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Silver nanostructures stabilized by starch derivatives for the determination of thallium in environmental samples

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Abstract: Thallium, a highly toxic heavy metal, presents significant analytical challenges due to its low concentrations in diverse sample matrices. Consequently, there is a growing interest in developing innovative electrode materials with superior sensitivity, selectivity, and low detection limits to replace traditional mercury-based electrodes in voltammetry. This study focused on modifying a glassy carbon electrode (GCE) with silver nanostructures stabilized by starch derivatives and evaluating the impact of this modification on key electrode parameters.

The modified electrode (GCE/AgNPs-E1451R) was applied for thallium determination using anodic stripping voltammetry. Analyses were conducted in a base electrolyte (EDTA solution) and a real groundwater sample from the Wielkopolska (Greater Poland) region. Silver nanostructures were synthesized using a doubly modified starch hydrolysate (E1451R) subjected to oxidation and acetylation. The stripping peak current of thallium showed linearity over concentrations ranging from 35 to 550 μg/L (1.71×10^{-7} to 2.69×10^{-6} M). The calculated limit of detection (LOD) was 9.75 μg/L (1.62×10^{-7} M). The GCE/AgNPs-E1451R electrode offers notable advantages, including a broad detection range, reduced analysis time by eliminating prolonged pre-concentration steps, and non-toxicity compared to mercury-based electrodes, providing a safer alternative for analytical applications, and making the electrode a promising alternative for environmental monitoring.

Introduction

Modern analytical chemistry continually seeks innovations to enhance the precision and sensitivity of measurement techniques. Particular attention has been devoted to the development of electrodes used in electroanalytical methods such as voltammetry - a technique based on the relationship between current intensity and the concentration of an electroactive substance in the analyzed solution. Indicator electrodes employed in these methods vary in surface area, mobility relative to the studied material, and construction material. Notable examples include mercury-based electrodes and carbon electrodes made from graphite, glassy carbon, or carbon paste (Hassan et al., 2020; Xiao et al., 2020; Švancara et al., 2005). Moreover, many electrodes are additionally modified to improve their selectivity and sensitivity (Wang, 2000).

Anodic stripping voltammetry (ASV), the oldest of the stripping techniques, is a method in which the preconcentration step occurs both on the surface of the electrode and within its volume. This dual-phase preconcentration significantly enhances sensitivity and lowers the detection limit, reaching values as low as 10^{-12} M for metals present in environmental samples. However, a challenge in this technique arises from the overlapping peaks of metals with similar oxidation potentials, such as cadmium, lead, and thallium. This issue, nevertheless, can be addressed by selecting appropriate masking agents or electrolytes (Karbowska, 2022).

The appropriate selection of the working electrode is a critical step in voltametric experiments. For an extended period, mercury electrodes, such as the classic hanging mercury drop electrode (CHMDE), static mercury drop electrode (SMDE), and controlled-growth mercury drop electrode (CGMDE), as well as the mercury film electrode (MFE), were widely favored due to their high sensitivity and excellent reproducibility. However, due to the toxicity of mercury, there is an ongoing search for alternative electrode materials that can deliver comparable performance to replace traditional mercury-based electrodes. One such alternative is the glassy carbon electrode. Nevertheless, this electrode requires meticulous surface polishing, as this process significantly impacts the reproducibility and precision of measurements (Wang et al., 2001).

Glassy carbon, introduced in the 1960s, gained recognition for its high chemical and thermal resistance, as well as its impermeability to gases and liquids. Its production process involves shaping a resin, followed by carbonization and firing in a vacuum furnace, which ensures the desired microstructure and mechanical properties. The surface of glassy carbon is chemically diverse, making it well-suited for interactions with a wide range of analytes (Jenkins and Kawamura, 1971; Pesin, 2002; Van der Linden and Dieker; Harris, 2005; Jurkiewicz et al., 2017).

Electrode modifications represent a significant area of development in electrochemistry. These techniques include the deposition of thin films, the incorporation of modifiers into the electrode structure, and the application of nanomaterials (Karbowska et al., 2014; Karbowska et al., 2018; Modrzejewska-Sikorska et al., 2022).

Modifiers can vary widely, from enzymes and metal nanostructures to biopolymers. The use of nanostructures, particularly those produced biologically using bacteria (Chojniak-Gronek et all. 2022), fungi, or plants, is especially promising. These eco-friendly methods are cost-effective and straightforward, eliminating the need for toxic solvents. However, recent studies have shown that metallic nanostructures also exhibit toxic effects (Krzyżewska et al. 2016; Zapór 2016). Biopolymers such as chitosan, cellulose, and pectin play a dual role as both reducing agents and stabilizers, making them effective tools in nanostructure synthesis (Praveene et al., 2020; Konował et al., 2015). Their application enables the creation of electrodes with enhanced sensitivity and selectivity, which is critical for detecting heavy metals, even at trace levels (Bankura et al., 2015).

