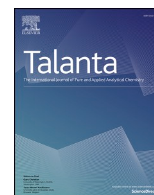
Talanta 266 (2024) 124980

Contents lists available at ScienceDirect

Talanta

journal homepage: www.elsevier.com/locate/talanta



A do-it-yourself electrochemical cell based on pencil leads and transparency sheets: Application to the enzymatic determination of histamine

Ricarda Torre [a], Estefania Costa-Rama [b,*], Henri P.A. Nouws [a], Cristina Delerue-Matos [a,**]

[a] REQUIMTE/LAQV, Instituto Superior de Engenharia Do Porto, Instituto Politécnico Do Porto, Rua Dr. António Bernardino de Almeida 431, 4249-015, Porto, Portugal
[b] Departamento de Química Física y Analítica, Universidad de Oviedo, Av. Julián Clavería 8, 33006, Oviedo, Spain

ARTICLE INFO

Handling editor: Agata Michalska

Keywords:
Electrochemical biosensor
Biogenic amine
Histamine
Diamine oxidase
Transparency sheet
Pencil leads

ABSTRACT

The availability of more efficient analytical methods that answer the world's demands is a challenge and their development continues to be a difficult task. In this work the construction of an electrochemical cell, based on low-cost and accessible materials, that can be easily constructed and used for electroanalytical purposes, is described. Pencil leads were used as electrodes and a transparency sheet as the base. This cell was used as transducer for developing an amperometric biosensor for the quantification of histamine, which is the only biogenic amine regulated by law. The analysis was based on the use of diamine oxidase as biorecognition element, hexacyanoferrate(III) as electron-transfer mediator, and chronoamperometry, at +0.5 V during 100 s, to record the analytical signal. A linear relationship between histamine concentration and the analytical signal was established between 5.0 and 35 mg L^{-1} and a low limit of detection (1.0 mg L^{-1}) was achieved. The analysis of different fish species (sardine and tuna) was performed, obtaining recovery values between 102% and 110%. The stability of the sensor is noteworthy: it maintained 95% of the initial analytical signal after 15 days.

R. Torre: Formal analysis, Investigation, Methodology, Writing – original draft. E. Costa-Rama: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Supervision, Writing – review & editing. H.P.A. Nouws: Formal analysis, Funding acquisition, Project administration, Resources, Validation, Supervision, Writing – review & editing. C. Delerue-Matos: Funding acquisition, Project administration, Resources, Writing – review & editing.

1. Introduction

Food safety and quality are growing concerns because of the rise of the world's population and globalization, increasing the amount of necessary foodstuffs and their transport around the globe. More than 200 diseases are caused by the intake of food contaminated with microorganisms and (bio)chemical toxins; every year almost 1 in 10 people in the world fall ill because of the consumption of contaminated food, and 420,000 of them die as a result of this intake [1]. One of the sources of foodborne illnesses are biogenic amines (BAs). These amines are produced through the microbial decarboxylation of amino acids. Histamine, produced through the decarboxylation of histidine, is considered the most harmful BA to human health, causing an illness known as histamine fish poisoning (or scombroid poisoning) when it is ingested in high amounts [2–4]. The main symptoms associated with this poisoning are headache, urticarial, abdominal pain, diarrhea, and nausea, the severity of which depends on the amount of ingested histamine and the affected individual's susceptibility. Nevertheless, histamine ingestion does not involve a health risk when its concentration is restrained, but, if fish is stored during long times and/or at temperatures above 4 °C, the histamine concentration rapidly increases, especially in histidine-rich species such as sardine and tuna. To increase consumer protection, the EU established maximum limits for histamine concentration in fish: 400 mg kg^{-1} for cured fish products and 200 mg kg^{-1} for fresh fish [5]. Histamine can also be present in many other foods (e.g., meat, cheese, and fermented beverages such as wine and beer); indeed, outbreaks of histamine poisoning related to cheese have also been reported. However, there is no legislation regarding histamine contents in cheeses or other dairy products [4].

Due to legal and consumer demands, there is an increasing interest in the development of efficient analytical systems that can guarantee food safety along the entire production chain. Apart from having suitable

* Corresponding author.
** Corresponding author.
E-mail addresses: costaestefania@uniovi.es (E. Costa-Rama), cmm@isep.ipp.pt (C. Delerue-Matos).

https://doi.org/10.1016/j.talanta.2023.124980
Received 23 April 2023; Received in revised form 10 July 2023; Accepted 22 July 2023
Available online 25 July 2023
0039-9140/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

