Bismuth as an Electrode Material in the Simultaneous Determination of Pb (II) and Cd (II) in Poplar (*Populus*) Leaves by SWASV

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Abstract

In this work we tested the performance of the bismuth film electrode in the detection and simultaneous determination of toxic metals on real samples in a complex matrix, by square wave anodic stripping voltammetry. The studied samples were white poplar leaves gathered in "2ª Circular", which is an area of major traffic intensity of the city of Lisbon. The determined metals were Pb (II) and Cd (II). After being dried, the white poplar leaves were submitted to an acid digestion process assisted by microwave technology. A complete optimization study of the voltammetric parameters was made in order to simultaneously determine the metals as well as to decrease the detection limits and improve the method's repeatability and sensitivity. The working electrode consisted in a bismuth film deposited on a vitreous carbon disc surface. The Ag/AgCl system was used as the reference electrode and a platinum wire as the auxiliary electrode. The concentrations (in mg of metal/kg of dry matter - leaves) obtained for Pb (II) and Cd (II) were of 3.0 and 1.7, respectively. Also, detection limits of 1.80×10^{-8} mol L^{-1} for Pb (II) and 6.90×10^{-9} mol L^{-1} for Cd (II) were estimated. In addition, a well shaped voltammogram obtained in the analysis of real samples opens excellent perspectives for the use of the bismuth electrode as an alternative to toxic metals such as mercury.

Keywords: bismuth electrode, toxic metals, stripping voltammetry, poplar leaves.

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Introduction

The development and implementation of methods and procedures in order to detect and determine toxic metals in environmental samples is, at present, an issue of major importance, regarding the negative impact and consequences brought by these agents to human health, environment and biological systems in general [1-4].

In this regard, Anodic Stripping Voltammetry, ASV, shows to be a powerful electroanalytical technique, namely due to its high sensitivity, repeatability, low detection limits, low cost of equipment, as well as to its possibility of performing *in-situ* field analysis [5-7].

Another significant advantage of this technique lies in its ability to simultaneously determine several metals, at trace level.

When ASV is-applied to the determination of toxic metals, it essentially involves two steps [8].

The pre-concentration or pre-deposition step which consists in reducing the metallic ions present in the sample solution onto the surface of a working electrode, by means of the application of an adequate cathodic potential, E_{dep}, for a certain period, t_{dep}. The mass transport in this step may be enhanced by means of solution magnetic stirring or by using a rotating electrode [9, 10].

The next step is the redissolution or determination step, where the metals deposited in the previous step are re-oxidized back into the solution by means of the application of an anodic potential sweep. If the potential is scanned in a potential-time square wave form, then the technique can be, in general terms, designated by Square Wave Anodic Stripping Voltammetry, SWASV [11, 12].

The resultant voltammogram (current-potential plot in peak shape) recorded during this step provides the analytical information of interest. The stripping current, Ip, due to the oxidation of a given metal, is proportional to its concentration at the electrode, and therefore to its concentration in the sample solution. Peak potentials, Ep, are characteristic of each metal, and therefore serve to identify the metals in the sample.

In terms of the working electrode materials, it can be seen that mercury, more frequently [13-16], but also gold [17, 18] or carbon (in its several forms) [19-24] have been the most used. Recently, however, bismuth has acquired a prominent stand in this context of electroanalysis [25-30]. This observation is due to the fact that in general terms bismuth exhibits an electroanalytical performance that compares favorably with the other referred electrode materials. Also, the low toxicity for bismuth is a major advantage, namely when compared with mercury, which is a very toxic element.

Like most of the analytical techniques, SWASV, can also be affected by some interferences, which can influence the quality of the final results.

The most important one is the presence of organic substances in the sample matrix [31]. These substances can be adsorbed onto the electrode surface and therefore make difficult or inhibit the pre-concentration of the metals and their re-oxidation in the subsequent step. Also, complexation of metal cations in solution may occur, leading to a change in their concentration.

The procedure used in this work in order to decompose the organic matter present in the studied samples (poplar leaves), thus minimizing the errors affecting the final results, consisted on a wet digestion of the samples, using adequate oxidizing agents and heating the mixture. This heating was performed using microwave radiation [32-34].

