Sustainable monitoring of Zn(II) in biological fluids using office paper

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ABSTRACT

Herein, we describe a sustainable and inexpensive approach to monitor Zn(II) in biological fluids by fabricating an office paper-based electrochemical sensor. By following two easy steps, consisting of wax patterning and electrode screen-printing, the office paper provides an effective electroanalytical tool that is easily extensible to a broad range of analytes. This approach would be able to develop affordable user-friendly sensing devices, tackling the lack of resources in regions with poor-settings/facilities. In order to provide more details regarding the screen-printed electrodes fabrication, office paper, Whatman #1 chromatographic paper, and polyester have been characterized with electrochemical, morphological, and mechanical tests and compared. Using office paper, Zn(II) has been detected linearly up to 2 μg/mL with a detection limit equal to 25 ng/mL and a relative standard deviation of 8%. To highlight the feasibility, reliability, and easiness of the proposed electrochemical sensor, Zn(II) has been detected in serum and sweat at physiological level (μg/mL), and the accuracy of the method has been verified by satisfactory recoveries close to 100%.

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1. Introduction

The European Commission has recently adopted a common strategy to enhance a circular economy, fostering a sustainable economic growth [1]. In this context, the focus with respect to chemistry pays attention to green aspects, starting from the 12 Principles of Green Chemistry established by Anastas and Warner through the most innovative sustainable routes in chemical synthesis, such as the use of ionic liquids [2]. Regarding analytical methodologies, the 11th principle is focused on the development of real-time, in-process monitoring, and control of the target analyte in order to accomplish the analysis in an environmentally friendly manner. A sustainable analytical method should minimize the production of hazardous waste during the analysis to reduce environmental impact and it should provide a more sustainable use of recyclable materials. Furthermore, the measurement should be cost-effective allowing for low cost analysis. In the biomedical field, the World Health Organization (WHO) suggested that point-of-care (POC) devices should accomplish ASSURED (affordable, sensitive, specific, user-friendly, rapid and robust, equipment-free and deliverable to end-users) criteria to develop POC devices useful for resource-limited environments [3].

Paper, thanks to its availability and affordability, is on top of the list of materials suitable to realize sustainable POC devices [4,5]. Although the lignin removal during pulping processes requires the use of chemicals that may pollute the environment, plastic is made by monomers derived from oil or gas, by addition of various additives, reflecting in a higher pollution when compared with paper. Whitesides' group [6–8] and others [9–16] reported intriguing paper-based sensing platforms capable of measuring glucose, ethanol, proteins, ions, pollutants, etc. To realize paper-based POC devices, the presence of hydrophobic/hydrophilic areas is necessary to accomplish the measurement. Depending on the need (and on the resources), different techniques, i.e. plasma oxidation [15], inkjet-printing [16], photolithography [17], wax printing [18], were used to fabricate the well-defined hydrophobic/hydrophilic areas where reagents can be stored and analytes can easily diffuse/react/purge before being detected. Among these, wax printing technology is a helpful and cost-effective method for paper patterning. The use of ecologic wax-based ink provides implementation in fabricating disposable microfluidic paper-based analytical devices (μPADs) [19]. Especially in resource-limited areas where laboratory facilities are not accessible, wax offers an alternative technology for fabricating smart platforms for point-of-use devices. For instance, Songjaroen et al. [20] produced a colorimetric μPAD to detect glucose and BSA by simply wax dipping chromatographic paper, while Zhang et al. [21] used heated patterned iron components, coated by wax, to stamp a wax pattern into chromatographic paper, detecting hydrogen peroxide. Among several chromatographic papers,

Whatman #1 is often chosen as substrate in realizing these new-generation diagnostic devices due to its surface area, cellulose purity, porosity, uniform thickness, and lightness [5]. Nie et al. successfully detected glucose, cholesterol, lactate, and alcohol by integrating an electrode screen-printed on Whatman #1 chromatographic paper in a commercial hand-held glucometer device. They impressively lowered the cost of the device, from 0.5 \$/strip to 0.014 \$/strip, by simply replacing the classic plastic-based test strips with chromatographic paper [22]. In spite of this relevant finding, office paper might serve as a novel substrate in sensor manufacturing and, along with Whatman #1, it represents a sustainable tool to reduce the use of non-cellulosic substrates, i.e. plastic-based, alumina, glass. According to the prices listed on the web, the cost of office paper is roughly 1% of the cost of Whatman #1, and it is available almost everywhere. With our laboratory facilities, the cost for a single device is ca. 0.033, 0.025, and 0.018 Euro, respectively using polyester, Whatman #1 filter paper, and office paper. Recently, office paper has been utilized in a 96-well configuration to optically detect bacteria (*Geobacter sulfurreducens*) in a culture medium [23].