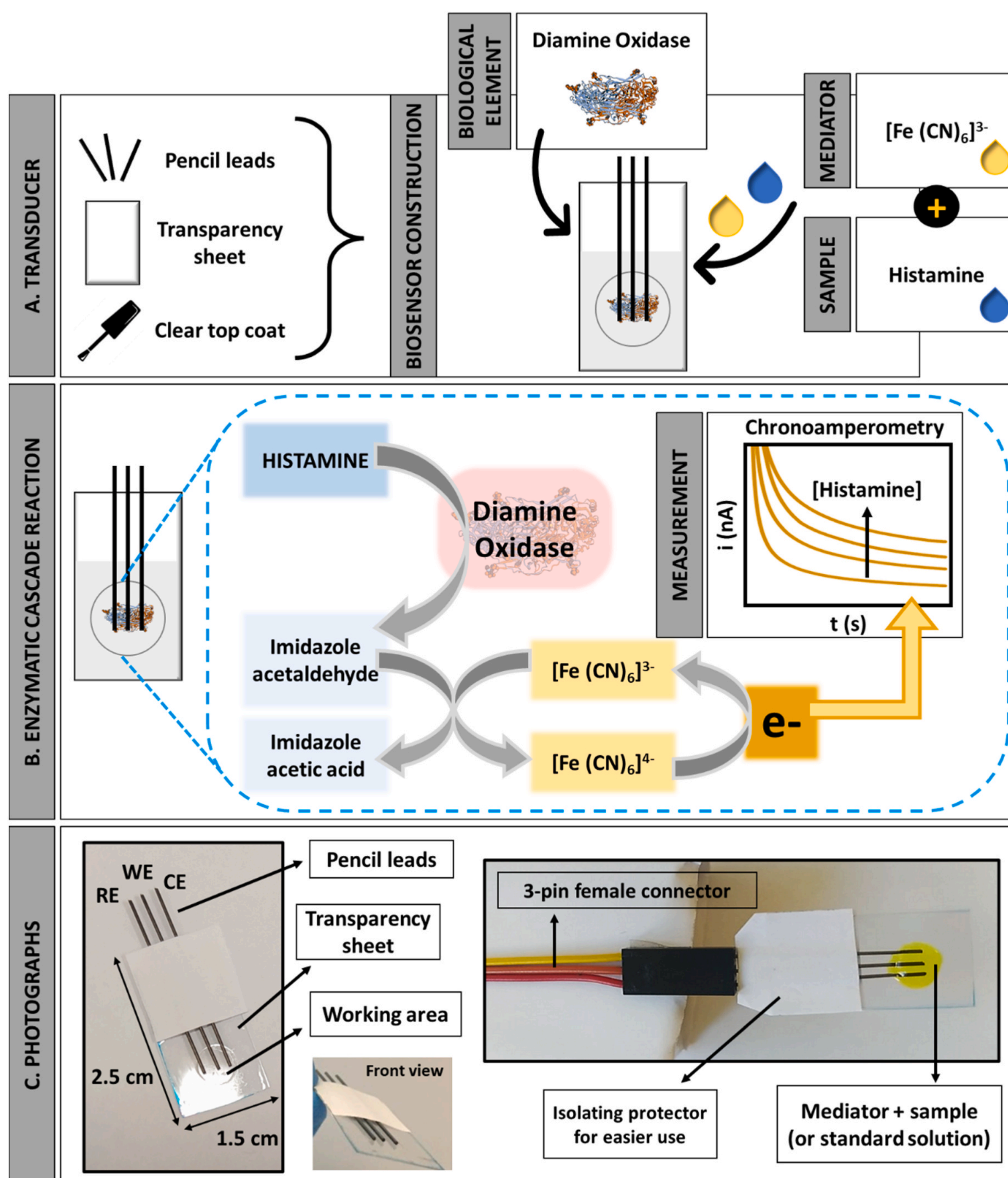


Fig. 1. Schematic representation of the **(A)** construction of the proposed biosensor, **(B)** mechanism of the enzymatic and electrochemical reactions that occur on the biosensor for histamine analysis and **(C)** photographs of the electrochemical cell (left) and the biosensor with histamine and mediator solutions (right).

analytical features, these systems should, ideally, be easy to construct and operate, cheap, portable, and have a short response, in order to be easily accessible even in remote places and low-income countries [6]. Nowadays, there is an enormous variety of analytical methods for food control. Most of these methods have great analytical characteristics, but can only be used in centralized laboratories, i.e., samples need to be transported to these laboratories that are equipped with complex and expensive instrumentation which must be operated by specialized operators. Examples are chromatographic methods that can determinate several analytes at the same time but require complex instrumentation and long analysis times. Therefore, the development of simple, small-sized, and low-cost analytical devices that allow fast analysis to guarantee food safety is a field of increasing interest. In this sense, electrochemical biosensors are an interesting alternative to conventional methods and commercial kits because of their good analytical features, low-cost, ability to be miniaturized, and the possibility of *in-situ* analysis. The exploration of new (bio)materials and sensing technologies plays a huge part in the implementation of cheap, accessible, and integrated sensors [7,8]. In the case of electrochemical transducers, the most frequently used electrode materials are based on carbon (e.g., glassy carbon, graphite, carbon black, and carbon fibers or carbon-based nanomaterials), metals (e.g., gold, platinum, silver), metal oxides (e.g., indium tin oxide –ITO-) and metal (nano)composites (e.g., based on Au, Ag or Pt nanoparticles and Cu, Zn or Ni nanostructures). For miniaturized electrochemical cells, the most common design consists of the printing or deposition of conductive inks (also based on carbon or

metallic materials) on rigid plane substrates such as ceramic or polymers. However, the great boom of the last decade in the use of common mass-produced materials for the construction of electroanalytical devices has led to the development of electrochemical cells based on the deposition or printing of conductive inks on flexible substrates such as paper and transparency sheets [9,10]. Moreover, common daily-used materials such as pins [11–13] and staples [14,15], and pencil leads have been used as electrodes [16–19] to achieve innovative and cheap electroanalytical platforms. Regarding the pencil leads, in most of the cases, only one pencil lead, acting as working electrode, is used in the electrochemical cell and it is combined with reference and counter electrodes based on conventional materials (e.g., Ag/AgCl and Pt, respectively). To the best of our knowledge, only one electrochemical cell using three pencil leads as working, reference and counter electrodes has been already reported [20]. In this work, the fungicide benzovindiflupyr was quantify, taking advantage of its electroactivity, using a 10-mL electrochemical cell.

Regarding histamine determination, several robust and sensitive methods are already available, but simple and portable devices that allow rapid histamine screening at any point of the fish production chain are still scarce. In the last years, different electrochemical devices have been developed for histamine analysis. Many of them were based on traditional electrochemical cells that need large volumes (milliliters) for analysis and use carbon electrodes modified with several (nano)composites [21–24]. Screen-printed electrodes (mainly carbon, but often modified with different (nano)materials [8,25–28]) on a rigid substrate were also used since they are robust and miniaturized, requiring low (microliter) sample volumes. There are also examples of electrochemical histamine sensors using flexible transducers fabricated by screen-printing [29] or photolithography [30] on polymeric substrates.