The aim of this study was to modify a glassy carbon electrode (GCE) with silver nanostructures stabilized by starch derivatives and to evaluate the impact of this modification on the key electrode parameters. Additionally, the study aimed to utilize the modified electrode (GCE/AgNPs-E1451R) for the determination of thallium using anodic stripping voltammetry. The analyses were conducted in both a base electrolyte (an EDTA solution) and a real sample, namely groundwater from the Wielkopolska (Greater Poland) region.

Materials and methods

Preparation and characterization of silver nanostructures

The study employed silver nanostructures synthesized using a starch hydrolysate that underwent dual modification through oxidation and acetylation, referred to as E1451R. The starch hydrolysis process followed the protocol described by Konował et al. (2024).

Nanosilver synthesis was initiated using an ammoniacal silver complex, $[Ag(NH_3)_2]^+$, containing silver ions at a concentration of 1 g/L. Silver nitrate and ammonia water, sourced from POCh, Poland, served as reagents. The starch derivative was added to the reaction mixture at a concentration of 10 g/L. To prevent complete gelatinization of the starch, the process was maintained at a controlled temperature of 45°C.

The reaction mixture was continuously stirred with a magnetic stirrer during a 60-minute heating phase. Subsequently, heating was ceased, and the synthesis continued under constant stirring for 7 days.

Characterization of the synthesized silver nanostructures was carried out using several techniques. Optical absorption spectra were recorded with an OceanOptics UV-vis USB4000 spectrophotometer. Particle size distribution was measured with a Zetasizer Nano ZS (Malvern Instruments Ltd., UK) employing the non-invasive backscattering (NIBS) technique. Electrophoretic mobility was evaluated with the same instrument equipped with an automatic titrator, which combines electrophoresis with laser-based particle mobility analysis based on the Doppler effect.

Figure 1 presents a summary of the selected physicochemical properties of the synthesized silver nanostructures.

The synthesized solutions exhibited a distinct adsorption band at approximately 420 nm, indicative of plasmonic silver nanoparticles (Figure 1A). The particle size distribution of the synthesized AgNPs is presented in Figure 1B. The particles ranged in size from 11 to 712 nm, with the dominant nanoparticle diameter being 18 nm, as illustrated in the inset.

The stability of nanoparticles suspended in a liquid medium is strongly influenced by their zeta potential. The zeta potential of the AgNPs synthesized in the presence of starch derivatives was measured, yielding a value of -17.2 mV. This value suggests moderate stability of the nanoparticle suspension.

Fabrication and Characterization of a Silver Nanostructure Modified Electrode Stabilized by Starch Derivatives

A clean glassy carbon electrode (3 mm in diameter) was modified by drop-casting 4 µL of a composite based on silver nanostructures stabilized with doubly modified starch hydrolysate. The electrode was then dried before being incorporated into the measurement system. The system consisted of a reference electrode (saturated calomel electrode,

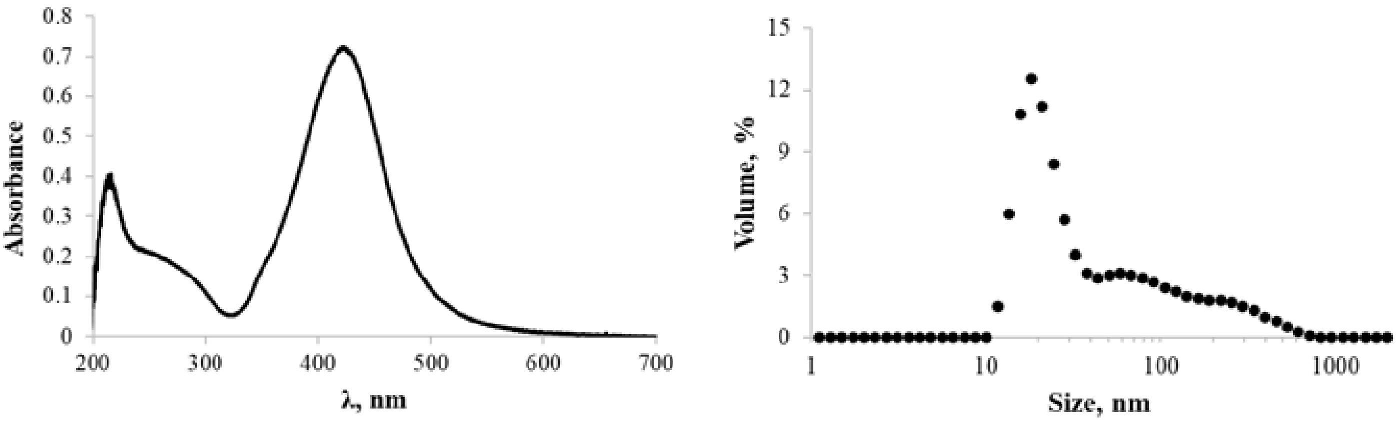

Figure 1. Selected physicochemical properties of AgNPs-E1451R: A) UV-vis analysis, B) particle size distribution