Herein, for the first time, we report the use of office paper as substrate to develop electrochemical sustainable POC devices for the analysis of biological matrices. In detail, this paper provides a facile strategy to manufacture sustainable, affordable, and home-made printed POC devices for biological matrices such as serum and sweat. Instead of the most used colorimetric detection, an electrochemical technique was selected for the transduction since it is already well established as a green solution in the analytical field [24], because 1) electrodes can be fabricated from non-toxic materials, 2) the manufacture is cost-effective, 3) miniaturization allows to minimize both sample size and the amount of waste, 4) it is easily transportable for *in situ* analysis, and 5) the energetic requirement is very low, i.e. portable potentiostat, smartphone. Furthermore, because the global POC market is expected to reach \$ 36.96 Billion by 2021, just employing office paper in the already existing sensor strips would represent a tremendous gain towards the decrease of production costs, as well as the environmental impact.

Paper, wax printing, and screen-printing have been combined to obtain a sensing platform that perfectly matches within the frame of green analytical chemistry and with the requirements established by WHO. To demonstrate the suitability of the proposed sustainable approach, an office paper-based POC device for zinc ion detection in serum and sweat was developed. Zinc has been selected because defined as "the metal of life" [25] and, even if the hyperzincemia is rare, zinc deficiency (below the physiological range, <0.59 μg/mL) is more spread and has an impact on growth, nervous system, immune system, and in severe cases its consequences are lethal. In this paper, morphological, mechanical, and electrochemical studies have been carried out to assess the suitability of the office paper in replacing plastic-based substrate towards electrochemical sensors fabrication.

2. Experimental

2.1. Reagents and equipment

Hexaammineruthenium (III) chloride (Ru(NH$_3$)$_6$Cl$_3$), potassium ferricyanide (K$_3$Fe(CN)$_6$), acetic acid (>99%), sodium acetate, sodium chloride, hydrochloric acid, zinc standard solution for atomic absorption (1000 μg/L), nickel (II) chloride hexahydrate, and human serum from male AB plasma, USA origin, sterile-filtered, were purchased from Sigma-Aldrich (USA). Bismuth standard solution for atomic absorption (1000 μg/L) and lead standard solution for atomic absorption (1000 μg/L) were purchased from Carlo Erba Reagenti (Italy). Copper standard solution for atomic absorp-
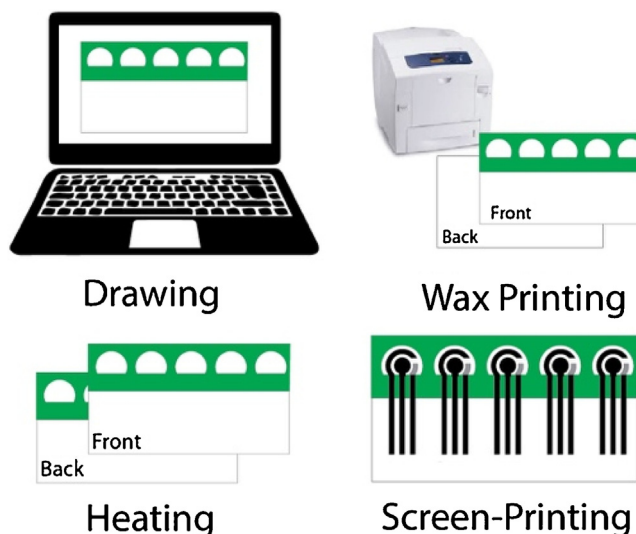

Fig. 1. Schematic representation of the method for the fabrication of office/Whatman #1 paper-based screen-printed electrodes.

tion (1000 μg/L), iron standard solution for atomic absorption (1000 μg/L), and magnesium chloride hexahydrate, were purchased from Fluka (Germany). All the solutions were prepared in distillate water. Cyclic voltammetry (CV), chronoamperometry, and square wave anodic stripping voltammetry (SWASV) were performed using a portable PalmSens Instrument (PalmSens, Netherlands) in connection with a laptop. The morphology of the SPEs was observed by field emission scanning electron microscopy (FEG-SEM, Leo Supra 35, UK), and A 3D surface profilometer (Veeco DEKTAK 150) was utilized to characterize the thickness of the SPEs.