In this work we present the design and development of a miniaturized (≈40 μL) electrochemical cell combining unmodified graphite pencil leads as working, reference and counter electrodes, and a transparency sheet as substrate. This cell was used to construct an enzymatic sensor for the analysis of histamine. The use of pencil leads for histamine sensors was already reported, but, as mentioned before, in these works only one pencil lead was used (as working electrode, modified with Cu@Pd core-shell nanostructures) while the reference and counter electrodes were an Ag/AgCl electrode and a Pt wire, respectively [31,32]. Pencil leads, and transparency sheet were chosen because they are easily accessible materials. Since the pencil leads are made of graphite, they can be used as electrodes without any pretreatment. It has been demonstrated that transparency sheets are suitable substrates because of their flexibility, chemical compatibility, and disposability [11,33]. Therefore, the combination of these materials results in a device that is highly attractive in terms of cost, using materials that almost everybody has at home, without the need for additional (nano)materials and printing, sputtering or deposition techniques. For the construction of the biosensor, diamine oxidase was used as biological recognition element and hexacyanoferrate(III) as redox mediator.

2. Experimental section

2.1. Reagents, materials, and equipment

Diamine oxidase (DAO, 0.11 U mg^{-1}), potassium hexacyanoferrate (II), potassium hexacyanoferrate(III), and the biogenic amines (histamine, putrescine, spermine, spermidine, phenylethylamine, and cadaverine) were supplied by Sigma-Aldrich. All the working solutions of DAO, potassium hexacyanoferrate, and the biogenic amines were prepared in 0.1 M phosphate buffer (PB, pH 7.2) since this is the optimum pH to dissolve the enzyme and the ideal pH when histamine is used as substrate [34]. Ultrapure water from a Millipore (Simplicity 185) water purification system was used throughout the work. All the chemicals were analytical reagent grade and were used without further treatment or purification. The fresh tuna and frozen sardine were purchased in a local market.

Pencil leads (type HB) from Staples (d = 0.5 mm, l = 6 cm) and clear nail polish were purchased in a local shop. Transparency sheets (Office tree – Overhead Folien) and the 3-pin Dupont cable, used as edge connector for the pencil leads, were purchased from Amazon. A Metrohm-Autolab potentiostat/galvanostat (PGSTAT 101) controlled by NOVA software (v.1.10) was used for the electrochemical measurements.

2.2. Fabrication of the electrochemical cell

For the construction of the electrochemical cell, transparency sheets were cut in rectangles (2.5 cm × 1.5 cm). The working area (a circle with a 0.5-cm diameter, i.e., 0.196 cm^2) was delimited by applying clear nail polish to create an area where the measurement solution is contained, which was left to dry for 15 min at room temperature (Fig. S1). Pencil leads for serving as working (WE), reference (RE) and counter (CE) electrodes were cut to a final length of 3 cm and immersed into PB pH 7.2 solution overnight before use. The 3-pin female cable allows the alignment of the pencil leads at the same distance and provides an easy, quick, and reproducible connection of the electrodes to the potentiostat (Fig. S1). The final design of the constructed electrochemical cell is shown in Fig. 1.

2.3. Enzyme immobilization

A very simple procedure was followed for the immobilization of DAO on the working area of the electrochemical cell. The procedure consisted of depositing 2 μL of a 0.50-mg μL^{-1} DAO solution [34] on the working area of the transparency sheet (creating an enzyme layer with a thickness of about 0.1 mm). After drying for 15 min at room temperature the biosensor was ready to use.

2.4. Electrochemical measurements

To study the electrochemical responses of the constructed electrochemical cell, cyclic voltammograms of a 5.0-mM hexacyanoferrate(II) solution were recorded between −0.6 and + 0.8 V at 50 mV s^{-1}. A 40-μL aliquot of the solution was placed on the working area of the cell, covering the three pencil leads.

For histamine analysis using the enzymatic sensor, 20 μL of a histamine solution (standard or sample) and 20 μL of a hexacyanoferrate(III) solution (5.0 mM in the optimized procedure) were deposited on the working area, again covering the three electrodes. The mixture was left to react for 10 min before recording the chronoamperograms at +0.5 V (optimized potential) for 100 s, assuring that the current plateau was reached. The averages of the currents of the last 5 s were used as the analytical signals for quantification purposes.

2.5. Sample analysis

The biosensor was applied to the analysis of fish (frozen sardine and fresh tuna). Histamine was extracted from the sardine and the tuna by a simple procedure based on the one provided with the commercial R-Biopharm enzymatic kit for histamine determination [35]. The procedure consisted of: (i) mixing 20 mL of deionized water with 5.0 g of fish sample using a vortex mixer, (ii) placing the mixture in a boiling water bath for 20 min and, after cooling to room temperature, (iii) centrifuging for 2 min at 10,000 g. Finally, (iv) the supernatant was collected and stored at −80 °C.

3. Results and discussion

Carbon-based electrodes are the most common electrodes used in electroanalytical platforms because of their excellent properties such as chemical inertness, low background current, and wide potential window