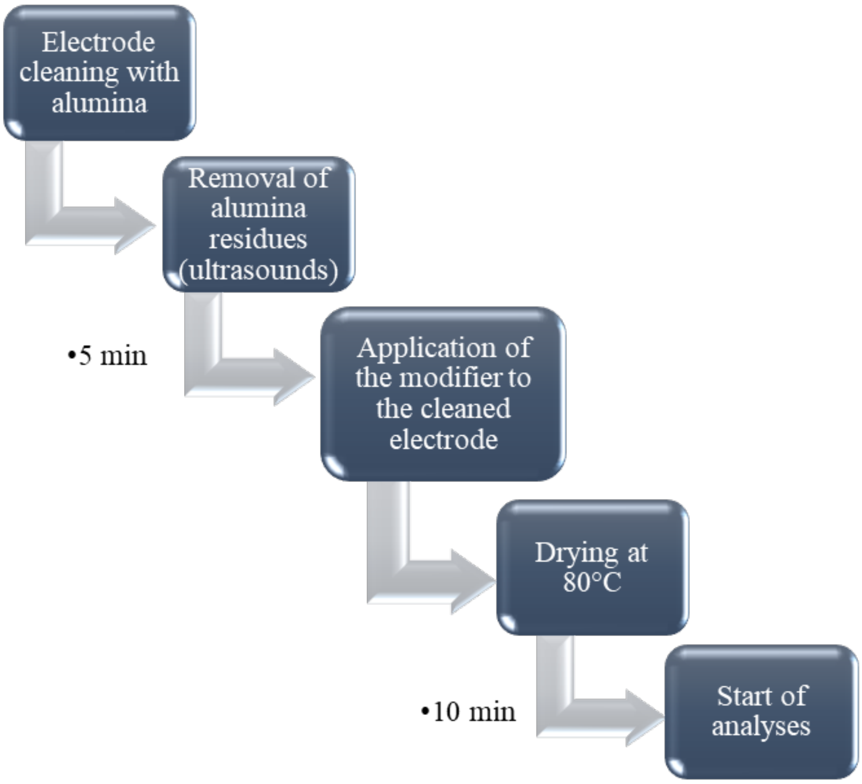

Figure 2. Block diagram of the electrode modification steps

$Hg_2Cl_2|Cl^-$, immersed in 3 M KCl solution) and a counter electrode made of platinum wire.

Measurements were performed using differential pulse anodic stripping voltammetry (DP-ASV) in a nitrogen-deoxygenated 0.2 M EDTA solution at pH 4.5, which served as the supporting electrolyte. The experimental parameters were carefully controlled: the preconcentration step lasted 120 s at a potential of –1.0 V, the differential pulse amplitude was set to 25 mV with a step potential of 5 mV, the scan rate was 0.01 V/s, the pulse duration was 0.07 s, and the equilibration period was 10 s.

The stages of electrode modification (GCE/AgNPs-E1451R) are presented in Figure 2.

Additionally, the morphology of the modified GCE/AgNPs-E1451R electrode was examined using scanning electron microscopy (SEM). The microscopic image shown in Figure 3 reveals that the surface of the modified electrode exhibits significant roughness and effective development, characterized by visible folds. These properties contribute to an enhanced sorption capacity of the electrode.

A series of experiments was carried out using differential pulse anodic stripping voltammetry in order to confirm the sensitivity of the modified electrode towards thallium ions (Tl^+), to stabilize the measurement system, and to characterize the GCE/AgNPs-E1451R electrode. During these experiments, the conditions for thallium detection were optimized.

