticized CA substrates to rapidly (3.28 min) and simultaneously detect agrochemicals directly on the surface of agricultural and food products. The wearable dual-sensor integrates diquat sensing by square wave voltammetry (SWV) with carbendazim and diphenylamine detection via differential pulse voltammetry (DPV) on a single platform with single microliter sample droplet. Reliable agrochemical measurements are conducted with low-cost environmentally friendly sensory platform (<US$ 0.077 per unit) in fruits, vegetables, saliva and water samples coupled with a Sensit BT portable analyzer connected via Bluetooth to a smartphone, laptop or tablet. Our sustainable wearable dual-sensor exhibits an attractive analytical performance with robustness against severe bending strains, reproducibility and selectivity offering on-site rapid, continuous, cost-effective, simultaneous and reliable monitoring, addressing the existing gap in integrated approaches for multiplexed agrochemical detection in nondestructive decentralized analysis.

1. Introduction

The demand for food continues growing driven by increasing global population projected to be 9.8 billion in 2025 and 11.2 billion in 2100 (Teixeira et al., 2025b). The agricultural productivity needs to be increased 100–110% by 2050 to avoid insufficient food supply (Teixeira et al., 2025b). Management of plant health is essential to improve crop yields in a scenario with losses of 40% in global agricultural productivity, exceeding ~220 billion dollars, per year owing plant diseases affecting crop yield, nutrition, and threatening food security worldwide as estimated by Food and Agriculture Organization (FAO) (Teixeira et al., 2025b).

Pesticides are broadly used in agriculture to combat diseases and pests ensuring access the global demand for food however generating the necessity of residues monitoring in wastewater effluents, soils, raw drinking water sources, surface water, and food products (Teixeira et al., 2023). Current standard analytical methods to determine agrochemicals require laboratory analysis demanding high-cost equipment and

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This article is part of a special issue entitled: Smart Biosensors published in Biosensors and Bioelectronics: X.

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https://doi.org/10.1016/j.biosx.2026.100758
Received 21 October 2025; Received in revised form 16 December 2025; Accepted 10 February 2026

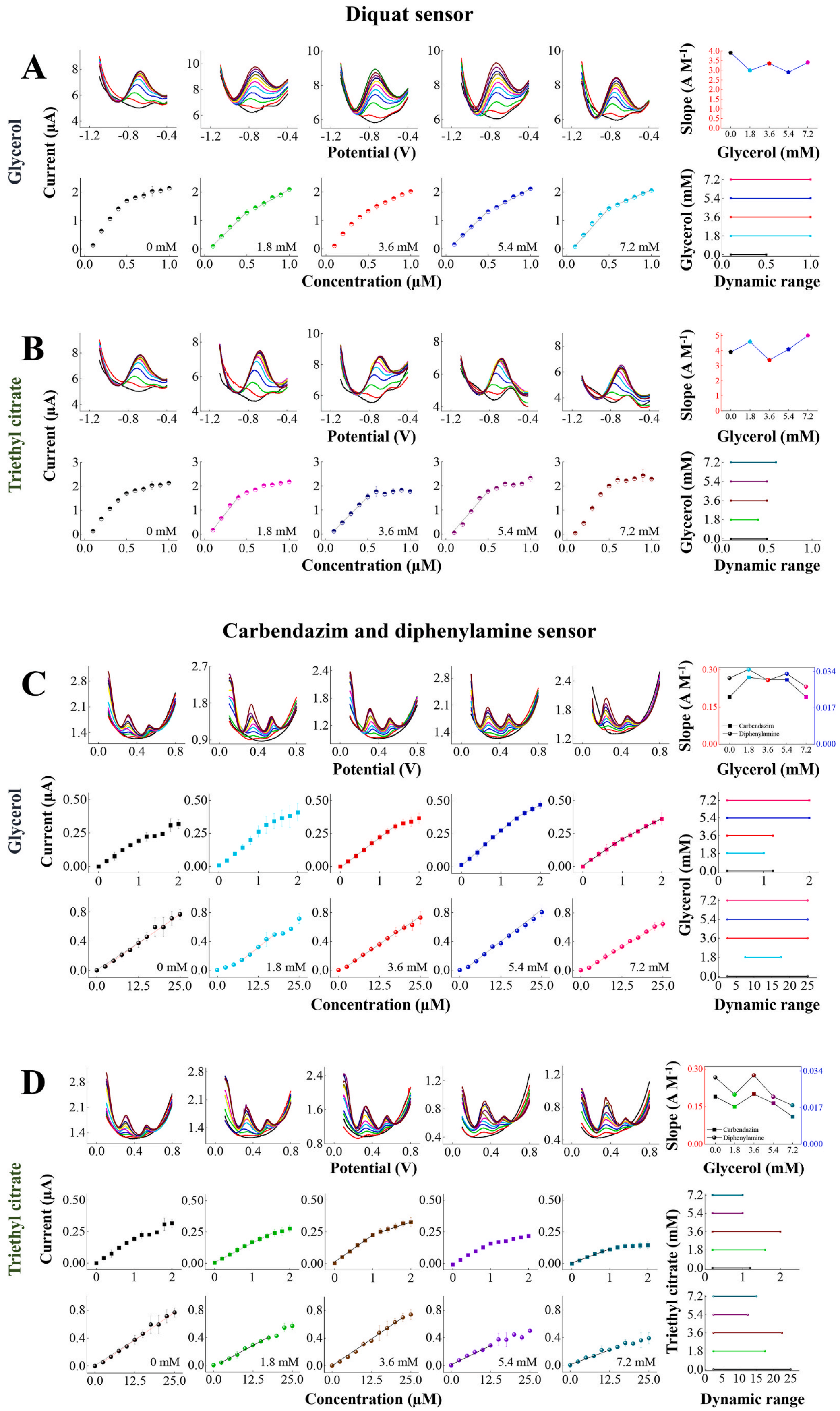

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Fig. 1. – In vitro electroanalytical evaluation of the wearable dual-sensor in 0.1 M phosphate buffer solution. SWV responses for diquat sensing in a concentration range of 0.1–1.0 μM with corresponding analytical curves using wearable dual-sensor made on cellulose acetate (CA) substrates plasticized with diverse amounts of glycerol (GLY) in **A** and triethyl citrate (TEC) in **B**. DPV responses with the corresponding analytical curves for pesticides simultaneous detection using wearable device printed on CA substrates plasticized with diverse amounts of GLY in **C** and TEC in **D**. Concentration range between 0.2 and 2.0 μM for carbendazim and diphenylamine from 2.5 to 25 μM. The mean and the error bars reflect the standard deviation of the measurements using three different devices.

time-consuming processing by specialized personnel limiting their feasibility for frequent tracking, convenient and real-time analysis for making decision (Teixeira et al., 2023). On-site, decentralized non-destructive management of pesticides can be made employing wearable sensors with portable instruments that may be conformable with different surfaces providing high sensitivity and rapid response (Teixeira et al., 2023).