Microwave heating presents significant advantages when compared to conventional heating (hot plate or sand bath), where part of the energy is lost heating the walls of the vessel containing the mixture.

Thus, the heating process becomes significantly slower, limiting the digestion temperatures that can be achieved, and affecting thus the overall effectiveness of the process.

In the present work we explore the potentialities of bismuth, as an electrode material, in the determination of Pb (II) and Cd (II) in real samples with complex matrix, by SWASV.

Following this objective, we performed a complete study on the optimization of the voltammetric parameters that characterize SWASV (deposition potential, deposition time, square wave frequency, square wave amplitude and potential step), in order to simultaneously detect both metals, decrease total analysis time and method detection limit and also to increase the method's sensitivity and repeatability.

Experimental

Reagents and solutions

The supporting electrolyte used in both test and real sample solutions was HNO_3 0.1 mol L^{-1}, pH=1, prepared from a Merck HNO_3 65% solution.

For the preparation of the bismuth electrode (deposition of a bismuth film on the surface of an adequate substrate) a 5×10^{-5} mol L^{-1} in Bi^{3+} solution, from a $Bi(NO_3)_3$ Atomic Absorption Standard Solution from Merck, with a concentration of 1000 mg L^{-1}, in Bi^{3+}, was used.

The Pb (II) and Cd (II) solutions used in the optimization study of the voltammetric parameters were prepared from $Cd(NO_3)_2$ and $Pb(NO_3)_2$ Atomic Absorption Standard Solutions from Merck, with a concentration of 1000 mg L^{-1}, in both metals.

Ultra pure water from Millipore, with a resistivity $\geq$ 18.2 MΩ, was always used in the preparation of all solutions as well as in glassware washing and electrode rinsing.

Instrumentation

For the voltammetric assays we used an AUTOLAB PGSTAT 10 potenciostat, with AUTOLAB GPES, version 4.6 software.

Microwave digestion of the samples was performed with an open vessel microwave digestor, CEM STAR SYSTEM 2.

The working electrode consisted on a bismuth film, BiFE, deposited onto the surface of a 3 mm diameter vitreous carbon disc, sealed with Teflon.

Before each assay the vitreous carbon disc was always polished with 0.02 μm grit alumina powder in order to remove any residues from the surface of the bismuth film deposition substrate. Abundant washing with ultra pure water followed this step.

As reference electrode we used the system Ag/AgCl (sat. KCl 3 mol L^{-1}). The counter electrode consisted on a spiral platinum wire, sealed with glass.

The electrochemical cell used was a conventional cell, capable of working with volumes up to 50 mL, covered with a Teflon lid.

For solution stirring we used a standard magnetic stirrer.

Procedure
Sample pre-treatment

As mentioned before, the sample was submitted to a microwave digestion program in order to eliminate the organic matter present in the sample complex matrix, thus minimizing the errors affecting the electroanalytical performance of the BiFE.

Before the digestion procedure the leaves were dried in an oven, for 96 h, at 65 ºC, followed by grinding until a fine dust was obtained.

A mass of ca. 2 g of this powder, accurately weighed to $\pm\ 10^{-5}$ g, was then submitted to the digestion procedure.

The oxidizing agents used in the digestion of the leaves were nitric acid and hydrogen peroxide, according to a digestion program described elsewhere [JCBS]

The residue resulting from the digestion procedure was then dissolved with 20 mL of a HNO_3 0.5 mol L^{-1} warm solution, filtered and diluted to a final volume of 100 mL.

Voltammetric parameters optimization

The SWASV parameters optimized were: Deposition Potential (E_{dep}), Deposition Time (t_{dep}), Square Wave Frequency (*f*), Square Wave Amplitude (*Esw*) and Potential Step (ΔE).

The concentration of Pb (II) and Cd (II) used in the voltammetric parameters optimization study was 1×10^{-7} mol L^{-1} for each metal.

Note that in each optimization assay as well as in real sample analysis, we used, in the pre-concentration step, a co-deposition procedure, in which de bismuth film is co-deposited with the metals present in solution.

After the reoxidation step, the bismuth film is removed and the vitreous carbon is electrochemically cleaned by means of the application of an adequate potential (+0.2 V).

In the subsequent cycle the bismuth film is, again, co-deposited with the metals.