2.2. Fabrication of paper-based platform

Firstly, the wax pattern was designed (15 mm × 13 mm rectangle, with a 10-mm diameter semi-circle not filled, Fig. S1-A in Supplementary material) that defines the testing area by using a drawing software (Adobe Illustrator) and office paper was used as a substrate for the fabrication of the paper-based screen-printed electrodes (SPEs). Office paper (Copy 2, 80 g/m^2, Fabriano, Italy) and filter paper (Whatman #1) were opportunely waxed with a solid-ink printer, ColorQube 8580 from Xerox (USA). Successively, wax printed office paper was thermally cured at 100 °C for 4 min, while filter paper required 2 min to be cured. This process allows the wax to diffuse through the paper, forming a hydrophobic confinement around the hydrophilic testing area. The thermal curing was responsible to pattern with the wax also the back-side of the paper, as shown in Fig. 1. After the hydrophilic area was surrounded by a hydrophobic wall, the three-electrode system was manually screen-printed using a squeegee. Firstly, Ag/AgCl ink (Electrodag 477 SS, Acheson, Italy) was used to print the connections and the pseudo-reference electrode (three 19 mm × 1.2 mm rectangles are used for electrode traces, and a 4 mm long and 1.2 mm width arc is used for the reference electrode, Fig. S1-B in Supplementary material) and successively, the working and counter electrodes (three 19 mm × 1.2 mm rectangles are used to cover the Ag/AgCl ink traces, and a 13 mm long and 1.2 mm width arc is used for the counter electrode, Fig. S1-C in Supplementary material) were obtained by screen-printing carbon ink (Electrodag 421, Acheson, Italy), as displayed in Fig. 1.

In order to evaluate the office-paper suitability, electrodes were also screen-printed onto polyester utilizing a 245 DEK (UK) screen-printing machine (Autostat HT5, Autotype, Italy), using the same conductive inks, as described above. In the case of polyester, wax

Table 1
Costs of the components for producing one device (all the costs have to be intended in Euro).

Substrate	Ag/AgCl ink	Carbon ink	Insulator	Substrate	Total cost	Saving[c]
Polyester	0.010	0.007	0.003[a]	0.013	0.033	45%
Whatman #1			0.001[b]	0.007	0.025	30%
Office paper			0.001[b]	0.0001	0.018	/

[a] Insulator ink.
[b] Wax.
[c] Calculated as 1 − [Office paper/Other] × 100.

was not used. To insulate the electrode traces, a layer of insulator ink (Vinilflat 38.101E, Argon, Italy) was screen-printed as the final step of the fabrication process. The different substrates that have been interrogated, displayed different profiles regarding the thickness of substrate, ink, and wax/insulator. The office paper is 100-μm thick (with a roughness of 2 μm), conductive ink is 15-μm thick (with a roughness of 3 μm), and the wax layer is 6 μm-thick (with a roughness of 3 μm); the Whatman #1 chromatographic paper is 215-μm thick (with a roughness of 6 μm), conductive ink is 13-μm thick (with a roughness of 3 μm), and the wax layer is 7.5 μm-thick (with a roughness of 5 μm); the polyester is 125-μm thick (with a roughness of 0.05 μm), conductive ink is 10-μm thick (with a roughness of 3 μm), and the insulating layer is 8 μm-thick (with a roughness of 1 μm). The SPEs are stable for more than a month, when stored at room temperature and in dark conditions, in order to limit the oxidation of silver due to light exposure. All the images related to these measurements have been included in the Supplementary material file, Figs S2–S4.

2.3. Production cost of a single printed device

The electrodes were screen-printed using three diverse substrates: office paper, Whatman #1 chromatographic paper, and polyester. In Table 1, the cost of each single device was calculated by considering the price (at our laboratory scale) of substrates, conductive inks, and insulators. Moreover, an estimation of the cost savings, using the office paper, was provided.

2.4. Zn(II) measurements in standard and biological fluids

The electroanalytical procedure adopted to measure Zn(II) was Square Wave Anodic Stripping Voltammetry (SW-ASV) using a bismuth-modified SPE. Prior to detecting Zn(II), a Bi(III) film was electrodeposited onto the working electrode by applying a potential of −1.4 V (vs. Ag/AgCl) for 300 s in a pH 4.6 buffered solution containing 0.05 M sodium acetate and 0.05 M NaCl. After the film was formed, standard solutions prepared in acetate buffer as well as serum and sweat were added onto the SPE and monitored.

3. Results and discussion

3.1. Characterization of the paper-based and polyester-based platforms

Fig. 1 provides a general guide to manufacture ready-to-use electroanalytical tools. Office paper is well-suited to replace plastic in sensor implementation. Fig. 2 displays a comparison among printing electrochemical sensors onto office paper, Whatman #1, and polyester. Office paper, Whatman #1, and polyester have been compared using $Ru(NH_3)_6Cl_3$ as the redox probe. While the electrochemical cell for the SPEs onto office paper and polyester was a 100 μL-drop, measurements for the Whatman #1-based SPE were performed exploiting the paper porosity, which was impregnated with 10 μL of solution. By varying the scan rate of cyclic voltam-

metry, in the interval comprised between 0.01 and 1 V/S, much information was obtained.