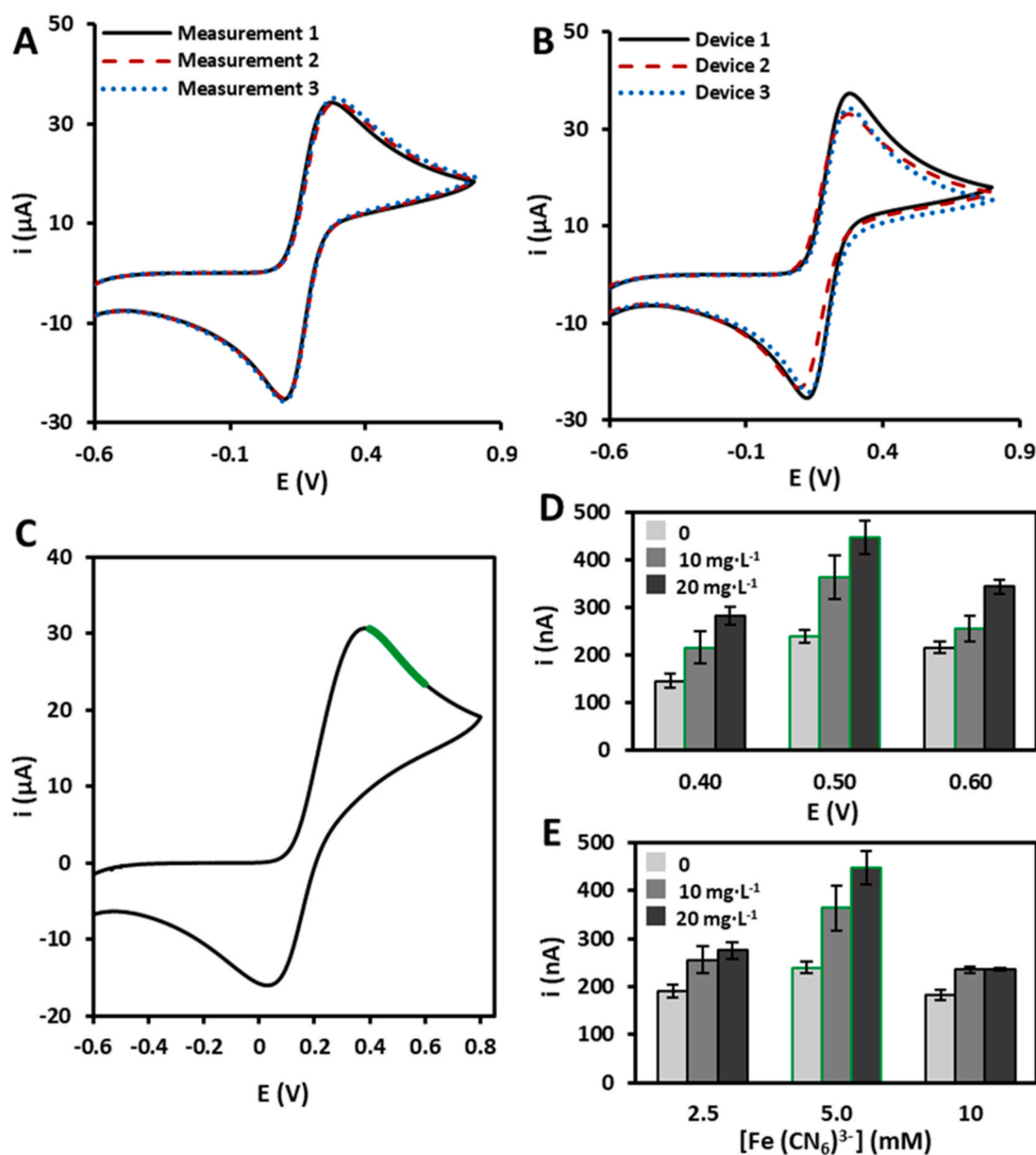


Fig. 2. (A, B) CVs of 5.0-mM $[Fe(CN)_6]^{4-}$ solutions using **(A)** the same electrode set and different transparency sheets, and **(B)** three different electrode sets (i.e., different WE, RE and CE) and transparency sheets; scan rate: 50 mV s^{-1}. **(C)** CV of a 5.0-mM $[Fe(CN)_6]^{4-}$ solution using the enzymatic sensor; scan rate: 50 mV s^{-1} (the potential range chosen for the optimization study is indicated in green); experimental conditions: DAO 0.50 mg μL^{-1}. **(D, E)** Optimization studies: **(D)** Effect of the measuring potential and **(E)** effect of $[Fe(CN)_6]^{3-}$ concentration on the analytical signal for different histamine concentrations (0, 10, and 20 mg L^{-1}). Error bars represent ±*SD* of three different measurements. Experimental conditions: D: DAO - 0.50 mg μL^{-1}/$[Fe(CN)_6]^{3-}$ - 5.0 mM; E: [DAO] = 0.50 mg μL^{-1}.

[8]. Considering this, and with the aim of developing a cheap and simple device, pencil leads were chosen as electrodes for the construction of an electrochemical cell because of their wide availability and low cost. The pencil leads were combined with other cheap and mass-produced materials: a transparency sheet as substrate, nail polish to delimit the working area, and a 3-pin Dupont cable to interface the electrodes and the potentiostat. Although the potentiostat used in this work was a bench instrument, small-sized commercial potentiostats are widely available. The developed electrochemical cell can be connected to them to achieve a completely portable device. Moreover, low-cost potentiostats that are easy to fabricate have also been reported [36–38]. By combining our biosensor with these instruments, a complete do-it-yourself device can be achieved.

3.1. Evaluation of the pencil lead-based electrodes

First, the reproducibility when using the pencil leads as electrodes was studied by recording several cyclic voltammograms (CVs) of a 5.0-mM $[Fe(CN)_6]^{4-}$ solution with the same electrode set (i.e., the same WE, RE and CE). Between the measurements, the transparency sheet was changed, and the electrodes were washed with PB. As can be seen in Fig. 2A, the typical electrochemical behavior of $[Fe(CN)_6]^{4-}$ was observed: an anodic peak, at 0.300 ± 0.003 V, with a current intensity of 34.0 ± 0.5 μA (Relative Standard Deviation (RSD) = 1.5%), and a cathodic peak, at 0.110 ± 0.009 V, with a current intensity of −25.0 ± 0.3 μA (RSD = 1.2%). These results demonstrated the high precision of the results and that hexacyanoferrate, which will be used as the mediator in the histamine sensor (sections 3.2 to 3.5), was not adsorbed on the electrodes. Then, several electrochemical cells were constructed using different electrode sets (i.e., different WE, RE and CE) and transparency sheets, and CVs of a 5.0-mM $[Fe(CN)_6]^{4-}$ solution were recorded (Fig. 2B). In this case an anodic peak at 0.29 ± 0.02 V, with a current intensity of 34 ± 3 μA (RSD = 7.1%), and a cathodic peak at 0.13 ± 0.02 V, with a current intensity of −23 ± 2 μA (RSD = 5.7%) were obtained.