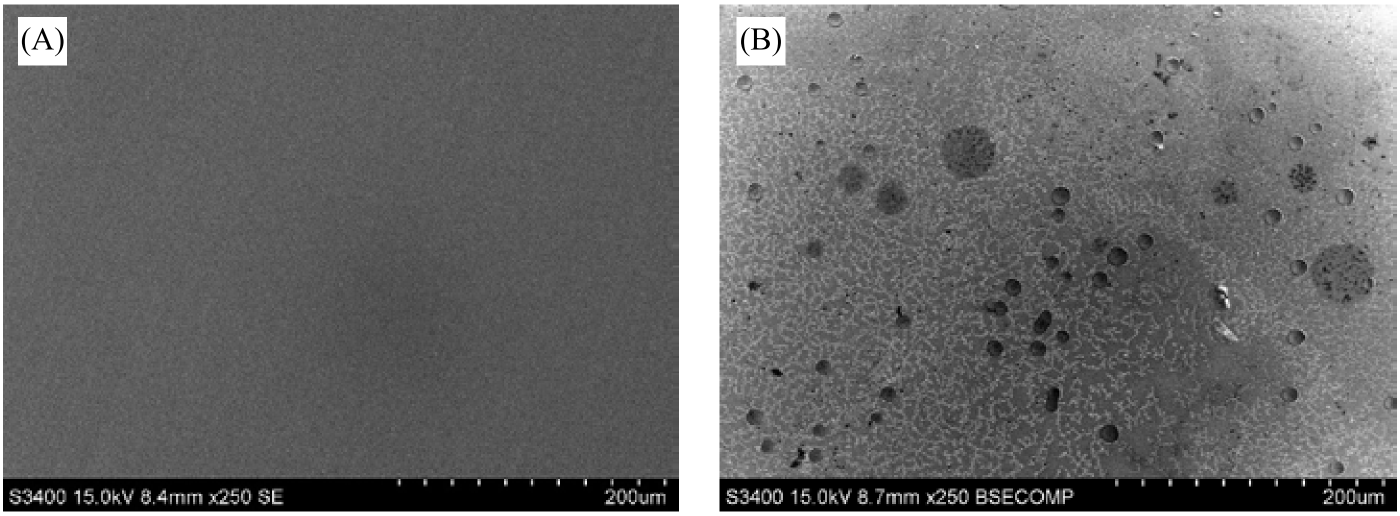

Figure 3. SEM image of the electrode surface: A) GCE before modification, B) GCE/AgNPs-E1451R

Results

Selection of Deposition Potential for the Modified Electrode

After modifying the electrode, the preconcentration potential for thallium was experimentally determined. The effect of the preconcentration potential on the thallium peak height was studied with reference to the calomel electrode, within a potential range from -0.7 V to -1.4 V. The preconcentration time was set to 120 seconds, with the thallium concentration in the electrolyte at 20 µg/L. Figure 4A shows the dependence of the thallium peak height on the applied preconcentration potential.

The highest thallium peak was obtained at a preconcentration potential of -1.0 V. Under these conditions, the thallium peak was well-formed, increasing proportionally with the studied concentration and preconcentration time.

Dependence of Tl Peak Height on Deposition Time for the GCE/AgNPs-E1451R Electrode

The experiment was conducted at the previously determined preconcentration potential of -1.0 V, with a thallium concentration of 20 µg/L in the analyzed system. The preconcentration time for thallium was varied from 40 s to 490 s. The obtained results are graphically presented as the dependence of thallium peak height on preconcentration time in Figure 4B.

The lack of thallium depletion in the solution was indicated by the linear increase of the analytical signal with preconcentration time. This established relationship between the thallium peak height and the preconcentration time allows for the determination of the optimal duration for the preconcentration process, which is necessary to achieve a peak of measurable height.

The relationship between peak current and Tl concentration for the GCE/AgNPs-E1451R electrode

A series of measurements was conducted to establish the calibration curve. The preconcentration time for thallium was set to 120 s, and the preconcentration potential was fixed at -1.0 V with respect to the calomel electrode. Figure 4C presents the obtained voltammograms for concentrations ranging from 35 µg/L to 550 µg/L.

Upon successive additions of thallium solution to the 0.2 M EDTA, a clear analytical response was recorded, indicating the excellent electroanalytical properties of the