1) The peak-to-peak separation (ΔE), calculated using 0.05 V/s as scan rate, resulted equivalent within the experimental errors. It was measured as 80 ± 10, 98 ± 6, and 87 ± 8 mV, respectively to office paper, Whatman #1, and polyester SPEs. ΔE provides a qualitative estimation of the electron transfer rate due to the redox process at the electrode surface. By using the Nicholson method [26], the observed standard heterogeneous electron transfer rates, k^0, were estimated. The ΔEs obtained in the presence of $Ru(NH_3)_6Cl_3$, in a wide range of scan rates, are consistent with k^0 of (5.5 ± 0.7) 10^{-3}, (5.1 ± 0.5) 10^{-3}, and (4.9 ± 0.6) 10^{-3} cm/s, respective to office paper, Whatman #1, and polyester SPEs. 2) Associated with the Nicholson equation, the Randles-Sevcik equation [27], which correlates the peak intensity to the scan rate, has been exploited to evaluate how the redox probe diffuses at the electrode surface. As displayed in Fig. 2G, H, and F, all the SPEs are consistent with a linear log (peak current) vs. log (scan rate) dependence. The slopes are close to 0.5, in agreement with Randles-Sevcik equation [28]. 3) In order to estimate the active area of the different substrates utilized, chronoamperometric experiments in presence of different concentrations of ferricyanide were performed and Cottrell equation, $i = nFAD^{0.5}C/\pi^{0.5}t^{0.5}$ [26], was used. Experiments have been carried out using 2.5, 5, and 10 mM ferricyanide, and a plot i vs. $t^{0.5}$ was obtained for each concentration tested (Fig. S5 in Supplementary material). The value of diffusion coefficient (D) for ferricyanide was approximated to 6.08 and $2.03*10^{-6}$ cm^2/s, respectively for office paper and polyester, and porous paper, as calculated in our previous work [13]. Electroactive area resulted to be equal to 0.21 ± 0.03, 0.15 ± 0.03, and 0.11 ± 0.01 cm^2, for office paper, Whatman #1 paper, and polyester, respectively. These results are in agreement with the different roughness of the