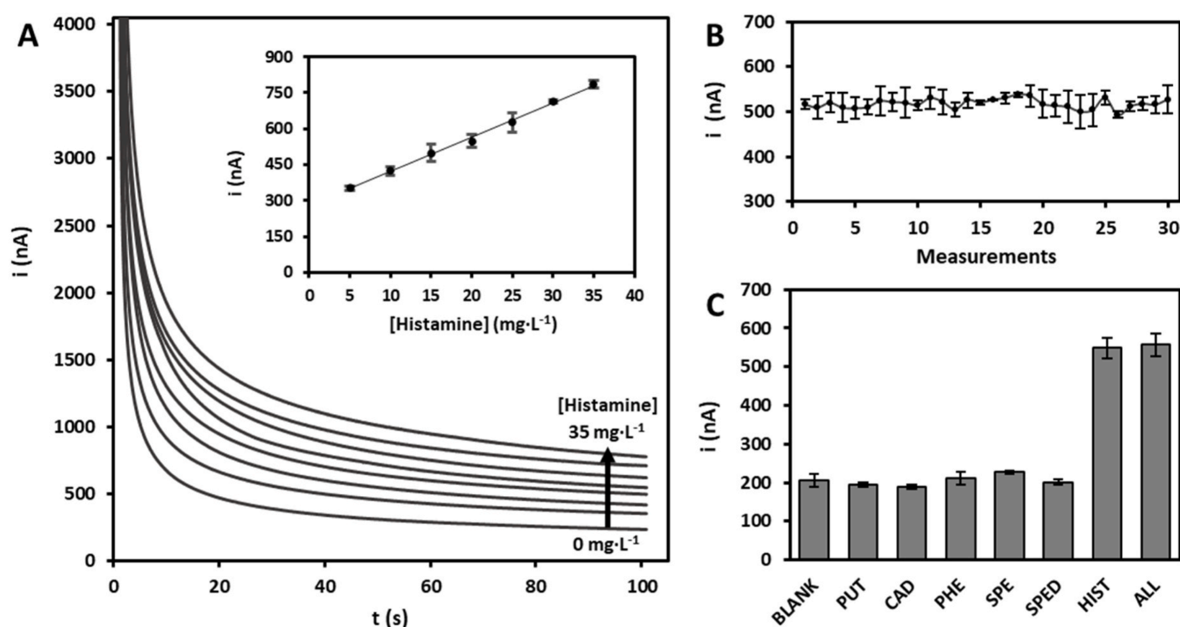


Fig. 3. (A) Chronoamperograms recorded at +0.5 V for 100 s for different histamine concentrations (0, 5.0, 10, 15, 20, 25, 30, and 35 mg L^{-1}) using the developed biosensor. Inset: the obtained calibration straight. **(B)** Currents obtained in repeated measurements (30) using the same device (transparent sheet and electrode set) of a 15-mg L^{-1} histamine solution. **(C)** Current intensities obtained for blank (absence of biogenic amines) and 25-mg L^{-1} solutions of histamine (HIST) putrescine (PUT), cadaverine (CAD), phenethylamine (PHE), spermine (SPE), spermidine (SPED), and for a mixture containing 25 mg L^{-1} of each of these biogenic amines. Error bars represent ±*SD* values of three different measurements.

These data show that the precision of the results is better when the same electrodes are used. However, considering the manual fabrication process (in which the pencils leads were cut by hand, a crucial process that determines the area of the electrodes), the precision can be considered highly satisfactory.

3.2. Optimization of the enzymatic histamine sensor

The biorecognition and electrochemical determination of histamine was based on our previous work [34]: the oxidation of histamine to the corresponding aldehyde (imidazole acetaldehyde), NH_3 and H_2O_2 is catalyzed by DAO, and $[Fe(CN)_6]^{3-}$, used as redox mediator, is reduced through the oxidation of the aldehyde (Fig. 1). Therefore, the reduced mediator generated from the enzymatic reaction can be simply measured through chronoamperometry at a suitable oxidation potential. Physical adsorption was used to immobilize the enzyme on the working area of the electrochemical cell because of its simplicity and quickness. Although this method is characterized by weak immobilization, involving van der Waals forces, hydrogen bonds, and ionic interactions between the enzyme and the material onto which it is immobilized, it is an interesting approach for the construction of single-use devices since it has demonstrated to provide a suitable performance of the sensor, maintaining the activity of the enzyme, and good storage stability [11, 12].

To determine the most suitable measuring potential, first a CV of a 5.0-mM $[Fe(CN)_6]^{4-}$ (the reduced form of the mediator) solution was recorded using a cell onto which DAO was previously immobilized. As can be seen in Fig. 2C, an anodic peak at 0.39 V and a cathodic peak at 0.04 V were obtained. Based on this voltammogram, to guarantee the oxidation of the mediator potentials equal or higher than +0.4 V (+0.40, +0.50 and + 0.60 V) were chosen to optimize the measuring potential (Fig. 2D). As expected, the currents for the blank (PB, without histamine) solutions were lowest at +0.40 V since these currents are proportional to the amount of electrochemically oxidized mediator and this amount increases when the applied potential is higher. However, for +0.50 and + 0.60 V, the current intensities for the blank were almost the same, indicating that +0.50 V is high enough to oxidize the mediator. Regarding the signals for histamine solutions (10 and 20 mg L^{-1}), the highest ones were obtained at +0.50 V, so this was the chosen measuring potential.

The most adequate mediator concentration was also evaluated (Fig. 2E). The highest signal for the used histamine concentrations (10 and 20 mg L^{-1}) was obtained when a 5.0-mM $[Fe(CN)_6]^{3-}$ solution was used, whereas the blank signal were almost the same. Therefore, this concentration was chosen for the subsequent studies.

3.3. Analytical characteristics of the histamine biosensor

Once the mediator concentration and the measuring potential were optimized, the analytical features of the developed biosensor were studied by recording chronoamperograms of different histamine solutions (0–35 mg L^{-1}) (Fig. 3A). The sensor showed a linear response between the current and histamine concentration between 5.0 and 35 mg L^{-1} (i (nA) = 14.3 [histamine] (mg L^{-1}) + 277, R = 0.998). The sensor exhibits a sensitivity of 178 nA L mg^{-1} cm^{-2} and limits of detection (LOD) and quantification (LOQ) of 1.0 mg L^{-1} (9.0 μM) and 3.4 mg L^{-1} (31 μM), respectively (calculated as $3S_b/m$ and $10S_b/m$, respectively, where S_b is the standard deviation of the blank and m is the slope of the calibration straight). Moreover, the sensor showed high precision (V_{x0} = 3.4%). In Table S1 these and other figures of merit of the sensor are indicated.