Wearable plant sensors or plant-wearable sensors, i.e., wearable sensors for plant monitoring, are flexible and miniaturized analytical tools able to be directly attached on diverse plant organs including stems, food skin, and leaves (Teixeira et al., 2025b), to frequently monitor temperature and humidity (Nassar et al., 2018), dehydration (A. Barbosa et al., 2022), biomarkers (Parrilla et al., 2024), diseases (Li et al., 2020), nutrient levels (Singh et al., 2023), pesticides (Teixeira et al., 2023), and diverse biotic and abiotic stress (Li et al., 2024). Wearable sensor technology for plants supplies a cutting-edge device for nondestructive, rapid, on-site, and decentralized noninvasive detection toward food safety and precision agriculture applications, offering real-time bioinformation into status of the plant health and environmental factors (Teixeira et al., 2025b). World Economic Forum included wearable sensors for plants as one of the Top 10 Emerging Technologies in 2023 due to the high relevance to enhance plant health and increase agricultural productivity revolutionizing modern agrifood practices (Seddaoui and Arduini, 2025; Teixeira et al., 2025b).

The most of wearable devices are fabricated on non-renewable-based plastic polymers of chemical materials originated from petroleum which are unsustainable materials and needs a long time for degradation, in addition they are inadequate to adhere on irregular, wavy and curved surfaces (Teixeira et al., 2023). Contrary to the petroleum-based plastics, sustainable, biocompatible, and biodegradable polymers from renewable sources emerge as a promising solution with a smaller market share, despite their potential to decrease the environmental impacts of plastic production in according with European Bioplastics and the OECD Global Plastics (Teixeira et al., 2025a). The market for biodegradable sensors estimates a substantial increase driven by escalating global demand for sustainable agricultural practices and environmentally responsible monitoring technologies (Teixeira et al., 2025b).

A relevant biocompatible and sustainable material is cellulose (the most abundant natural polysaccharide on Earth) and its derivatives to produce biodegradable devices due to their exceptional biocompatibility, environmental sustainability, high thermal stability, flexibility, high-abundance and favorable degradation behavior in physiological environments (Seddaoui and Arduini, 2025; Teixeira et al., 2025b). CA was chosen because is plant-based material that can be produced from agricultural residues which contain cellulosic units as a source (Teixeira et al., 2023). Cellulose is atoxic, cost-effective, affordable, biodegradable, lightweight and easy-to-handle material that can be used to design and fabrication of wearable sensors with interesting features in according with Principles of Green Chemistry (Teixeira et al., 2023). Cellulose acetate polymers fabricated with plasticizers under controlled conditions offer predictable and consistent mechanical and disintegration features. To the best of our knowledge, plasticized cellulose acetate substrates/supports with decreased biodegradation time have not been used in wearable sensors and biosensors. The specific novelty of our work relative to recent studies on sustainable or wearable pesticide sensors is related to the dual-channel biodegradable design that differs from prior single-analyte or non-biodegradable wearable platforms in terms of sequential and simultaneous analysis (trial analyte detection), full biodegradability, and integration with a portable analyzer.

We demonstrate here the first example of a biodegradable wearable dual-sensor integrated with portable wireless analyzer toward rapid decentralized nondestructive sequential and simultaneous analysis of diquat, carbendazim and diphenylamine pesticides for environmental and health monitoring, food safety assurance and precision agriculture. Our new biodegradable wearable dual-sensors were confectioned by screen-printing technology on flexible and biodegradable cellulose acetate substrates/supports plasticized with triethyl citrate or glycerol in which they prepared by casting method or solvent casting. The new wearable dual-sensor consists of two working, auxiliary and reference electrodes onto a single platform to detect independently, sequentially and simultaneously three agricultural defensive targets. The single platform containing wearable dual-sensor was integrated with a commercial handheld wireless potentiostat offering a rapid (3 min) assessment of the pesticides and displays the analysis in real-time on a mobile device through wireless communication (Bluetooth). A sensory unit is employed for SWV measurements to detect diquat, while carbendazim and diphenylamine analysis were conducted at the second sensor by DPV measurements. The portable wireless analyzer automatically shifts the electrochemical techniques (SWV by DPV) through of a software PStouch protocol. The wearable dual-sensor offers sequential and simultaneous three analyte detection in microliter sample droplets within 3.28 min, with SWV diquat measurement performed during the first 52 s, followed by DPV measurement for simultaneous sensing of carbendazim and diphenylamine completed in an additional 197 s. The wearable device with dual sensors works independently on the single platform, verifying the robustness of the electroanalytical system. Improvements in sustainability practices in (bio)sensing are essential to a better future for all, our biodegradable wearable dual-sensor is in according with the criteria of Agenda 2030 Goals for Sustainable Development created by the United Nations (Teixeira et al., 2025a). The wearable dual-sensor integrated with portable wireless analyzer could frequently, non-invasively, and wirelessly monitor a broad spectrum of pesticides and provide routine simple, rapid and frequent reliable sensing of diquat, carbendazim and diphenylamine agrochemicals paving the way to remarkable promise for decentralized multiplexed monitoring of diverse pesticides representing the first step toward realizing the vision of “laboratories under the plant” for nondestructive sequential and simultaneous detection of different targets in precision agriculture, food safety, environmental and health monitoring.

2. Experimental

All of the specifications for the materials employed in the biodegradable wearable sensors and in the measurements are given in the Supporting Information.