substrates used. 4) SEM micrographs displayed in Fig. 2J–L, highlight the different structure of the substrates where electrodes have been printed. The high porosity of Whatman #1 (Fig. 2K) is reflected by a less uniform carbon coating, while office paper (Fig. 2J) and polyester (Fig. 2L) display a better coverage. However, polyester, due to its smoothness, allows a homogenous carbon ink deposition. 5) The three typologies of SPEs have been mechanically investigated to verify the flexibility. Their electrochemical responses in the presence of ferricyanide as redox probe were unchanged after 50 bendings (data not shown). Considering all these studies, when compared with Whatman #1 and polyester, office paper exhibited promising electrochemical features. Office paper and polyester display similar value of ΔEs, while the tiny difference observed in regards to Whatman #1 could be attributable to the different electrochemical cell used in performing the characterization. However, the porous structure of Whatman #1 did not affect significantly the electron transfer rate at the electrode surface. Due to its suitability in fabricating valuable SPEs, office paper has been challenged towards complex matrices analysis. Because of the estimated growth of the healthcare market [29] and the necessity to develop lower cost devices, office paper has been tested in serum and sweat. Zinc has been chosen as the model analyte for several reasons:
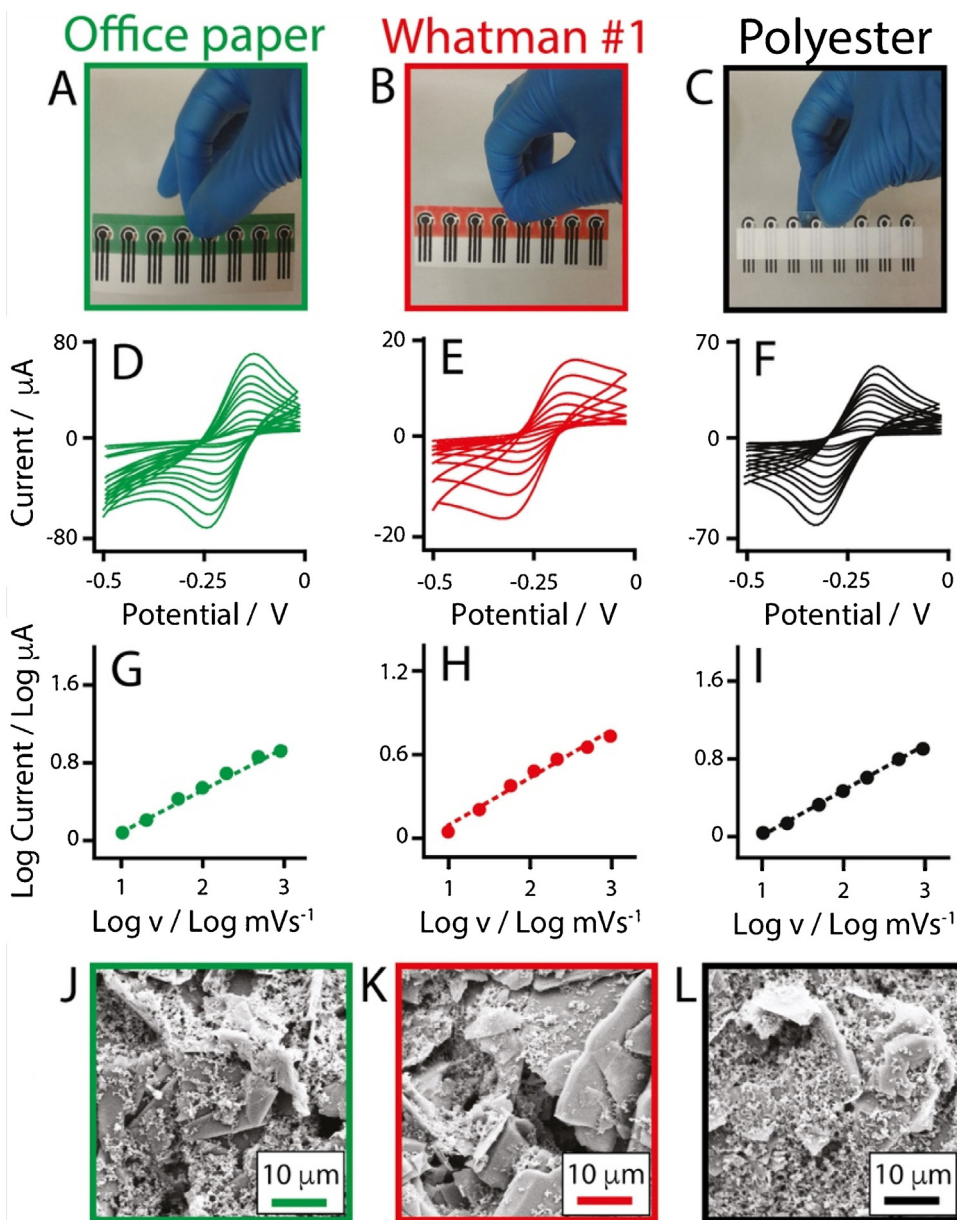
Fig. 2. Photographs of SPEs realized on A) office paper, B) What-man #1, and C) polyester. Cyclic voltammograms of SPEs onto D) office paper, E) Whatman #1, and F) polyester. Log (peak current) vs log (scan rate) correlation for SPEs onto G) office paper, H) Whatman #1, and I) polyester. CV experiments have been carried in 2 mM Ru(NH$_3$)$_6$Cl$_3$ prepared in acetate buffer (pH 4.6). Scan rate has been varied from 0.01 to 1 V/s. SEM micrographs related to J) office paper, K) Whatman #1, and L) polyester SPEs.