Results and discussion

The results obtained from the parameters optimization assays, where it was studied their influence in each metal peak current, are shown in the plots of Fig.

1. We only present the results for E_{dep}, t_{dep} and f, due to their relevance in method's figures of merit.

The assays for the remaining parameters (*Esw* and ΔE) were performed in a similar manner and the same criteria were assumed when choosing their optimized values.
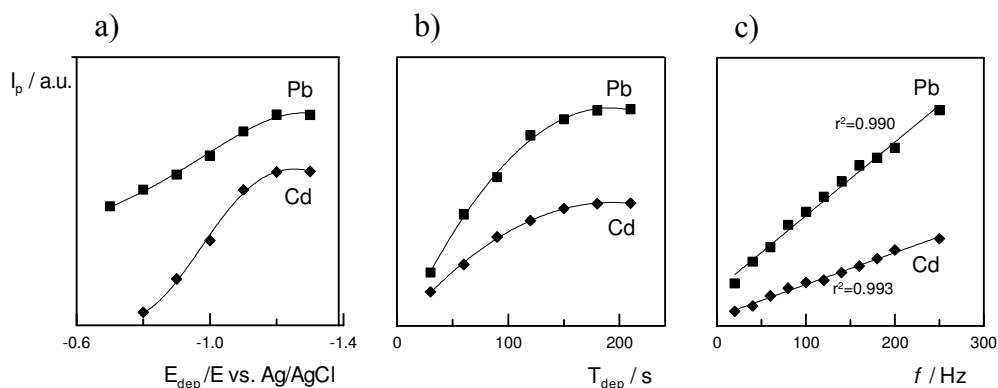
Figure 1. Voltammetric parameters: a) deposition potential; b) deposition time; c) square wave frequency.

In Fig. 1 a) we can see that for both metals peak current increases as E_{dep} becomes more negative. This behavior is due to the fact that Pb (II) and Cd (II) are positively charged ions which are thus preferentially reduced at more negative potentials.

The limiting current [35] for Pb (II) and Cd (II) is reached at -1.2 V. We took -1.0 V as the optimum value for E_{dep}, considering the simultaneous determination of the studied metals in conditions of significant sensitivity and repeatability.

The results on Fig. 1 b) show that peak current for both metals increases with deposition time, since the amount of metal deposited is higher for higher deposition times. At about 175 s a deviation from linearity can be observed due to bismuth film saturation for higher deposition times, rendering impossible a further increase of Ip [36]. Therefore, in order to prevent saturation and to reduce total analysis time, a deposition time of 60 s was chosen as the optimum value.

With the optimum values of -1.0 V and 60 s for E_{dep} and t_{dep}, respectively, we proceeded with square wave frequency optimization.

In Fig. 1 c) we can see that, for both metals, the relation between peak current and frequency is linear. However, frequency values above 150 Hz, invariable produced an increase in background noise and a decrease in the voltammogram shape and definition. We thus decided to take 100 Hz as the optimum value for square wave frequency [8].

Table 1 summarizes the values obtained for each voltammetric parameter as well as further experimental conditions for SWASV assays.

With the optimized conditions summarized in Table 1, the calibration of the BiFE (establishment of the linear range between peak current and metal concentration) followed. Calibration plots are shown in Fig. 2.

Table 1. Experimental condition for SWASV assays.