3. Results and discussion

3.1. In vitro electroanalytical performance investigation of the biodegradable wearable dual-sensor

The electroanalytical performance of the biodegradable wearable dual-sensor for the detection of diquat, carbendazim and diphenylamine agrochemicals in Fig. 1 was individually compared between cellulose acetate substrates plasticized with diverse amounts of glycerol and triethyl citrate. SW voltametric responses in Fig. 1A–B and DP voltametric responses in Fig. 1C–D displays increasing concentrations of diquat from 0 to 1.0 μM, and between 0.2 and 2.0 μM and 2.5 and 25 μM

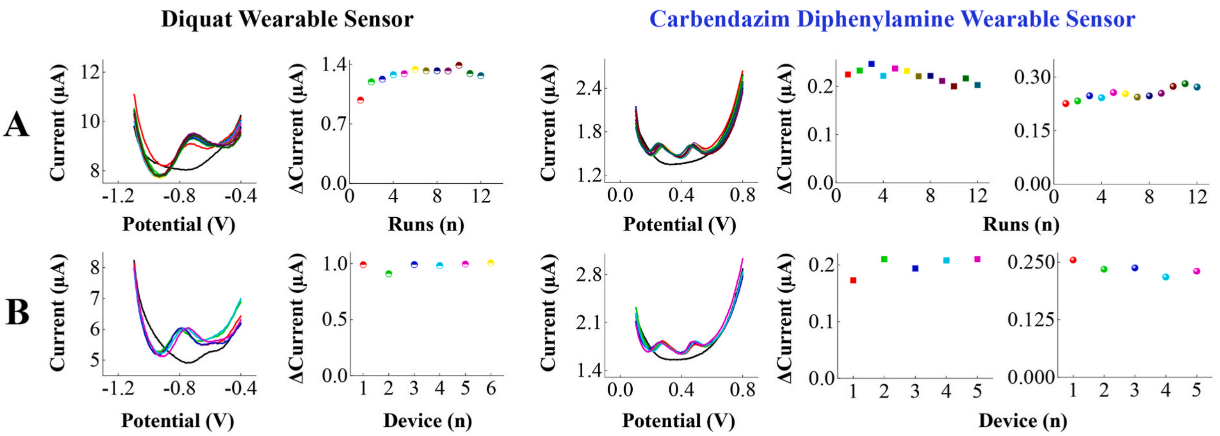

Fig. 2. – Performance of the biodegradable wearable dual-sensor. **A –** DPV and SWV responses on stability study of the plant-wearable dual-sensor after twelve consecutive runs. **B –** Reproducibility of the voltammetric responses obtained by six devices for sequential and simultaneous detection of diquat, carbendazim and diphenylamine.

for carbendazim and diphenylamine using wearable platform plasticized with 0, 1.8, 3.6, 5.4 and 7.2 mM of glycerol in Fig. 1A and C and triethyl citrate in Fig. 1B and D. Wearable devices printed on cellulose acetate plasticized with triethyl citrate in Fig. 1B and D demonstrated ill-defined voltametric responses with poor-distinction of the anodic peak potential, moreover, the analytical curves had narrow linear range probably due to worsening of the interaction/adhesion of the ink to the substrate with triethyl citrate. On the other hand, the CA substrates prepared with 5.4 mM glycerol showed well-defined voltametric responses with satisfactory linearity in the analytical curves to detect the three analytes concomitantly, i.e., diquat, carbendazim and diphenylamine.

Fig. 1A and C displays the voltammetric response of biodegradable wearable dual-sensor in which low variations in target levels led to very well-defined SW and DP voltammograms in 0.1 M phosphate buffer solution containing increased molecules concentrations in the range from 0.1 to 1.0 μM for diquat; 0.2–2.0 μM for carbendazim and 2.5–25 μM for diphenylamine. The anodic current response at −0.73 V in Fig. 1A exhibited two linear ranges with increase of diquat levels from 0.1 to 0.5 μM according to: $I\ (\mu A) = -0.6 + 1.6\ C_{\text{Diquat}}\ (\mu M)$, $R^2 = 0.99$, N = 5, with a sensitivity of 12.7 A M^{-1} cm^{-2} and from 0.6 to 1.0 μM according to: $I\ (\mu A) = -0.1 + 2.9\ C_{\text{Diquat}}\ (\mu M)$, $R^2 = 0.99$, N = 5, with a sensitivity of 23.1 A M^{-1} cm^{-2}. The oxidation peak at +0.49 V in Fig. 1C also exhibited two linear ranges with increase of carbendazim levels from 0.2 to 1.4 μM according to: $I\ (\mu A) = 0.11 + 0.26\ C_{\text{Carbendazim}}\ (\mu M)$, $R^2 = 0.99$, N = 8, with a sensitivity of 2.1 A M^{-1} cm^{-2} and from 1.4 to 2.0 μM according to: $I\ (\mu A) = 0.12 + 0.173\ C_{\text{Carbendazim}}\ (\mu M)$, $R^2 = 0.99$, N = 4, with a sensitivity of 1.4 A M^{-1} cm^{-2}. The oxidation peak at +0.27 mV in Fig. 1C increased linearly with the diphenylamine concentrations between 2.5 and 25 μM with linear regression $I\ (\mu A) = -0.023 + 0.032\ C_{\text{diphenylamine}}\ (\mu M)$, $R^2 = 0.99$, N = 10, with a sensitivity of 0.25 A M^{-1} cm^{-2}. The theoretical LOD values of 0.0032 μM (or 3.2 nM); 0.18 μM and 1.34 μM were estimated for the diquat, carbendazim and diphenylamine, respectively. The LODs are lower than the maximum residue levels (MRL's) for diquat, carbendazim, and diphenylamine of 5.52×10^{-8} M (apple) and 2.76×10^{-8} M (pepper), 1.05×10^{-6} M (apple) and 5.2×10^{-7} M (pepper), 2.95×10^{-7} M (apple and pepper) established by European Commission Food Safety and of 5.52×10^{-8} M (apple) and 2.76×10^{-8} M (pepper), 1.57×10^{-5} M (apple), 5.91×10^{-5} M (apple) and 1.81×10^{-5} M (pepper) established by Food and Agricultural Organization/World Health Organization, respectively.

The wearable devices made on CA substrates/supports plasticized with 5.4 mM glycerol exhibited superior dynamic range, linearity and sensitivity than those ones made on CA films plasticized with triethyl citrate to concomitantly detect diquat, carbendazim and diphenylamine agrochemicals. The use of glycerol plasticizer did not show negative impact on electroanalytical performance of wearable devices when compared to the CA pure substrates as illustrated in Fig. 1A and C. The design of the biodegradable wearable dual-sensor can be implemented for decentralized non-destructive detection of other bioindicators related to different purposes in noninvasive analysis.