The reproducibility was evaluated using three different sensors, obtaining RSDs of 4.3% and 4.8% for 10 and 20 mg L^{-1} histamine solutions, respectively. The same electrode set and transparency sheet with immobilized DAO was used for 30 subsequent measurements of a 15-mg·L^{-1} histamine solution and no signal loss was observed (Fig. 3B). This was performed with 3 different electrode sets and transparency sheets. The RSD (4.2%) of the 90 measurements demonstrates the high precision of the results provided by the device. This indicates the adequate precision of the results and, although the developed biosensor was conceived as a single-use device, it can be used for several measurements.

Although the developed sensor shows a short linear range and an LOD that is not very low when compared with previously reported

Table 1
Results of the recovery tests for the quantification of histamine in fish extracts. Average values ± SD obtained with three different sensors are indicated.

Fish specie	[Histamine] before spiking (mg L^{-1})	[Histamine] added (mg L^{-1})	[Histamine] expected (mg L^{-1})	[Histamine] found (mg L^{-1})	Recovery (%)
Sardine	6.0 ± 0.5	5.0	11.0	11.7 ± 0.9	107 ± 4
		15.0	21.0	21.4 ± 0.6	102 ± 2
Tuna	12.4 ± 0.7	5.0	17.4	18 ± 2	106 ± 5
		15.0	27.4	30.3 ± 0.5	110 ± 4

electrochemical (bio)sensors for histamine analysis [39], it provides a comparable LOD and a better precision than sensors based on commercial and well-stablished transducers (Table S2). This is valuable considering the low-cost and easy fabrication of the transducer and the simplicity of the preparation of the sensing phase by drop casting. However, it is important to note that the focus of the developed sensor is the determination of histamine in fish, in which low levels do not cause harmful effects on human health; therefore, the European legislation [5] established a limit of 200 mg kg^{-1}. Considering that the proposed device is able to quantify histamine between 5 and 35 mg L^{-1}, i.e., between 20 and 140 mg kg^{-1}, the biosensor could be a suitable tool for determining the freshness and quality of fishery products.

The evaluation of the storage stability of the platform was assessed by preparing different transparency sheets with DAO and storing them protected from light at 4 °C until their use. At different times, a set of electrodes was placed on these transparency sheets and a chronoamperogram of a 15-mg mL^{-1} histamine solution was recorded (Fig. S2). After 15 and 60 days, 95.3% and 88.4% of the initial signal was obtained, respectively.

3.4. Selectivity and interference studies

The selectivity of the sensor was tested by analyzing other biogenic amines that can be present in fish samples: putrescine, cadaverine, phenethylamine, spermine, and spermidine. Individual solutions (25 mg L^{-1}) and a mixture of all the biogenic amines (25 mg L^{-1} of each one) were analyzed. As shown in Fig. 3C the signals obtained for the non-target biogenic amines were very close to the blank signal (PB, pH 7.2). This indicates that the sensor is selective towards histamine. Moreover, the signal obtained for the solution containing all the biogenic amines (including histamine) is very similar to the one obtained for a histamine solution (557 nA *vs.* 548 nA, respectively). This shows that the non-target biogenic amines do not interfere in the analysis of histamine.

3.5. Sample analysis

To evaluate the feasibility of the developed biosensor for the analysis of histamine in fish samples, recovery tests using spiked tuna and sardine extracts were performed. Extracts from both fish species were prepared as indicated in Section 2.5 and those extracts were analyzed before and after spiking with 5.0 and 15.0 mg L^{-1} of histamine (Table 1). Recoveries values between 102% and 110% were obtained, demonstrating the ability of this biosensor to determine histamine in fish samples and the accuracy of the results. It is worth mentioning that in our previous work [34] the developed histamine sensor was based on the same enzymatic sensing strategy but using commercial screen-printed carbon electrodes and showed similar recovery values, which indicates the suitable performance of the hand-made electrochemical cell proposed in the present work.

4. Conclusions

A very simple to construct enzymatic biosensor for histamine determination was developed using pencil leads as electrodes, a transparency sheet as substrate, diamine oxidase (immobilized by adsorption) as biological recognition element, and hexacyanoferrate(iii) as redox mediator. The construction of this biosensor only takes approximately 30 min and, despite that it is hand-made, good precision and short response times were achieved. After construction, the device can be used for at least 15 days since it maintains 95.3% of the initial signal. Therefore, the proposed sensor, besides satisfactory analytical features, is easy and simple to construct, without the need to employ nanomaterials and expensive substrates to achieve a suitable analytical performance. Moreover, its low cost and small size allow its combination with portable readers to obtain integrated and ready-to-use devices for on-site histamine determination along the whole fish production chain. Furthermore, the developed electrochemical cell for the construction of the biosensor using common use mass-produced materials shows a good electrochemical behavior and reproducibility, so it could easily be applied for the development of other (bio)sensors. On the other hand, and not less important, the proposed sensor also follows many of the current requirements of sustainability and green analytical chemistry since it needs low reagent and sample volumes, produces low amounts of waste, does not need toxic reagents, and is able to perform in-field measurements.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Acknowledgment

This research received financial support from the European Union (FEDER funds through COMPETE POCI-01-0145-FEDER-030735) and National Funds ("Fundação para a Ciência e a Tecnologia" (FCT)) through the project PTDC/QUI-QAN/30735/2017 - TracAllerSens. This work was also financially supported by Portuguese national funds through projects UIDB/50006/2020 and UIDP/50006/2020 from FCT/"Ministério da Ciência, Tecnologia e Ensino Superior" (MCTES). E. Costa-Rama thanks the support of the grant "Beatriz Galindo" (BG20/00027) funded by the "Ministerio de Universidades" of the Spanish Government. R. Torre thanks FCT and the European Social Fund (ESF), through the "Programa Operacional Capital Humano" (POCH), for her PhD grant (SFRH/BD/143753/2019).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.talanta.2023.124980.

References

[1] World Health Organization. https://www.who.int/NEWS-ROOM/FACT-SHEETS/DETAIL/FOOD-SAFETY.