1) its level is correlated to a patient's health status [30,31];
2) it represents one of the most utilized targets to develop wearable fitness device [32];
3) it can provide a general starting-point for the analysis of other relevant metals (As, Hg, Pb, Cd, Cu, Fe).

3.2. Detection of zinc ions via anodic stripping voltammetry

Beyond the use of office paper, the analytical method itself is sustainable. To detect Zinc as Zn(II), anodic stripping voltammetry (ASV) using a bismuth film electrode (Bi-SPE) has been utilized. Briefly, after the Bi film has been electrodeposited on SPE, Zn(II) is first accumulated at Bi-SPE (Zn(II) → Zn^0) and then re-dissolved (stripped, Zn^0 → Zn(II)) giving a detectable signal (Fig. S6 in Supplementary material).

Prof. Wang introduced Bi-film (on glassy carbon and carbon fiber substrates) for ASV measurements of heavy metals as a sustainable alternative of mercury, i.e. hanging mercury drop electrode (HMDE), mercury film electrode (MFE) [33,34]. Bismuth-based electrodes address the growing concerns regarding the toxicity and the ease of measurement, because i) bismuth is less toxic than mercury, and ii) bismuth film allows for the measurement in the presence of oxygen, avoiding the expensive and tedious oxygen removing.

In order to obtain the best sensitivity, all the experimental parameters (i.e. concentration of bismuth, deposition time of bismuth and zinc, deposition potential of zinc deposition and stripping, frequency and step of square wave) were finely optimized (Supplementary material, Figs. S7–S12). Acetate buffer (pH = 4.6) was chosen as the working media taking as reference a previous work reported by the group of Wang [32] and considering that an
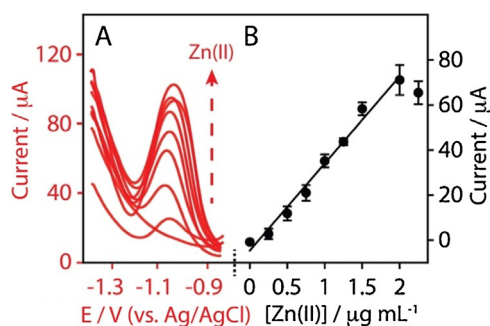
Fig. 3. Characterization of the office paper SPE stripping metal sensor in buffer. A) Stripping voltammograms for increasing Zn levels up to 2.5 µg/mL. B) Corresponding calibration plot. SW-ASV conditions: 0.05 M acetate buffer containing 0.05 M NaCl (pH 4.6), 50 µg/mL bismuth, deposition potential at −1.4 V for 300 s; SW stripping scan up to −0.8 V using a frequency of 50 Hz, an amplitude of 20 mV, and a potential step of 10 mV.

Fig. 4. Selectivity of the office paper-based SPE has been evaluated in the presence of zinc (1 ppm), copper (1 ppm), iron (1 ppm), magnesium (20 ppm), lead (150 ppb), and nickel (5 ppb). Inset: Signals of the blank solution for creating the Bismuth film on the SPE. Operating parameters as reported in Fig. 3 of the manuscript.

Fig. 5. Stripping voltammograms performed in unspiked buffer (black dashed line), serum (red dashed line), sweat (cyan dashed line), and after a 0.5 ppm-spiking of Zn in buffer (black solid line), serum (red solid line), sweat (cyan solid line). Operating parameters as reported in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

acidic pH is often recommended for the stripping analysis of metals in solution, as in the case of arsenic, mercury, copper, etc. [35–37]. The platform was challenged up to 2.5 µg/mL using just a 100 µL-droplet. As displayed in Fig. 3, the device response was linear in a wide range (up to 2 µg/mL) showing well-defined Zn stripping peaks around −1.05 V vs. Ag/AgCl (Fig. 3).

A current (µA) vs [Zn(II)] (µg/mL) relationship was described by the equation y = (38.6 ± 1.58) × − (3.77 ± 1.63), with a detection limit (S/N = 3) equal to 25 ng/mL. The repeatability of the response was evaluated for five measurements of a 1 µg/mL Zn(II) solution, utilizing different sensors. A relative standard deviation (RSD) of 8% was estimated, and it should be noted that all points of the calibration curve were obtained by using a single one-shot sensor.

In order to further characterize the developed method, Zn(II) was also detected using a polyester-based and a Whatman No.1 paper-based SPE. In the first case, a sensitivity of 49 µAmL/µg was achieved, while it was not possible detect Zn(II) at the Whatman #1 paper-based SPE (no signal was detected up to 10 µg/mL Zn(II)), as shown in Fig. S13 in Supplementary material. This could be ascribed to the different electrochemical cells utilized depending on the substrate used for SPE fabrication. Measurements at office paper and polyester were performed by covering the electrodes with a drop of sample (100 µL), and it is possible that a better Bismuth layer was formed. In the case of the Whatman #1-based SPE the measurements were performed exploiting the paper porosity, which was impregnated with the sample (10 µL), and the species in solution have to pass through a cellulosic network,before to reach the electrodes. Fig. S14 in Supplementary material.

This first example of a office paper-based Zn sensor, compared favorably with other existing electrochemical platforms, in terms of linearity, detection limit, and fabrication route, Table 2.

The office paper-based SPE developed in this work is characterized by the best detection limit when compared with the other SPEs based on the bismuth film [32,42,43]. Although some methods, i.e. oxidized graphene-fluorine doped tin-oxide [38], and photolithographed gold [39], displayed a superior sensitivity, it should be noted that these methods require more sophisticated material and equipment. The paper office provides a low-cost and easy-to-fabricate device for the detection of Zinc, and it can be adopted for the realization of diverse sensing platforms.