The electroanalytical performance of the biodegradable wearable dual-sensor for the detection of diquat in Fig. S1A, and carbendazim and diphenylamine in Fig. S1B was compared between DPV and SWV techniques. In Fig. S1A, the anodic peak potential (Epa) for diquat detection is −0.71 V and −0.73 V while for carbendazim and diphenylamine simultaneous detection in Fig. S1B the Epa was of +0.49 V and +0.24 V, and +0.57 and + 0.35 for DPV and SWV techniques, respectively. The analytical curves depicted currents signals increasing linearly with the diquat, carbendazim and diphenylamine concentration as illustrated in Figure S1A and Figure S1B. Using the DP voltammetry, the slopes (sensitivity) were similar when compared with the SWV technique for carbendazim and diphenylamine however the DPV responses for diquat detection between 0.5 and 1.0 μM demonstrated poor-definition of the E_{pa} and poor-distinction from the concentrations. SWV for simultaneous detection showed elevated standard deviation. Thus, we selected SW voltammetry for diquat detection and the DP voltammetry for carbendazim and diphenylamine simultaneous detection. The use of a specific potential range for each channel was strategically chosen because it was not possible to detect diquat, carbendazim and diphenylamine with high sensitivity and selectivity using the same experimental setup. The peaks are poorly defined for low concentrations in DP and SW voltammograms for agrochemicals simultaneous detection owing to high capacitive currents (background currents) and fouling effects of by-products within the wide potential range. The potential cross-talk was assessed by detecting diquat in the presence of carbendazim and diphenylamine and vice-versa. Fig. S2 depicts no additional oxidation peaks in DP and SW voltammograms and the slopes of the calibration curves for pesticides are similar to those ones in Fig. 1A and B indicating also that there was no cross-reactivity between the agrochemicals. The fitting of the experimental data was only performed on linear concentration range, e.g. the three highest concentration values of Fig. S2 were not included in the fitting process.

The current responses from twelve consecutive measurements with 0.3 μM diquat +1 μM carbendazim +12.5 μM diphenylamine in Fig. 2A revealed an RSD of 8.2%, 6.1% and 6.6% suggesting that the electrochemically active surface area was not kept constant due to polymerization or biofouling effects meanly on diquat measurements. However, these issues can be tackled with disposable sensors and only one measurement per sensor. The reproducibility is indispensable for accurate detection in single-use disposable devices. The biodegradable wearable

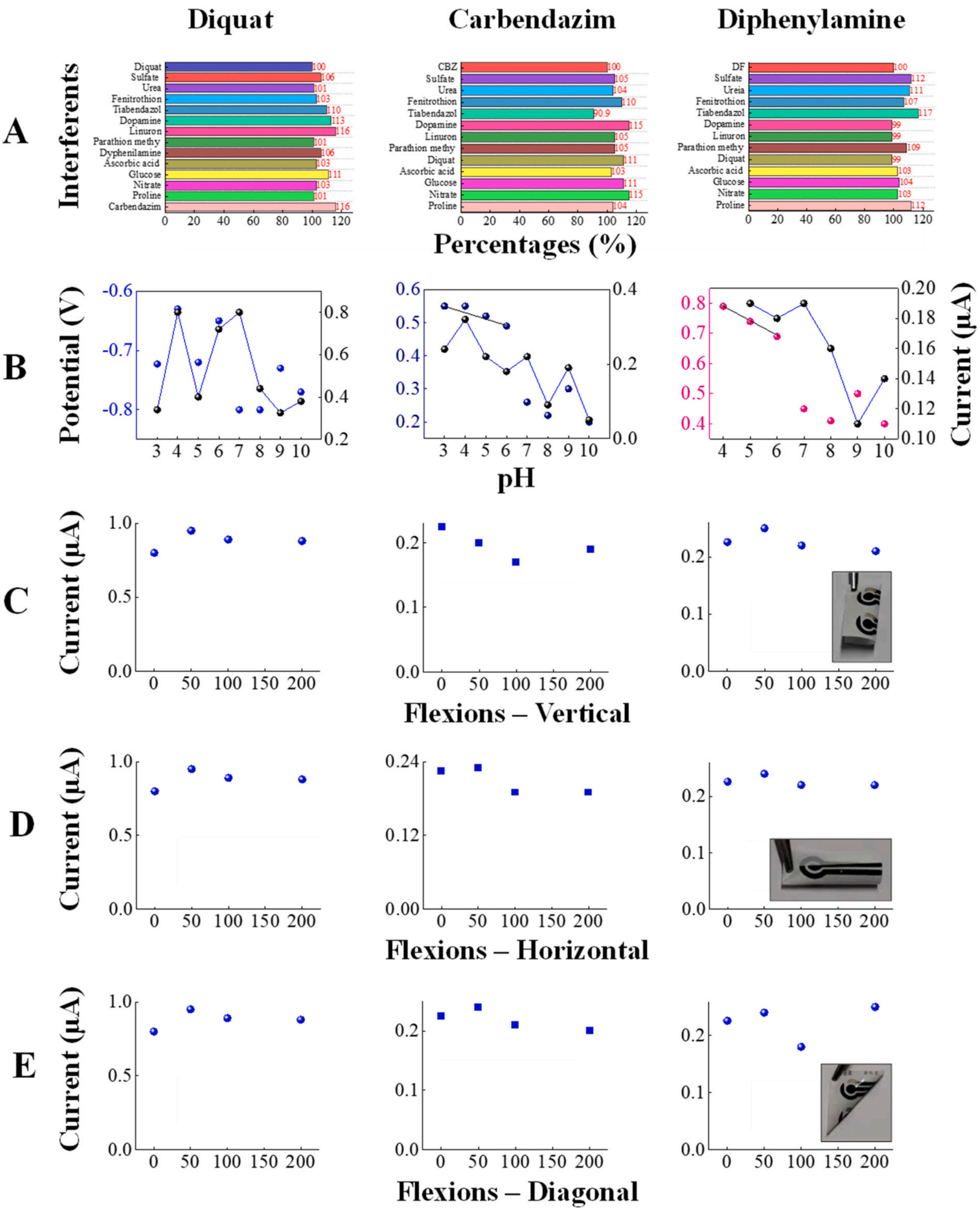

Fig. 3. – Interference and crosstalk assessment, pH influence and mechanical stability evaluation for biodegradable wearable dual-sensor on the diquat, carbendazim and diphenylamine sequential and simultaneous detection. **A –** Bar plot of the selectivity and impact of potential electroactive species: 100 µM of nitrate, sulfate, glucose and urea, and 10 µM of fenitrothion, thiabendazole, dopamine, linuron, parathion methyl, carbendazim, diphenylamine, diquat, ascorbic acid and proline on the signal sensing of 0.3 µM diquat, 1.0 µM carbendazim and 12.5 µM diphenylamine. **B –** Relation between pH (3–10) versus potential (V) and current variation (Δcurrent, µA). Electrochemical mechanical integrity of devices for undeformed devices (0 × bending), after 100 × and 200 × of bending cycles in the vertical in **C**, horizontal in **D** and diagonal in **E**.