[2] C. Feng, S. Teuber, M.E. Gershwin, Histamine (scombroid) fish poisoning: a comprehensive review, Clin. Rev. Allergy Immu. 50 (2016) 64–69, https://doi.org/10.1007/s12016-015-8467-x.

[3] M. Hrubisko, R. Danis, M. Huorka, M. Wawruch, Histamine intolerance — the more we know the less we know, Nutrients 13 (2021) 2228, https://doi.org/10.3390/nu13072228.

[4] M. Moniente, D. García-Gonzalo, I. Ontañón, R. Pagán, L. Botello-Morte, Histamine accumulation in dairy products: microbial causes, techniques for the detection of histamine-producing microbiota, and potential solutions, Compr. Rev. Food Sci. F. 20 (2021) 1481–1523, https://doi.org/10.1111/1541-4337.12704.

[5] m. Regul. No 2073/2005 15 Novemb. 2005 Microbiological criteria for foodstuffs, Off. J. Eur. Union. Com (2005). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007R1441. Last accessed July 2023.

[6] M.A. López, M. Moreno-Guzman, B. Jurado, A. Escarpa, Food microfluidics biosensors, in: V. Scognamiglio, G. Rea, F. Arduini, G. Palleschi (Eds.), Comprehensive Analytical Chemistry, Elsevier, 2016, pp. 273–312, https://doi.org/10.1016/bs.coac.2016.04.008.

[7] C. Dincer, R. Bruch, E. Costa-Rama, M.T. Fernández-Abedul, A. Merkoçi, A. Manz, G.A. Urban, F. Güder, Disposable sensors in diagnostics, food, and environmental monitoring, Adv. Mater. (2019), 1806739, https://doi.org/10.1002/adma.201806739.

[8] R. Torre, E.C. Rama, H.P.A.A. Nouws, C.D. Matos, E. Costa-Rama, H.P.A.A. Nouws, C. Delerue-Matos, Screen-printed electrode-based sensors for food spoilage control: bacteria and biogenic amines detection, Biosensors 10 (2020) 139, https://doi.org/10.3390/bios10100139.

[9] E. Noviana, C.P. McCord, K.M. Clark, I. Jang, C.S. Henry, Electrochemical paper-based devices: sensing approaches and progress toward practical applications, Lab Chip 20 (2020) 9–34, https://doi.org/10.1039/c9lc00903e.

[10] T. Ozer, C. McMahon, C.S. Henry, Advances in paper-based analytical devices, Annu. Rev. Anal. Chem. 13 (2020) 85–109, https://doi.org/10.1146/annurev-anchem-061318-114845.

[11] E.C. Rama, A. Costa-garcía, M.T. Fernández-abedul, Pin-based electrochemical glucose sensor with multiplexing possibilities, Biosens. Bioelectron. 88 (2017) 34–40, https://doi.org/10.1016/j.bios.2016.06.068.

[12] O. Amor-Gutiérrez, E. Costa-Rama, M.T. Fernández-Abedul, Fully integrated sampler and dilutor in an electrochemical paper-based device for glucose sensing, Microchim. Acta 188 (2021) 302, https://doi.org/10.1007/s00604-021-04946-3.

[13] A. González-López, E. Costa-Rama, M.T. Fernández-Abedul, Electrochemical micropipette-tip for low-cost environmental applications: determination of anionic surfactants through their interaction with methylene blue, Talanta 224 (2021), https://doi.org/10.1016/j.talanta.2020.121732.

[14] P.I. Nanni, A. González-López, E. Nunez-Bajo, R.E. Madrid, M.T. Fernández-Abedul, Staple-based paper electrochemical platform for celiac disease diagnosis, Chemelectrochem 5 (2018) 4036–4045, https://doi.org/10.1002/celc.201800743.

[15] A. González-López, M.C. Blanco-López, M.T. Fernández-Abedul, Micropipette tip-based immunoassay with electrochemical detection of antitissue transglutaminase to diagnose celiac disease using staples and a paper-based platform, ACS Sens. 4 (2019) 2679–2687, https://doi.org/10.1021/acssensors.9b01096.

[16] E. Alipour, F.M. Bolali, S. Norouzi, A. Saadatirad, Electrochemically activated pencil lead electrode as a sensitive voltammetric sensor to determine gallic acid, Food Chem. 375 (2022), 131871, https://doi.org/10.1016/j.foodchem.2021.131871.

[17] T.S. Martins, J.L. Bott-Neto, P.A. Raymundo-Pereira, E.A. Ticianelli, S.A. S. Machado, An electrochemical furosemide sensor based on pencil graphite surface modified with polymer film Ni-salen and $Ni(OH)_2$/C nanoparticles, Sensor. Actuat. B-Chem. 276 (2018) 378–387, https://doi.org/10.1016/j.snb.2018.08.131.

[18] A. Wong, A.M. Santos, R.F. Alves, F.C. Vicentini, O. Fatibello-Filho, M.P. T. Sotomayor, Simultaneous determination of direct yellow 50, tryptophan, carbendazim, and caffeine in environmental and biological fluid samples using graphite pencil electrode modified with palladium nanoparticles, Talanta 222 (2021), 121539, https://doi.org/10.1016/j.talanta.2020.121539.

[19] Z. Huang, Y. Zhang, J. Sun, S. Chen, Y. Chen, Y. Fang, Nanomolar detection of chlorogenic acid at the cross-section surface of the pencil lead electrode, Sensor. Actuat. B-Chem. 321 (2020), 128550, https://doi.org/10.1016/j.snb.2020.128550.

[20] R.M. Carvalho, E.R. Pedão, F.M.R. Guerbas, M.P. Tronchini, V.S. Ferreira, J. M. Petroni, B.G. Lucca, Electrochemical study and forensic electroanalysis of fungicide benzovindiflupyr using disposable graphite pencil electrode, Talanta 252 (2023), 123873, https://doi.org/10.1016/j.talanta.2022.123873.

[21] N. Kumar, R.N. Goyal, Silver nanoparticles decorated graphene nanoribbon modified pyrolytic graphite sensor for determination of histamine, Sensor. Actuat. B-Chem. 268 (2018) 383–391, https://doi.org/10.1016/j.snb.2018.04.136.