3.3. Interference study

In order to investigate the selectivity of the office-paper SPE toward the detection of Zn(II), it was interrogated in the presence of different metals, such as of copper (1 ppm), iron (1 ppm), magnesium (20 ppm), l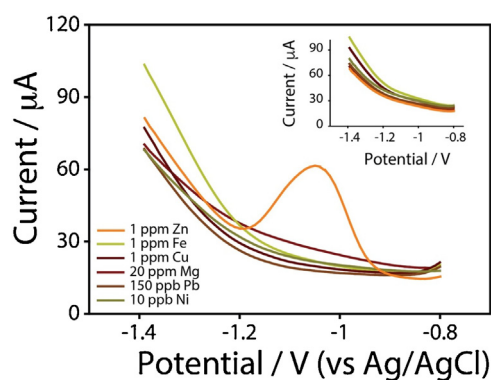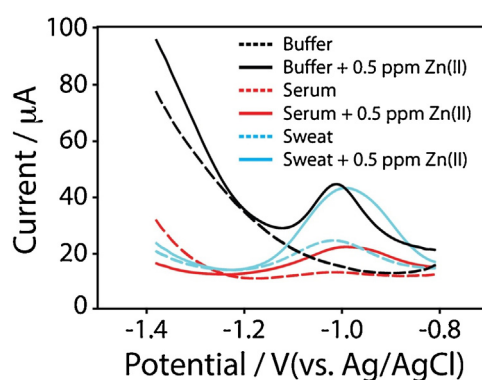ead (150 ppb), and nickel (5 ppb). These species may be present in biological fluids, i.e. blood, serum, sweat, and their concentrations were selected in agreement with their mean concentrations found in biological fluids [44]. As shown in Fig. 4, the signals recorded with the interfering species were not effective in comparison with the signal related to zinc.

3.4. Detection of zinc ions in serum and sweat samples

In order to verify the applicability of office paper to biological fluids, we detected Zn(II) in serum and sweat, Fig. 5.

No chemical treatments were necessary to work with the office paper SPE: serum and sweat were just added on top of that. 20 µL of real matrix were monitored after having formed the bismuth film in 80 µL of acetate buffer. The composition of these matrices played an important role in terms of sensitivity. Serum and sweat are composed of proteins, fat, and salts. A 20-µL addition was chosen as the optimal amount depending on two major contributions: protein/fats stacking onto paper and salt concentration. For instance, a huge amount of serum/sweat will cause an increase of the fouling at the SPE, determining a decrease of the signal. On the other hand, too little amount of sample will be responsible for the diminution of electrolytes, reflecting a decrease of the signal. 20 µL was the most favorable compromise between a low protein/fat stack and sufficient electrolyte level. The effectiveness of the paper-based device has been evaluated in different serum and sweat samples, which have been provided by volunteers (one of the serum sample was of commercial grade, purchased from Sigma Aldrich), Fig. 6.

Table 2
Comparison of different electrochemical sensors for Zn(II) detection.

Sensing element	Substrate	Method	Linear range	LOD	Biological matrix	Ref.
Aptasensor on core-shell SiO$_2$-Pt@meso-SiO$_2$	Hydroxylated fluoride doped thin oxide	DPASV	100 pM – 50 μM (6.5 ng/mL–3.2 μg/mL)	65 pM (4 ng/mL)	Blood, human cells	[38]
Tin film/AuNPs	Photolithographed gold microelectrode chip-	SWASV	10–500 ng/mL	5 ng/mL	/	[39]
Mercury film	Carbon tip	DPASV	Up to 10 μg/mL	600 ng/mL	Artificial plasma	[40]
Gold	Bare gold	SWASV[a]	25–250 ng/mL	5 ng/mL	/	[41]
Bismuth oxide	Carbon SPE on plastic substrate	SWASV	75–600 ng/mL	33 ng/mL	/	[42]
Bismuth	Photolithographed Gold on glass	SWASV	Up to 50 μM (3.3 μg/mL)	6 μM (400 ng/mL)	Acid digested Serum	[43]
Bismuth	Carbon SPE on wearable tattoo	SWASV	0.1–2 μg/mL	50 ng/mL	Sweat	[32]
Bismuth	Carbon SPE on office paper	SWASV	0.08–2 μg/mL	25 ng/mL	Serum, Sweat	This Work