dual-sensor revealed high reproducibility in Fig. 2B with a relative standards deviation (RSD) of 3.7, 7.0 and 5.7% using five platforms to measure 0.3, 1.0 and 12.5 µM diquat, carbendazim and diphenylamine. The robustness of the wearable dual-sensor design confirms the usability for single-signal recording per measurement.

The bar plot in Fig. 3A reveal a negligible impact of interfering species on the anodic peaks signals of the agrochemicals using biodegradable wearable dual-sensor. The high selectivity reflects the

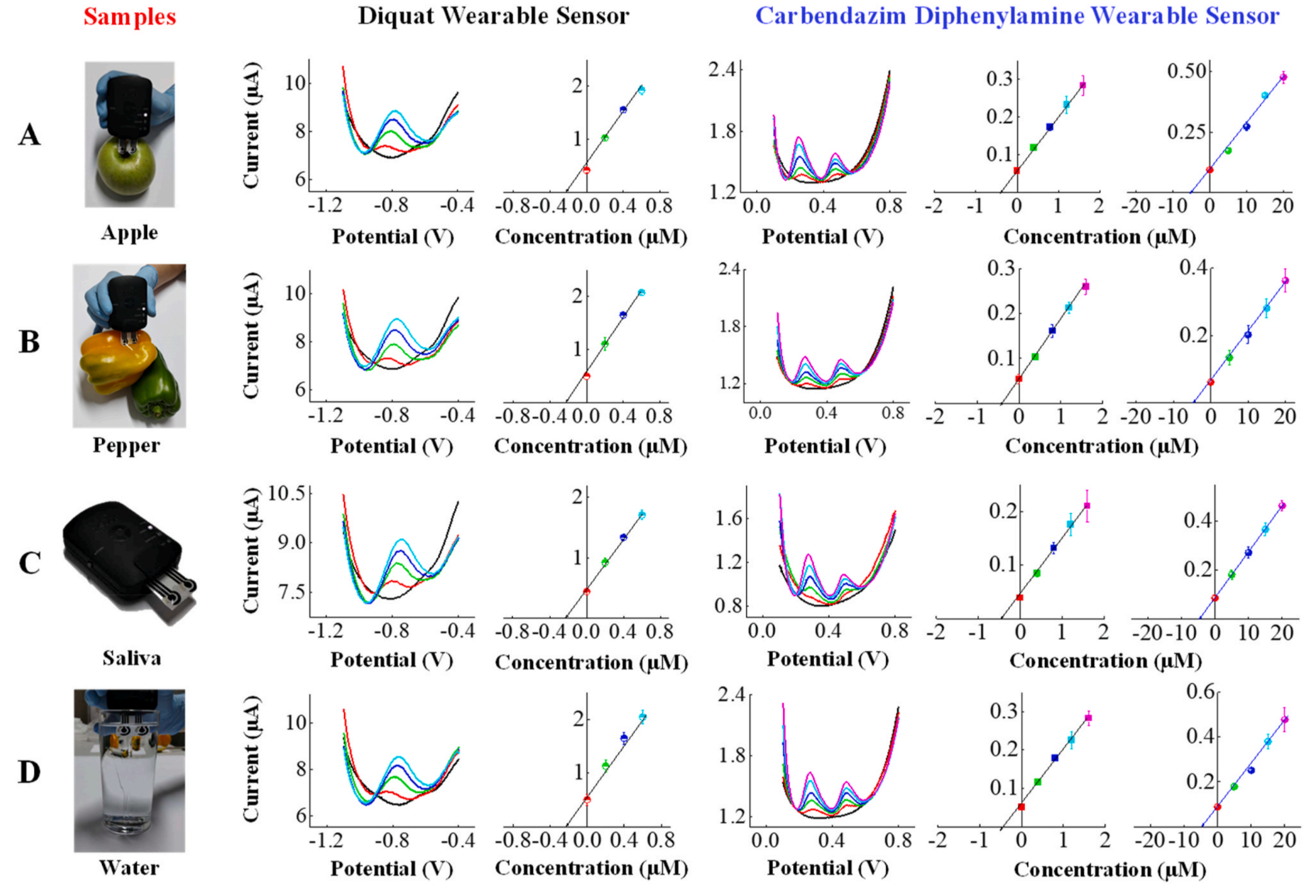

Fig. 4. – Multi samples analysis employing biodegradable wearable dual-sensor and the standard addition method. DPV and SWV responses with respective analytical curves for decentralized detection of diquat, carbendazim and diphenylamine in apple (**A**) and pepper (**B**) skin, human saliva (**C**) and water (**D**) samples.

judicious choice of the detection conditions in SWV and DPV protocols mainly potential range. Fig. 3B depicts the absence of linearity between potential (V) and pH (3–10) for diquat, carbendazim and diphenylamine detection revealing that proton species are not involved in the target oxidation. The value of pH = 7.0 was chosen for measurements due to high current values for diquat and diphenylamine analysis and meanly because neutral pH will not affect the food samples for consumption after measurements. Mechanical stability was evaluated with a series of bending deformations on the biodegradable wearable dual-sensor, and voltammetric responses were compared with undeformed sensors. Fig. S3 depicts the voltammetric responses of biodegradable wearable dual-sensor in 0.1 M phosphate buffer solution (dotted lines, without analytes) and with the 0.3 μM of diquat and 1.0 μM of carbendazim plus 12.5 μM of diphenylamine (full lines) for undeformed devices (0 × bending), and after 50 × , 100 × and 200 × repeated vertical (Fig. S3A and S3D), horizontal (Fig. S3B and S3E) and diagonal (Fig. S3C and S3F) bending cycles. The voltametric response showed negligible change after stress cycles as depicted in the plots of flexion numbers vs. current of Fig. 3C–E, confirming satisfactory mechanical resistance to attach wearable dual-sensor on irregular and curvilinear areas of the plants, fruits and vegetables.