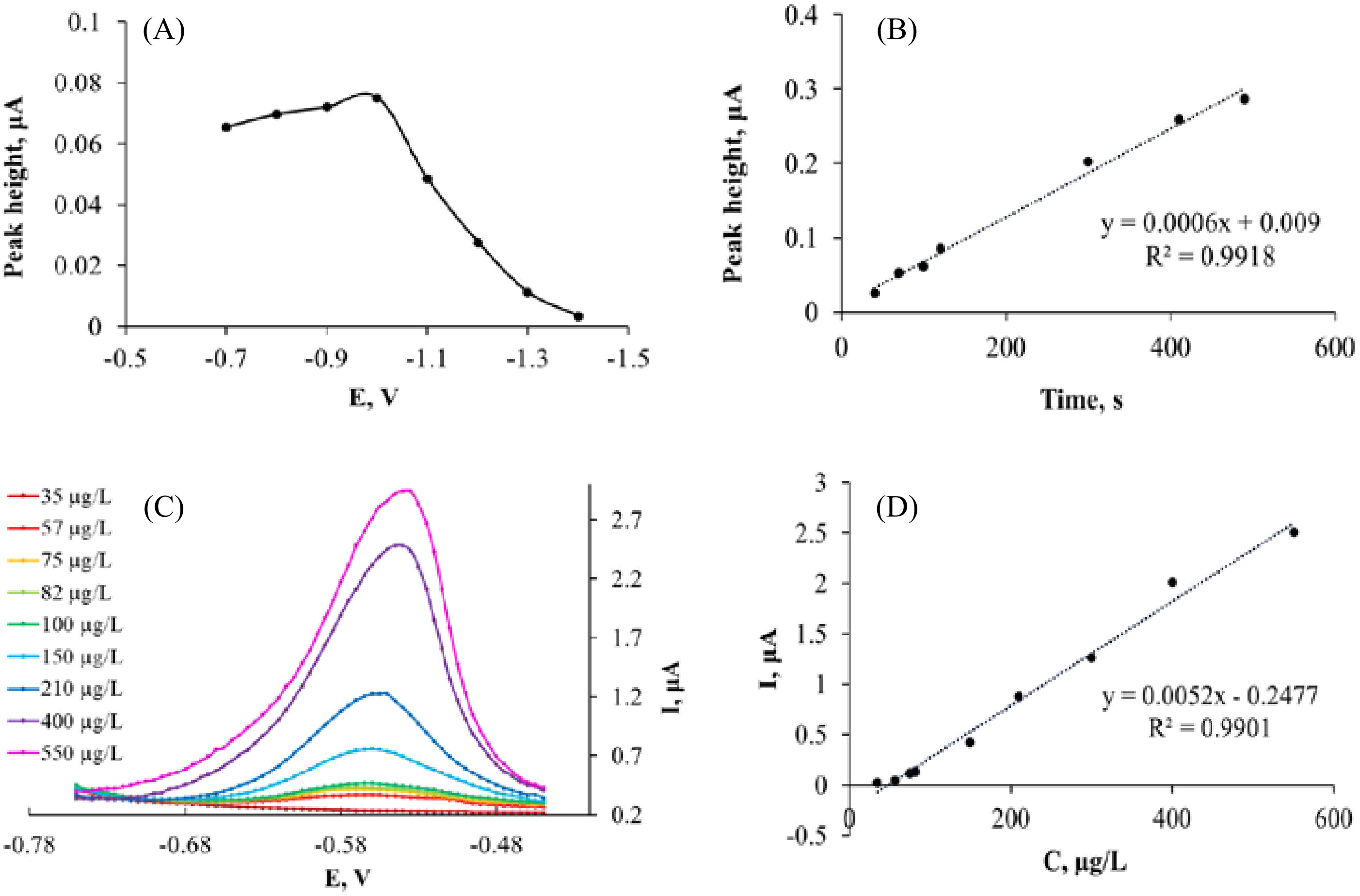

Figure 4. (A) Dependence of thallium peak height on the preconcentration potential in 0.2 M EDTA with 20 µg/L Tl$^+$ (preconcentration time: 120 s, potential range: –0.7 V to –1.4 V). (B) Effect of deposition time on Tl peak current in 0.2 M EDTA with 20 µg/L Tl$^+$ (deposition potential: –1.0 V, time range: 40–490 s). (C) DPV spectra for GCE/AgNPs-E1451R electrode in 0.2 M EDTA with Tl$^+$ concentration from 35 to 550 µg/L (deposition time: 120 s, potential: –1.0 V). (D) Calibration curve: Tl peak current vs. concentration under the same conditions as in (C). All measurements were performed using differential pulse voltammetry with a step potential of 5 mV and a pulse amplitude of 25 mV.

modified GCE/AgNPs-E1451R electrode. This is reflected by the linear relationship between the current and the increasing thallium concentration, studied in the range of 35 - 550 µg/L, corresponding to 1.71×10^{-7} to 2.69×10^{-6} M (Figure 4D).

From the calibration curve, the equation $y = 0.0052x - 0.2477$ was derived, with a correlation coefficient (R^2) of 0.9901.

The limit of detection (LOD) was calculated based on the regression parameters from the calibration curve, according to the following formula:

$$\mathrm{LOD} = (\kappa \times \mathrm{SDa}) / b \qquad (1)$$

where $\kappa = 3.3$, SDa represents the standard deviation of the intercept, and b is the slope of the calibration line.

The calculated LOD value was 1.62×10^{-7} M (9.75 µg/L). Therefore, the limit of quantification (LOQ = 3 LOD) corresponded to a concentration of 4.86×10^{-7} M (29.25 µg/L).

Checking the selectivity of the electrode

The main interferences in the voltammetric determination of thallium are cadmium and lead, which generate peaks at very similar potentials. In practice, the presence of these similar potentials makes it extremely difficult to distinguish the electrochemical thallium peaks from those of cadmium and lead, complicating accurate voltammetric analysis in their presence. Therefore, it is necessary to apply advanced analytical techniques, such as the use of specific complexing agents, to minimize the impact of cadmium and lead on the resulting thallium measurement outcomes.

The use of a base electrolyte with complexing properties, such as 0.2 M EDTA, enables accurate thallium determination in the presence of cadmium and lead ions. These ions form stable complexes with the electrolyte, reducing their adverse effects on the electrochemical thallium signal.

The selectivity of the method using the GCE/AgNPs-E1451R electrode was evaluated in the presence of thallium, lead, zinc, cadmium, and copper. The concentration ratio of $Tl^+ : Pb^{2+} : Zn^{2+} : Cd^{2+} : Cu^{2+}$ was 1 : 1 : 10 : 5 : 8, respectively. The preconcentration time was 120 s, and the preconcentration potential was -1.0 V. The determination was performed over a potential range from -1.0 V to -0.03 V (Fig. 5A).

The peaks recorded in the voltammogram were sufficiently separated, with the thallium signal appearing at -0.59 V, and the copper signal at -0.09 V. The results confirm that the determination of thallium concentration is feasible in the presence of other metals, such as cadmium, lead, copper, and zinc. However, the use of a complexing base electrolyte (EDTA) is necessary.