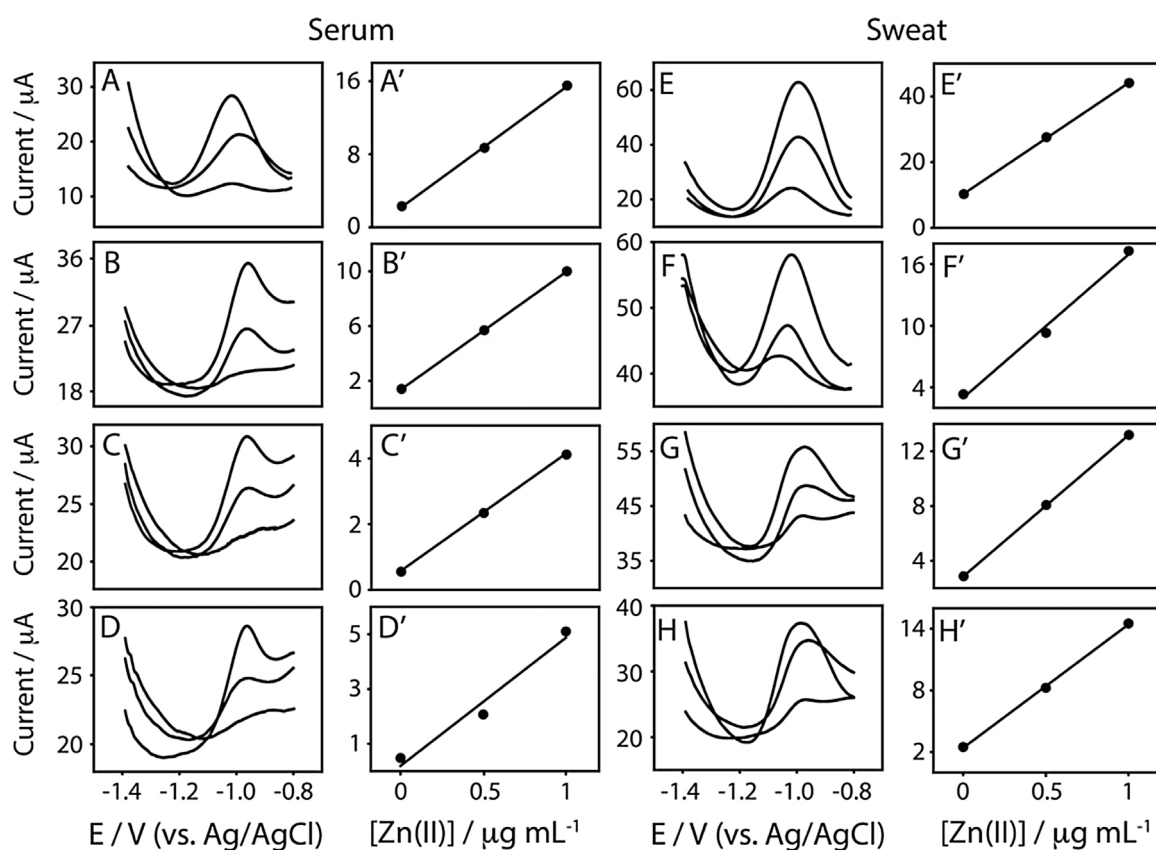[a] SWASV has been associated with batch injection analysis (BIA).

Fig. 6. Stripping voltammograms obtained by measuring Zn(II) in serum (A–D) and sweat (E–H) samples, and their corresponding calibration plots, (A'–D') for serum and (E'–H') for serum. Operating parameters as reported in Fig. 3.

Although the different matrices gave slightly different sensitivities, by using the standard addition method, the office paper-based SPE was capable to estimate the initial concentration of zinc in both matrices. The obtained results (Tables S1 and S3 in Supplementary material) have been perfectly compatible with the physiological levels of zinc both in serum and sweat, respectively, 0.59–1.18 μg/mL [43] and 0.39–1.56 μg/mL [32].

Moreover, the accuracy of the method was evaluated by spiking serum and sweat with concentration of Zn(II) comprised between 0.5 and 1 μg/mL. In serum, recoveries equal to 95 ± 9% and 103 ± 9%, relative to 0.5 and 1 μg/mL Zn(II) were obtained. In sweat, 0.5 and 1 μg/mL Zn(II) concentrations were recovered with an accuracy of 97 ± 9% and 96 ± 11% respectively.

4. Conclusions

In this work, we reported the first example of biological fluid analysis by using electrodes screen-printed on office paper. This paper provides a more sustainable substrate when compared to polyester, which is widely used for the development of the existing diagnostic tools, because it can be easily incinerated reducing the environmental impact especially in those poor-setting areas. The combination of office paper as a substrate, wax printing to define the testing area as well as isolate the electrical contacts, and

environmentally friendly bismuth to modify the SPEs, allowed a sustainable and sensitive zinc ion detection in sweat and serum samples.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.snb.2017.07.161.

Dimensions of wax pattern and screen-printed electrodes, thickness of the fabricated platforms, determination of active area of the different SPEs, optimization of the experimental parameters, comparison of sensitivity at at office paper, polyester, and Whatman #1 paper-based SPE, electrochemical configurations at different substrates for SPE fabrication, and two tables that contain sensitivities to Zn(II) obtained in serum and sweat samples.

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