3.2. Ex-situ and on-site analysis of fruit, vegetable, human saliva and water samples

An outstanding practicality of our biodegradable wearable dual-sensor design is the capability to quickly analyze agrochemicals using a single droplet in ex-situ and on-site analysis of fruit, vegetables, human saliva and tap water. Apple and pepper samples were washed with buffer solutions to remove crop protection agent residues from the skin. The samples including human saliva and tap water were spiked with pesticides followed by SWV and DPV measurements and the standard addition method was employed to predict the residues levels. Voltammetric response in Fig. 4 depicts increasing levels of diquat, carbendazim and diphenylamine in the fruit, vegetable, human saliva and tap water samples with the respective calibration curves. Table S1 lists the recoveries values estimated for spiked samples with a maximum variation of 6%, 3% and 11% for diquat, carbendazim and diphenylamine revealing the potential of our biodegradable wearable dual-sensor as a useful and effective tool for sequential and simultaneous monitoring of pesticides in fruits, vegetables, human saliva and tap water samples.

The pesticides were applied spraying 1000 μM of agrochemicals solution on apple and pepper skin and dried by 5 h simulating the use in real-world applications. The on-site crop protection agent measurements were conducted on the agricultural product surface by attachment the sustainable plant-wearable dual-sensor directly on the apple and pepper skin adding 500 μL of phosphate buffer solution and taking the DP and SW voltammetric responses as indicated in Fig. 5. The measurements are sequential (channel 1 followed by channel 2) using only one chip containing two full electrochemical sensor that are directly connected to the portable wireless analyzer. The well-defined oxidation peak at −0.87 V, +0.24 V and +0.47 V in Fig. 5 indicate residues of the diquat, carbendazim and diphenylamine on the yield surface. For human saliva and water testing, all targets were detected from the same 150 μL sample droplet in under 3.28 min. The diquat voltametric signature is captured within the first 52 s via SWV, followed by DPV carbendazim and diphenylamine simultaneous detection after an additional 197 s measurement. This sequential and simultaneous detection enable triple-analyte readout with no washing steps and any additional reagents in single microliter human saliva or water sample

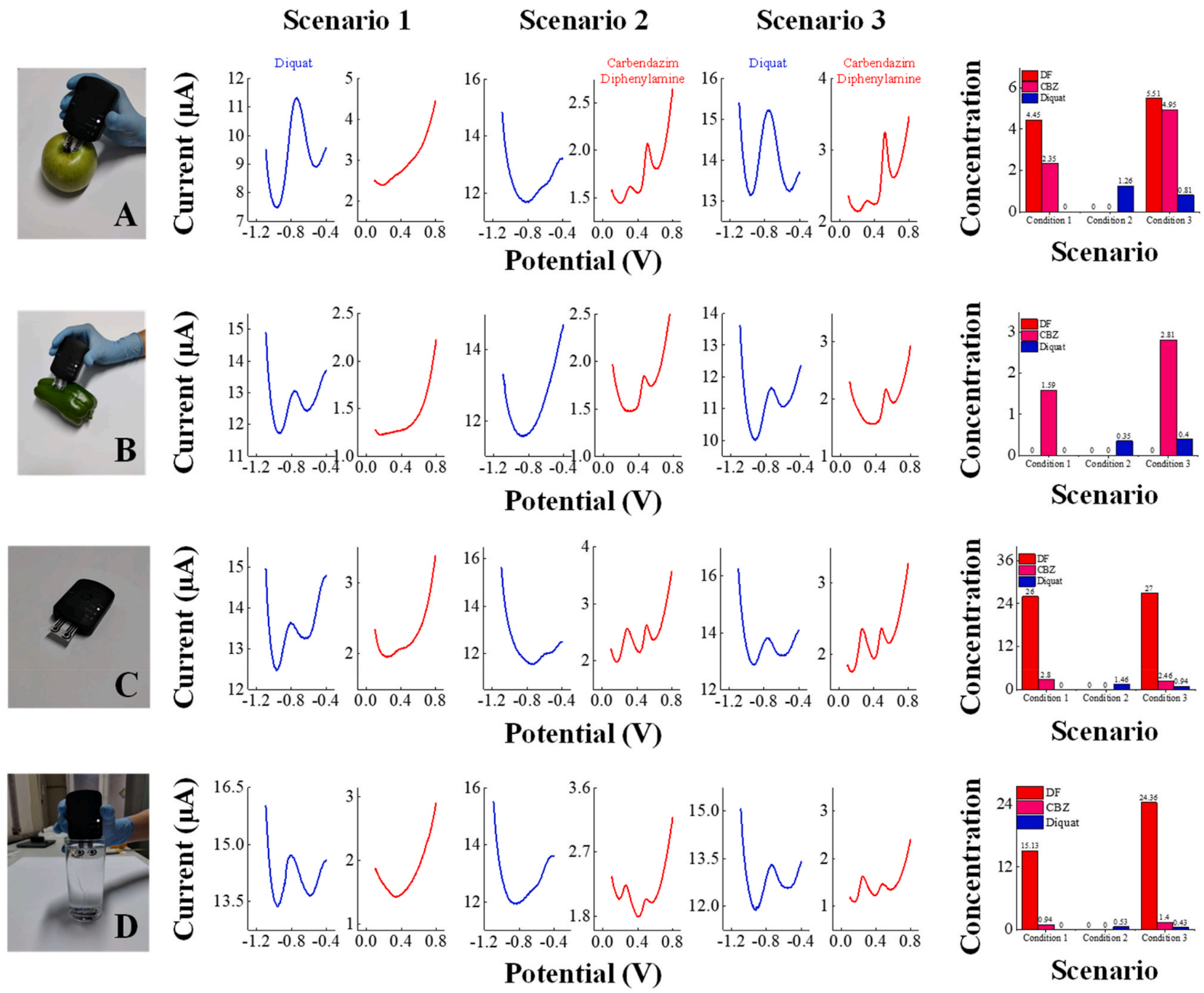

Fig. 5. – In situ analysis of diquat, carbendazim and diphenylamine using sustainable wearable dual-sensor in diverse real-world scenarios. DPV and SWV on the skin of **A** – apple and **B** – pepper; in single µL sample droplet of **C** – human saliva and **D** – water samples. Corresponding plot of the concentration vs scenarios.

droplets. In the real-world scenarios can exist only diquat or carbendazim and diphenylamine or the three pesticides in the food, human saliva and water samples. Fig. 5 highlight the capability of the sustainable wearable dual-sensor integrated with handheld and wireless dual-channel potentiostat to selectively identify and quantify the pesticides in the real-world samples. The sustainable plant-wearable dual-sensor enabled reliable sequential and simultaneous measurements of diquat, carbendazim and diphenylamine in a single sample droplet (apple, pepper, human saliva or water) without crosstalk between the plant-wearable sensors as illustrated in Fig. 5. In particular, a simple, decentralized, easy and rapid sequential and simultaneous on-site detection of agrochemicals via a single sample droplet is pivotal for effective precision agriculture and food safety.