[22] Y. Xu, Y. Cheng, Y. Jia, B.C. Ye, Synthesis of MOF-derived Ni@C materials for the electrochemical detection of histamine, Talanta 219 (2020), 121360, https://doi.org/10.1016/j.talanta.2020.121360.

[23] N. Butwong, J. Khajonklin, A. Thongbor, J.H.T. Luong, Electrochemical sensing of histamine using a glassy carbon electrode modified with multiwalled carbon nanotubes decorated with Ag-Ag_2O nanoparticles, Microchim. Acta 186 (2019) 714, https://doi.org/10.1007/s00604-019-3860-4.

[24] A.M. Mahmoud, S.A. Alkahtani, B.A. Alyami, M.M. El-Wekil, Dual-recognition molecularly imprinted aptasensor based on gold nanoparticles decorated carboxylated carbon nanotubes for highly selective and sensitive determination of histamine in different matrices, Anal. Chim. Acta 1133 (2020) 58–65, https://doi.org/10.1016/j.aca.2020.08.001.

[25] M.-Y. Lee, C.-C. Wu, M.I. Sari, Y. Hsieh, A disposable non-enzymatic histamine sensor based on the nafion-coated copper phosphate electrodes for estimation of fish freshness, Electrochim. Acta 283 (2018) 772–779, https://doi.org/10.1016/j.electacta.2018.05.148.

[26] X.X. Dong, J.Y. Yang, L. Luo, Y.F. Zhang, C. Mao, Y.M. Sun, H.T. Lei, Y.D. Shen, R. C. Beier, Z.L. Xu, Portable amperometric immunosensor for histamine detection using Prussian blue-chitosan-gold nanoparticle nanocomposite films, Biosens. Bioelectron. 98 (2017) 305–309, https://doi.org/10.1016/j.bios.2017.07.014.

[27] S. Knežević, M. Ognjanović, N. Nedić, J.F.M.L. Mariano, Z. Milanović, B. Petković, B. Antić, S.V. Djurić, D. Stanković, A single drop histamine sensor based on AuNPs/MnO_2 modified screen-printed electrode, Microchem. J. 155 (2020), 104778, https://doi.org/10.1016/j.microc.2020.104778.

[28] C. Kaçar, P.E. Erden, B. Dalkiran, E.K. İnal, E. Kiliç, Amperometric biogenic amine biosensors based on Prussian blue, indium tin oxide nanoparticles and diamine oxidase– or monoamine oxidase–modified electrodes, Anal. Bioanal. Chem. 412 (2020) 1933–1946, https://doi.org/10.1007/s00216-020-02448-4.

[29] B. Shkodra, B.D. Abera, G. Cantarella, A. Douaki, E. Avancini, L. Petti, P. Lugli, Flexible and printed electrochemical immunosensor coated with oxygen plasma treated SWCNTs for histamine detection, Biosensors 10 (2020) 1–12, https://doi.org/10.3390/bios10040035.

[30] S. Venkatesh, C.C. Yeung, T. Li, S.C. Lau, Q.J. Sun, L.Y. Li, J.H. Li, M.H.W. Lam, V. A.L. Roy, Portable molecularly imprinted polymer-based platform for detection of histamine in aqueous solutions, J. Hazard Mater. 410 (2021), 124609, https://doi.org/10.1016/j.jhazmat.2020.124609.

[31] R.K.R. Gajjala, S.K. Palathedath, Cu@Pd core-shell nanostructures for highly sensitive and selective amperometric analysis of histamine, Biosens. Bioelectron. 102 (2018) 242–246, https://doi.org/10.1016/j.bios.2017.11.038.

[32] R.K.R. Gajjala, B. Naveen, P. Suresh Kumar, Cu@Pd core-shell nanostructures on pencil graphite substrates as disposable electrochemical sensors for the detection of biological amines, ACS Appl. Nano Mater. 4 (2021) 5047–5057, https://doi.org/10.1021/acsanm.1c00530.

[33] D. Martín-Yerga, I. Álvarez-Martos, M.C. Blanco-López, C.S. Henry, M. T. Fernández-Abedul, Point-of-need simultaneous electrochemical detection of lead and cadmium using low-cost stencil-printed transparency electrodes, Anal. Chim. Acta 981 (2017) 24–33, https://doi.org/10.1016/j.aca.2017.05.027.

[34] R. Torre, E. Costa-Rama, H.P.A. Nouws, C. Delerue-Matos, Diamine oxidase-modified screen-printed electrode for the redox-mediated determination of histamine, J. Appl. Sci. Technol. 11 (2020) 5, https://doi.org/10.1186/s40543-020-0203-3.

[35] M. Lacorn, G. Garrido, B. Reck, M. Sutterlüti, S. Lindeke, Meinhardt Patricia, Validation of the R-Biopharm AG RIDASCREEN® histamine (enzymatic) kit, J. AOAC Int. 102 (2019) 1472–1491, https://doi.org/10.5740/jaoacint.19-0087.

[36] FreiStat, Freiburg potentiostat. https://github.com/IMTEK-FreiStat last accessed June2023.

[37] S.D. Adams, E.H. Doeven, K. Quayle, A.Z. Kouzani, MiniStat: development and evaluation of a mini-potentiostat for electrochemical measurements, IEEE Access 7 (2019) 31903–31912, https://doi.org/10.1109/ACCESS.2019.2902575.

[38] A. Ainla, M.P.S. Mousavi, M.N. Tsaloglou, J. Redston, J.G. Bell, M.T. Fernández-Abedul, G.M. Whitesides, Open-source potentiostat for wireless electrochemical detection with smartphones, Anal. Chem. 90 (2018) 6240–6246, https://doi.org/10.1021/acs.analchem.8b00850.

[39] S. Givanoudi, M. Heyndrickx, T. Depuydt, M. Khorshid, J. Robbens, P. Wagner, A review on bio- and chemosensors for the detection of biogenic amines in food safety applications: the status in 2022, Sensors 23 (2023) 613, https://doi.org/10.3390/s23020613.