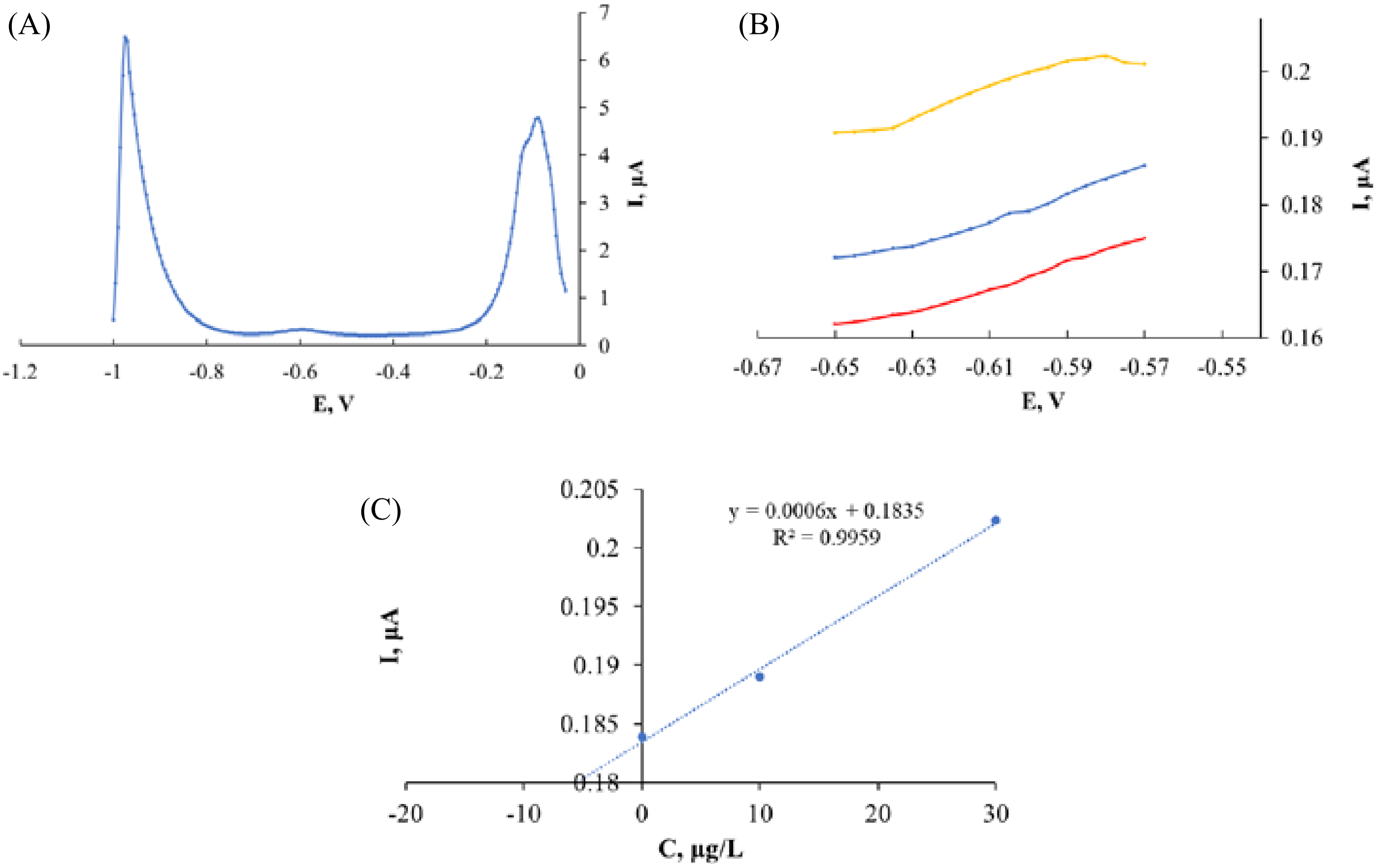

Figure 5. (A) Differential pulse voltammogram for the GCE/AgNPs-E1451R electrode recorded in 0.2 M EDTA containing 50 µg/L Tl^+, 50 µg/L Pb^{2+}, 500 µg/L Zn^{2+}, 250 µg/L Cd^{2+}, and 400 µg/L Cu^{2+}. (B) Relationship between Tl peak height and its concentration for the GCE/AgNPs-E1451R electrode in a real sample (— background, — real sample, — 30 µg/L Tl^+ addition). (C) Standard addition curve (30 µg/L Tl^+) for a groundwater sample. All measurements were conducted using DPV with a deposition time of 120 s, deposition potential of –1.0 V, step potential of 5 mV, and pulse amplitude of 25 mV.

Table 1 Repeatability of voltammetric measurements

No.	Maximum peak height [µA]
1	0.450
2	0.461
3	0.463
4	0.467
5	0.457
6	0.463
7	0.457
8	0.459
9	0.467
Arithmetic mean ± standard deviation	0.4604 ± 0.0051

The use of the modified electrode in the determination of thallium in groundwater.