Biodegradation assessment in Fig. 6A depicts wearable sensor made with CA plasticized with GLY completely degraded after 240 days while the devices fabricated with CA remain intact demonstrating that the GLY reduces the time of the biodegradation process. The electroanalytical performance of partially degraded wearable dual-sensors was not evaluated during or after soil exposure because visually the printed carbon electrodes appeared cracked. Additional quantitative metrics including thermogravimetric, Fourier transform infrared spectroscopy (FTIR) and Raman analysis after exposure of biodegradation are shown in Fig. S7. The greenness of detecting pesticides with biodegradable wearable sensor was verified using the Analytical Greenness Metric Approach (AGREE) (Pena-Pereira et al., 2020) and the Analytical Eco-Scale (AES) (Gałuszka et al., 2012). A numerical score is given to each criterion of the 12 Green Analytical Chemistry (GAC) principles, and the aggregate score is listed in the middle of a clock-shaped pictogram ranging from 0 to 1, with 1 expressing the greenest option and the visual representation with a colored pictogram: green, yellow, or red, attributed to excellent, medium, and bad environmental impact, respectively (Pena-Pereira et al., 2020; Yosrey et al., 2024). AES is estimated by AES = 100 – penalty points (PP) of four parameters that harm the environment: occupational hazards, the quantity and type of chemicals used, energy consumption and waste generation, with scores above 75 denoting excellent environmental friendliness, scores above 50 indicating acceptable green analysis, and scores below 50 signifying inadequate environmental friendliness (Gałuszka et al., 2012). The AGREE pictogram depicted in Fig. 6B with a score predicted of 0.77 is coherent with the AES score of 81 in Table S2 for the biodegradable wearable dual-sensor revealing a sustainable and green analytical method to detect pesticides (Gałuszka et al., 2012; Pena-Pereira et al., 2020).

The Blue Applicability Grade Index (BAGI) was used to assess a manifold evaluation of the practicality (blueness) of the electroanalytical methodology in addition to the well-established green metric tools (Manousi et al., 2023, 2024; Yosrey et al., 2024). BAGI examines the principles of sustainable environmental practices that define the practicality of an analytical method, i.e., type of analysis, number of

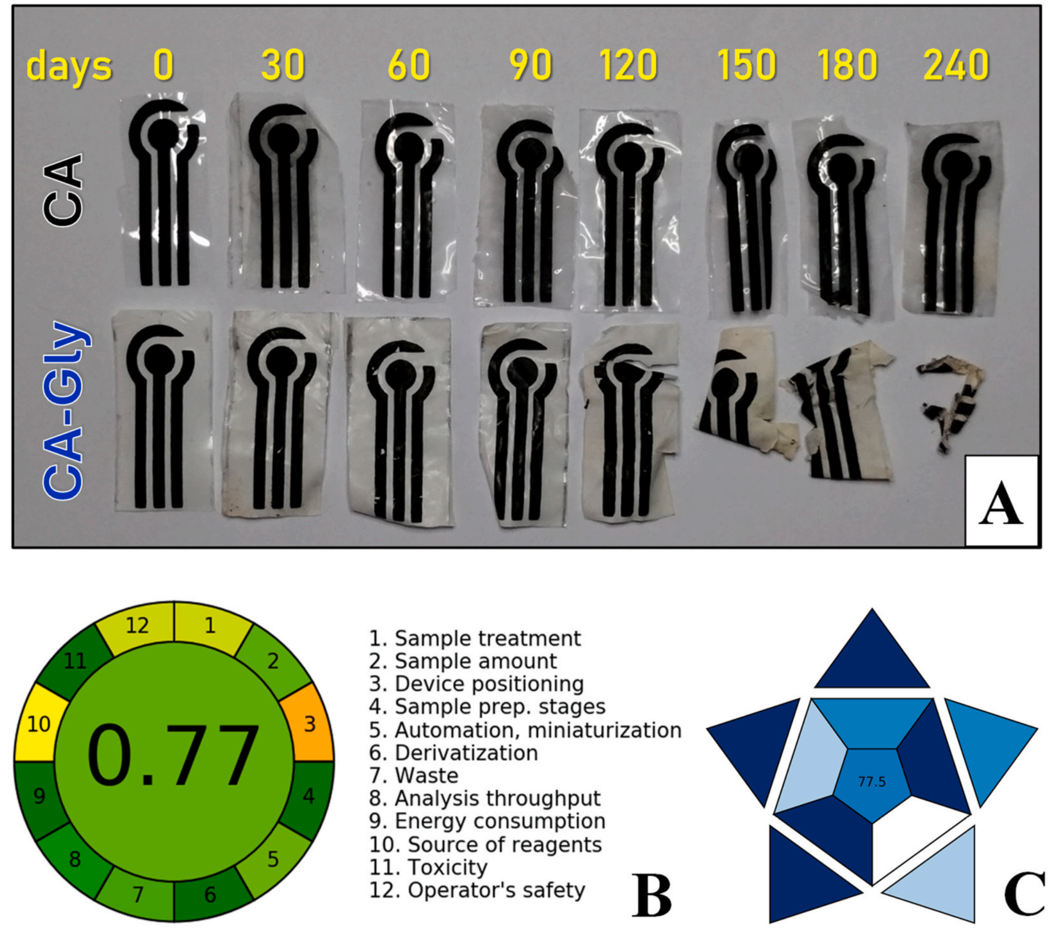

Fig. 6. – Biodegradability evaluation of wearable dual-sensor during 240 days in **A**. Agree metrics in **B** and blue applicability grade index (BAGI) pictograms for the electroanalytical method using wearable sensors to detect pesticides in food skin, human saliva and water samples in **C**. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