Parameter	Value
Co-deposition potential	-1.0 V
Co-deposition time	60 s
Conditioning potential	+ 0.2 V
Conditioning time	30 s
Square wave frequency	100 Hz
Square wave amplitude	25 mV
Potential step	2 mV
Bismuth concentration	5×10^{-5} mol L^{-1}
Nitric acid concentration	0.1 mol L^{-1}
Stirring	1000 rpm
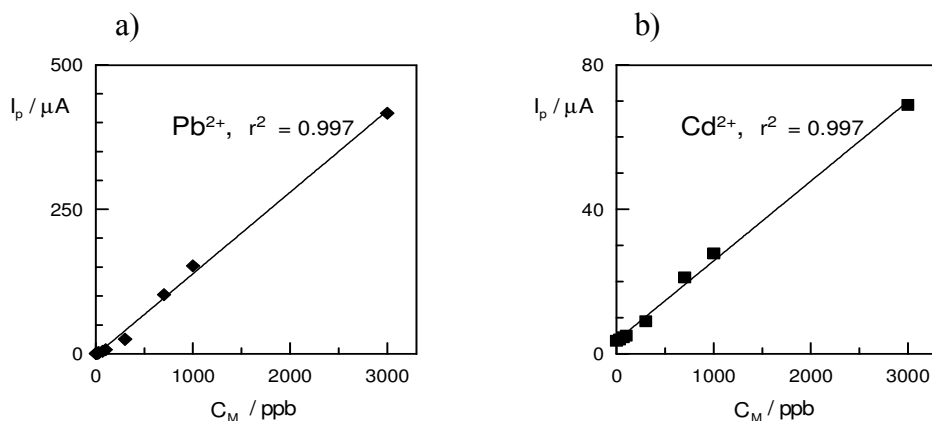
Figure 2. Calibration plots for: a) lead, and b) cadmium, with BiFE .

In Table 2 we can see the linear concentration range for Pb (II) and Cd (II). Note that, in both cases, and for higher concentrations, a deviation from linearity was observed due to the BiFE's saturation.

Table 2. Linear concentration range for cadmium and lead with BiFE.

Metal	Linear concentration range (mol.L^{-1})		
Pb (II)	6×10^{-9}	-	3×10^{-6}
Cd (II)	3×10^{-8}	-	3×10^{-6}

After establishing the linear range between peak current and concentration we estimated the limit of detection, L_d, for BiFE in the determination of Pb (II) and Cd (II) [37]. The results are shown in Table 3.

Table 3. Values of L_d for the determination of cadmium and lead with BiFE.

Metal	L_d (mol L^{-1})
Pb (II)	1.8×10^{-8}
Cd (II)	6.9×10^{-9}

Next the analysis of real samples was performed. The amount of Pb (II) and Cd (II) in poplar leaves was determined trough the standard addition method [38], using a standard solution with adequate concentrations of Pb (II) and Cd (II).
Fig. 3 shows the voltammograms resulting from the voltammetric assay performed on the poplar leaves sample. The base voltammogram corresponds to the sample signal and the other curves result from the 1st to the 4th addition of standard solution, to 25 mL of sample solution.
The insertion in Fig. 3 depicts standard addition calibration plots for Cd (II) and Pb (II).
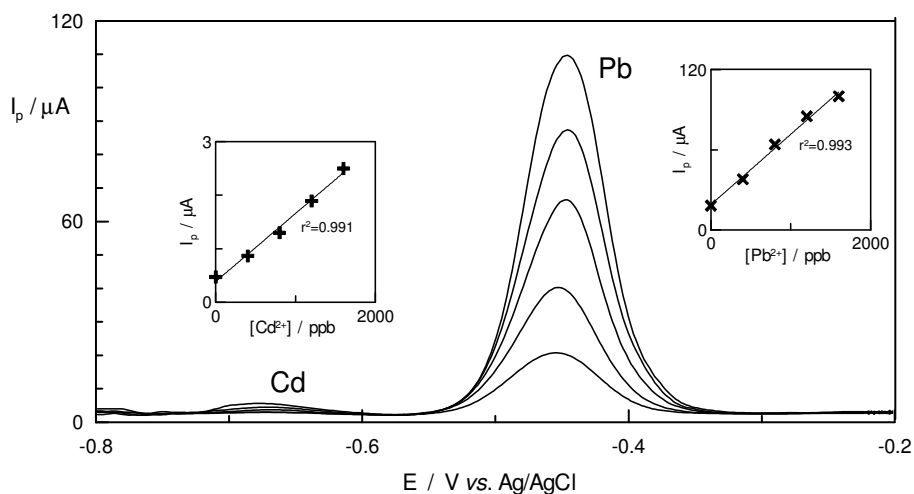
Figure 3. Voltammograms and calibration lines (inserted) obtained in the analysis of cadmium and lead in poplar leaves with BiFE.

The concentrations obtained for Cd (II) and Pb (II) in poplar leaves, by SWASV, using the BiFE are shown in Table 4.
The values are expressed in mg of metal/kg of dry matter (leaves), as these units are usually used in environmental analysis.

Table 4. Concentration obtained for cadmium and lead in poplar leaves.