The electrode was modified to enhance the sensitivity of thallium detection, enabling the measurement of low concentrations – an important requirement for environmental monitoring, including water quality assessment. The conducted thallium determination in groundwater confirmed the effectiveness of the modified GCE/AgNPs-E1451R electrode in both the base electrolyte and real samples. The electrode demonstrated high selectivity, minimizing interference from other metals present in the water, thereby contributing to precise analytical results (Fig. 5B).

The thallium peaks recorded on the voltammogram were reproducible within the same range (thallium signal at a potential between -0.60 V and -0.58 V). Groundwater studies confirmed that thallium concentrations can be reliably determined in real samples using the modified GCE/AgNPs-E1451R electrode. These findings are further supported by the standard addition curve (Fig. 5C).

Table 2 Repeatability of voltammetric measurements arranged in ascending order

No.	Maximum peak height [µA]
1	0.450
2	0.457
3	0.457
4	0.459
5	0.461
6	0.463
7	0.463
8	0.467
9	0.467

Repeatability of obtained voltammetric signals Q-Dixon test.

To verify the repeatability of the obtained signals, a series of measurements were performed under identical conditions. The preconcentration time was 120 seconds, the preconcentration potential was -1.0 V, and the thallium standard addition was 100 µg/L. Nine repetitions were performed. A statistical analysis using the Q-Dixon test was performed to check whether the set of these values contained a gross error. The results are presented in Table 1.

The results were ranked in descending order and are presented in Table 2.

For:

$n = 9$, $x_1 = 0.450$, $x_3 = 0.457$, $x_{n-2} = 0.463$, $x_{n-1} = 0.467$, $x_n = 0.467$

$$Q_1 = \frac{0.457 - 0.450}{0.467 - 0.450}$$

$$Q_1 = \frac{0.007}{0.017} = 0.412$$

$$Q_9 = \frac{0.467 - 0.463}{0.467 - 0.457}$$

$$Q_9 = \frac{0.004}{0.01} = 0.4$$

The critical value, taken from the statistical distribution table for n=9 at a significance level of $\alpha = 0.05$ is 0.512.

$$Q_1 = 0.412 < Q_{cr} = 0.512$$

$$Q_9 = 0.4 < Q_{cr} = 0.512$$

Both parameter values are lower than the critical value (Q_{cr}), which indicates that there are no gross errors in the series of voltammetric measurements.

Determination of the standard uncertainty of repeatability measurements.

The standard repeatability uncertainty was estimated using the relative standard deviation of the measurement results.

$$\text{sur} = \frac{RSD}{\sqrt{n}}$$

sur – standard uncertainty of repeatability
RSD – relative standard deviation
n – number of measurements (repetitions)

$$\text{sur} = \frac{0.011}{\sqrt{9}}$$

$$\text{sur} = 0.0037$$

$$\text{sur} = 0.37\%$$

Verification of the method's accuracy.

The precision of the method was determined by estimating the standard deviation (SD), relative standard deviation

(RSD) and coefficient of variation (CV) using the following equations:

$$RSD = SD / C_{average}$$
$$CV = RSD \cdot 100\%$$

$$RSD = \frac{0.0051}{0.4604}$$

$$RSD = 0.011$$

$$CV = 0.011 \cdot 100\% = 1.11\%$$

Discussion

As part of the modification of the glassy carbon electrode with silver nanostructures stabilized by starch derivatives, a series of significant experiments was conducted to improve the detection of thallium using voltammetric methods. A key initial step involved selecting the optimal deposition potential, which was tested in the range from -0.7 V to -1.4 V. The best results were obtained at a deposition potential of -1.0 V, which provided a foundation for subsequent experiments, ensuring the formation of well-defined thallium peaks.

An experiment designed to assess potential thallium depletion and the dependence of peak height on deposition time confirmed that thallium does not deplete. The peak height increased almost proportionally with deposition time, as evidenced by an R^2 value of 0.9918.

A significant step in the research was the analysis of the peak current dependence on thallium concentration. To determine the calibration curve, a series of measurements was performed, which confirmed the high sensitivity of the electrode. This was demonstrated by the linear increase in current with rising thallium concentration. Statistical analysis supported the calibration curve, yielding an R^2 value of 0.9901. The limit of detection (LOD) was calculated based on the regression parameters of the calibration curve. The LOD value was 1.62×10^{-7} M (9.75 µg/L), and the limit of quantification (LOQ) corresponded to a concentration of 4.86×10^{-7} M (29.25 µg/L). These results provide strong confirmation of the electrode's effectiveness in detecting even very low thallium concentrations.

In terms of selectivity, a major challenge was determining thallium in the presence of its interferents such as cadmium and lead. Due to their similar electrochemical properties, cadmium, lead, and thallium generate very similar peaks, complicating the accurate determination of each component. However, employing an appropriate supporting electrolyte, namely an EDTA solution, enabled effective peak separation on the voltammogram, thus preventing potential issues in the accurate determination of thallium.