analytes, sample preparation, sample volume, sample throughput and simultaneous sample preparation, reagents and materials, instrumentation and automation degree, the fitness for purpose, and the automation degree (Manousi et al., 2023, 2024; Yosrey et al., 2024). Employing the provided software in the open-source platform mostwiedzy.pl/bagi, an asteroid pictogram is generated with a score ranging from 25 to 100, which should exceed 60.0 to qualify as a suitable analytical method (Manousi et al., 2023, 2024). The color scale of dark blue, blue, light blue, and white represents high, medium, low, and no compliance with the established criteria, respectively (Manousi et al., 2024). A score of 25.0 indicates a method with the poorest applicability, whereas a score of 100 denotes outstanding method applicability. (Manousi et al., 2023, 2024). The score of 77.5 depicted in the BAGI pictogram of Fig. 6C highlights that our electroanalytical method using biodegradable wearable dual-sensor to detect pesticides in food skin, human saliva and water samples is an applicable analytical method (Manousi et al., 2023, 2024; Yosrey et al., 2024).

Our biodegradable wearable dual-sensor fulfill the requirements of Sustainable Development Goals (SDGs) contained in Agenda (2030) from United Nations in special the goals 1–3, 6, 12–15 (Arduini, 2025) in which also is directly linked to the 12 principles of GAC: 1) Direct analytical techniques should be applied to avoid sample treatment; 2) Minimal sample size and minimal number of samples are goals; 3) In situ measurements should be performed; 4) Integration of analytical processes and operations saves energy and reduces the use of reagents; 5) Automated and miniaturized methods should be selected; 6) Derivatization should be avoided; 7) Generation of a large volume of analytical waste should be avoided and proper management of analytical waste should be provided; 8) Multi-analyte or multi-parameter methods are preferred versus methods using one analyte at a time; 9) The use of energy should be minimized; 10) Reagents obtained from renewable source should be preferred; 11) Toxic reagents should be eliminated or replaced; 12) The safety of the operator should be increased (Gałuszka et al., 2013).

3.3. *Potential physiological impacts of plant-wearable sensors*

Wearable sensors for plants may interfere with key physiological processes, particularly photosynthesis and transpiration, if not properly designed. When attached to leaves or stems, sensors can partially obstruct incident photosynthetically active radiation (PAR), leading to localized shading and potential reductions in photosynthetic efficiency. This effect is especially relevant for opaque or thick devices, as well as for long-term deployments on actively growing tissues. Transpiration may also be affected through physical blockage or partial occlusion of stomatal pores, which can alter water vapor fluxes and limit CO_2 diffusion into the leaf mesophyll. In addition, the presence of a sensor can modify the leaf boundary layer by trapping heat and moisture, thereby changing local temperature and relative humidity conditions at the leaf surface. Such microclimatic alterations may influence stomatal conductance and transpiration rates, ultimately affecting plant water use efficiency. To mitigate these effects, recent advances have focused on ultrathin, lightweight, and flexible materials with high optical transparency and gas permeability. Intermittent sensing strategies and non-invasive attachment methods further reduce the risk of chronic physiological perturbation. Overall, minimizing interference with photosynthesis and transpiration is a central design requirement for plant-wearable sensors, and future developments must prioritize bio-integrated, breathable, and mechanically compliant architectures to ensure reliable measurements without compromising plant health (Lo Presti et al., 2024; Qu et al., 2021).

4. Conclusions

We have investigated sustainable, biodegradable and flexible wearable dual-sensor for decentralized and fast non-destructive analysis of diquat, carbendazim and diphenylamine agrochemicals on the apple and pepper skin surface, water and saliva samples. The sensory platform was made by screen-printing technology on eco-friendly CA substrates/support plasticized with 1.8, 3.6, 5.4 and 7.2 mM of glycerol or TEC. The biodegradable wearable dual-sensor plasticized with 5.4 mM of glycerol exhibited an attractive analytical performance with high reproducibility, stability, selectivity, sensitivity, robustness and easy to use in the linear ranges between 0.1 and 1.0 μM, 0.2 and 2.0 μM and from 2.5 to 25 μM with limit of detections of 3.2 nM, 180 nM and 1.34 μM for diquat, carbendazim and diphenylamine pesticides. The attractive sensing performance was achieved combining judicious integration of transduction/detection principles with distinct analytic techniques on wearable dual-sensor integrated in a single platform. The handheld biosensing system using dual-channel Sensit BT analyzer can be connected via Bluetooth to a laptop, smartphone or tablet is ready to be used by any non-specialized operator in decentralized non-destructive screening of agrochemicals for monitoring, detection, on-site rapid decision, interventions in food safety and precision agriculture. With biodegradable wearable dual-sensor, new opportunities emerge for simultaneous and sequential on-site decentralized measurements with handheld biosensing systems. Biodegradable polymeric materials are particularly beneficial to fabricate bioelectronics platform for handheld systems in which decentralized nondestructive tracking requires disposable biosensing platforms. The results obtained with biodegradable wearable dual-sensor attached on apple and pepper skin surface, saliva and water samples indicate that the devices can be enclosed on any type of agricultural product or food samples including vegetables and fruits for rapid, decentralized, non-destructive and on-site monitoring with possibility of expand to diverse agrochemicals and samples applications. The sustainable and biodegradable wearable dual-sensor emerges as a significant advancement for rapid, decentralized and on-site nondestructive multiplexed tracking of agrochemicals within 3.28 min using a single microliter sample droplet toward food safety and precision agriculture.

CRediT authorship contribution statement

Samiris Côcco Teixeira: Visualization, Investigation. **Nathalia O. Gomes:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Sergio A.S. Machado:** Resources. **Taíla Veloso de Oliveira:** Writing – review & editing, Resources, Conceptualization. **Nilda F.F. Soares:** Resources. **Paulo A. Raymundo-Pereira:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Acknowledgments

The authors are thankful to São Paulo Research Foundation – FAPESP (grants 2023/08858-6, 2022/02164–0 and 2023/09685-8), National Council of Technological and Scientific Development – CNPq (grants 151113/2023-8, 307070/2022–0, 315244/2025-9 and 447026/2024–0). The authors are especially grateful to Mr. Marcio de Paula (CAQI/IQSC/USP) for the SEM images.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosx.2026.100758.

Data availability

The authors do not have permission to share data.

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