Metal	Concentration (mg / kg dry matter)
Pb (II)	3.0
Cd (II)	1.7

As mentioned above the assays performed on the leaves samples consisted, firstly, in measuring the metal's signal in the sample, and after the volume additions of the standard solution. The current intensity values considered for each standard addition resulted from the average of five replicates. Table 5 shows the results obtained in the determination of Pb (II) and Cd (II) in the studied sample. The precision of the method is evaluated by means of the standard deviation calculation.

The resulting coefficient of variation ($sd / \overline{Ip}$ × 100) is about 1.6% for the two metals, showing the good overall precision of the method. This significant precision is partially due to the digestion program optimized by us in order to decompose any organic matter present in the sample, thus, minimizing errors arising from the presence of these components.

The coefficient of variation obtained for the analysis of Cd (II) and Pb (II) in poplar leaves with BiFE, coincides with that obtained for MFE when applied to the determination of these metals in the same real sample [39]. Note that MFE can be taken as a reference since it is, perhaps, the most frequently used electrode material, in SWASV of toxic metals.

Regarding the limit of detection estimated for both electrodes, we can see that BiFE can also be compared to MFE [40].

The L_d, estimated for Pb (II) using BiFE (1.8×10^{-8} mol L^{-1}), is identical to that estimated when MFE is used (9.1×10^{-9} mol L^{-1}). In the case of Cd (II) the L_d estimated with MFE (6.9×10^{-10} mol L^{-1}) is about ten times lower than the one estimated with BiFE (6.9×10^{-9} mol L^{-1}). However, we find most relevant the low detection limits achieved with BiFE.

Conclusions

The analysis of the obtained results allows us to conclude that the BIFE has a favorable electroanalytical performance in comparison with MFE taken as the reference for this type of work. This conclusion is supported both by the comparable values of method precision associated to BiFE and MFE and the observed detection limits. These immediately lead us to foresee the possibility of using BiFE to analyze toxic metals at trace level. On the other hand, the excellent voltammograms' definition together with the excellent correlation between metal peak current and concentration also support the same conclusion. This evidence is partly related to the sample's pre-treatment, including the acid digestion step to ensure full decomposition of its content in organic matter. This microwave digestion process shows to be extremely effective towards minimizing the

interferences typically associated with this type of compounds in SWASV assays.

Table 5. Evaluation of the precision of the SWASV method using the BiFE.

Standard addition	Replicate	Peak current I_P /µA		Average peak current $\bar{I}_P$ /µA		Standard deviation $sd(\bar{I}_P)$ /µA	
		Pb^{2+}	Cd^{2+}	Pb^{2+}	Cd^{2+}	Pb^{2+}	Cd^{2+}
Sample	1	18.75	0.49				
	2	18.26	0.49				
	3	18.08	0.50	18.32	0.50	0.31	0.01
	4	18.00	0.51				
	5	18.50	0.50				
1st Standard addition	1	38.50	0.92				
	2	38.20	0.90				
	3	38.00	0.90	38.07	0.91	0.29	0.01
	4	37.90	0.90				
	5	37.77	0.93				
2nd Standard addition	1	64.09	1.30				
	2	65.55	1.26				
	3	63.37	1.25	64.10	1.27	0.87	0.02
	4	64.00	1.30				
	5	63.50	1.25				
3rd Standard addition	1	85.48	1.95				
	2	85.06	1.84				
	3	84.73	1.84	85.35	1.88	1.04	0.05
	4	87.00	1.86				
	5	84.50	1.93				
4th Standard addition	1	100.30	2.52				
	2	100.60	2.62				
	3	106.00	2.60	101.28	2.54	0.57	0.07
	4	100.0	2.52				
	5	99.50	2.45				

A reference is due to a significant disadvantage of BiFE relative to MFE related to the difficulties in analyzing some metals which are traditionally determined by MFE because their reoxidation potentials are more positive than the potential at which bismuth itself reoxidizes. This is the case for copper and antimony among others.

As a final remark, if some conditions are met, not very specific but mostly related to the type and concentration of the metals under study, the results

obtained with BiFE are in complete agreement with those from MFE with an obvious advantage in human and environmental health terms, considering that bismuth is far less toxic than mercury.

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