In the final stage, thallium was determined in groundwater, confirming the effectiveness of the modified GCE/AgNPs-E1451R electrode in both the supporting electrolyte and real samples. However, it is crucial to regularly clean and repeat the modification every 5-7 measurements in order to maintain the analytical properties of the electrode and ensure reliable and accurate results.

In summary, the studies clearly indicate a significant improvement in the efficiency of thallium determination using the glassy carbon electrode modified with silver nanostructures stabilized by starch derivatives (GCE/AgNPs-E1451R) in voltammetric methods. The deposition potential of -1.0 V was identified as a critical parameter, ensuring optimal analytical performance. These findings suggest the potential applicability of this electrode modification for precise quantitative thallium analyses in various matrices. The modified GCE/AgNPs-E1451R electrode demonstrates competitive analytical performance, functioning effectively over a wide concentration range without requiring long deposition times, thereby shortening the overall analysis duration.

In contrast to electrodes containing mercury, the modified GCE/AgNPs-E1451R electrode is non-toxic. Its parameters are comparable to those of the GCE/AuNPs–LS/Hg electrode, which has a reported detection limit of 1.4×10^{-7} M (Karbowska et al., 2017). However, the modified electrode is much safer for the environment, as it does not contain toxic mercury.

Conclusions

The conclusions from this study make a significant contribution to the advancement of thallium determination using glassy carbon electrodes in voltammetric methods:

1) The established deposition potential of –1.0 V is a key factor in achieving optimal analytical results. This potential enables the effective formation of well-defined thallium peaks, thereby improving both the precision and sensitivity of the electrode.
2) Experimental confirmation of the absence of thallium depletion in the solution, along with the analysis of the relationship between peak height and deposition time, confirmed the stability and consistency of the electrode's properties. This ensures reliable and reproducible results in practical thallium detection.
3) The correlation between peak current and thallium concentration, supported by the calibration curve, confirmed the high sensitivity of the electrode, making it a promising tool for quantitative thallium analysis.
4) Studies of electrode selectivity demonstrated its ability to effectively distinguish thallium from cadmium, and lead, highlighting the potential of this modification in challenging conditions where the electrochemical similarity of these elements can pose a challenge.
5) The application of the modified electrode for thallium determination in groundwater confirmed its practical effectiveness.
6) The developed electrode modification is a promising tool in electrochemistry, particularly for precise quantitative thallium analysis in diverse matrices. These results lay the foundation for further work on refining this technology.

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Nanostruktury srebra stabilizowane pochodnymi skrobi do oznaczania talu w próbkach środowiskowych

Streszczenie: Tal, będący wysoce toksycznym metalem ciężkim, stawia przed analitykami istotne wyzwania ze względu na jego niskie stężenia występujące w różnorodnych matrycach próbek. W związku z tym wzrasta zainteresowanie tworzeniem innowacyjnych materiałów elektrodowych charakteryzujących się wysoką czułością, selektywnością oraz niskimi granicami wykrywalności, które mogłyby zastąpić tradycyjne elektrody rtęciowe w woltamperometrii. Celem niniejszego badania była modyfikacja elektrody z węgla szklistego (GCE) za pomocą nanostruktur srebra stabilizowanych pochodnymi skrobi oraz analiza wpływu tej modyfikacji na kluczowe parametry elektrody. Zmodyfikowaną elektrodę (GCE/AgNPs-E1451R) zastosowano do oznaczania talu metodą anodowej woltamperometrii strippingowej. Analizy przeprowadzono zarówno w elektrolicie podstawowym (roztwór EDTA), jak i w rzeczywistej próbce wody gruntowej z terenu Wielkopolski. Nanostruktury srebra zostały syntetyzowane przy użyciu podwójnie modyfikowanego hydrolizatu skrobi (E1451R), który poddano procesom utleniania i acetylacji. Prąd szczytu strippingowego talu wykazał liniowość w zakresie stężeń od 35 do 550 µg/L ($1{,}71\times10^{-7}$ do $2{,}69\times10^{-6}$ M). Obliczony limit wykrywalności (LOD) wyniósł 9,75 µg/L ($1{,}62\times10^{-7}$ M). Elektroda GCE/AgNPs-E1451R oferuje istotne zalety, w tym szeroki zakres wykrywalności, skrócony czas analizy dzięki eliminacji długotrwałych etapów prekoncentracji oraz działanie nietoksyczne w porównaniu do elektrod rtęciowych. Badana elektroda GCE/AgNPs-E1451R wykazuje istotne zalety w porównaniu z innymi typami elektrod, stanowiąc wszechstronne i efektywne rozwiązanie dla różnych zastosowań analitycznych. Charakteryzuje się wysoką skutecznością w szerokim zakresie stężeń, eliminując potrzebę przeprowadzania długotrwałych etapów wstępnego zatężania, co znacząco skraca całkowity czas analizy. Dodatkowo, w odróżnieniu od elektrod rtęciowych, elektroda GCE/AgNPs-E1451R jest nietoksyczna, stanowiąc bezpieczniejszą alternatywę dla zastosowań analitycznych.