


 Cite this: *RSC Adv.*, 2026, 16, 2801

# A novel optical chemical sensor for germanium determination in food and environmental samples

 Alaa S. Amin <sup>a</sup> and Mostafa Y. Nassar <sup>\*b</sup>

A colorimetric optode for germanium ( $\text{Ge}^{4+}$ ) detection was developed by incorporating 2-(((3,5-dimercapto-4*H*-1,2,4-triazole-4-yl)imino)methyl) phenol (DMTMP) and the liquid ion-exchanger trioctylmethylammonium chloride (Aliquat-336) into a cellulose triacetate (CTA) matrix plasticized with tri-(2-ethylhexyl) phosphate (TEHP). The transparent optode quantitatively preconcentrates  $\text{Ge}^{4+}$  from aqueous samples, inducing a distinct color change ( $\lambda_{\text{max}} = 545 \text{ nm}$ ). Optimal equilibration was achieved in 5.00 min in borate medium and 25.0 min in natural water. On the other hand, an optode sample without Aliquat-336 showed no change in color corresponding to the  $\text{Ge}^{4+}$ -DMTMP complex after equilibration with the same aqueous solution containing the  $\text{Ge}^{4+}$  ions. The uptake of  $\text{Ge}^{4+}$  is pH dependent and at pH 7.50 the maximum uptake was greater than 97.5 percent. In the detection of the  $\text{Ge}^{4+}$  ion, no significant interference of more than 750 times the concentration of the number of potentially interfering ions was detected. This optode showed a linear increase in absorbance at 545 nm with a peak absorbance of 545 nm for a concentration range of 6.00 to 174  $\text{ng mL}^{-1}$  of  $\text{Ge}^{4+}$  ions in aqueous solution over 5.00 min. The detection and quantification limits were assessed as 1.75 and 5.75  $\text{ng mL}^{-1}$ , respectively. The optode proposed in this study has been proven to be reusable. The optode is an effective tool for the detection of germanium in food and environmental samples with high accuracy and selectivity.

Received 20th November 2025

Accepted 31st December 2025

DOI: 10.1039/d5ra08967k

[rsc.li/rsc-advances](https://rsc.li/rsc-advances)

## Introduction

Winkler first identified germanium in 1885,<sup>1</sup> and since then, many studies have explored its properties and compounds. Although germanium may be essential to evolution, it can also adversely affect basic biological functions. Research focused on the effects of germanium compounds on living organisms and on human health, including their ingestion and associated health risks.<sup>2-5</sup> It is a key ingredient in a wide range of technological applications, including spiro-germanium for cancer therapy, high refractive-index glass, corrosion inhibitors in alloys, phosphors, identification systems, and infrared sensing devices. Global production of germanium-based products is growing, which is leading to a gradual increase in environmental germanium concentration.<sup>6,7</sup>

Germanium is naturally rare, with an average concentration of only 1.50  $\mu\text{g mL}^{-1}$  in the Earth's crust.<sup>8</sup> Germanium is a grey-white semiconductor element with properties similar to those of metals and insulators, along with physicochemical characteristics similar to silicon and tin. Due to its different physicochemical properties and compounds, it has found applications

in a wide range of industrial and advanced technological sectors.<sup>9-11</sup> The assessment of trace and ultra-trace concentrations of germanium in environmental matrices has become of considerable importance.<sup>12</sup>

Germanium is considered to be a scarce and strategically important element,<sup>13</sup> and its unique properties are increasingly utilized in renewable energy technologies and in electronic devices. The increasing use of graphene in emerging technologies, including semiconductor sensors, optical systems, wind energy, solar cells and electronic devices, has raised concerns about its potential environmental impact, in particular landfills.<sup>14,15</sup> Growing industrial interest in this element necessitates an evaluation of its potential environmental effects.<sup>16</sup> Classified as one of the Technology Critical Elements (TCE),<sup>17-19</sup> germanium plays a significant role in various technological and industrial applications, including semiconductor sensors, optical systems, telecommunications, wind energy systems, electric vehicles, solar cells, and energy-saving lighting solutions.<sup>20</sup> The growing reliance on advanced technologies results in the continuous discharge of increasing amounts of TCE into the environment. As a result, the scientific community has increased its interest in the natural processes associated with TCEs, their effects on living organisms, and their potential risks for human health.<sup>21</sup> Therefore, it is crucial to track the presence of this element in food, soil, water, and other possible intake sources, as well as to measure its levels in biological

<sup>a</sup>Chemistry Department, Faculty of Science, Benha University, Benha, Egypt. E-mail: [asamin2005@hotmail.com](mailto:asamin2005@hotmail.com); Tel: +00201205225223

<sup>b</sup>Department of Chemistry, College of Science, King Faisal University, Al-Ahsa 31982, Saudi Arabia. E-mail: [mynassar@kfu.edu.sa](mailto:mynassar@kfu.edu.sa); Tel: +00966538871438



tissues using accurate and highly selective analytical techniques.

The detection of trace amounts of germanium in food has attracted interest because of its important role in promoting hygienic food quality and its potential anti-cancer properties.<sup>22</sup> Intake of germanium dioxide is associated with serious adverse effects, such as organ failure and possibly fatal outcomes. Globally, the average concentration of germanium (Ge) in surface soils is approximately 2.00 mg kg<sup>-1</sup>, with ranges ranging from 0.10 mg kg<sup>-1</sup> to as high as 15.00 mg kg<sup>-1</sup>, due to different soil types formed under different geological and environmental conditions.<sup>23</sup> The concentration of germanium in soils worldwide is influenced by both natural (geogenic) and human-related (anthropogenic) factors. For instance, research carried out in the mining area of Freiberg, Germany, has shown a large variation in the total Ge levels in soil, with values ranging between 1.00 and 4.30 mg kg<sup>-1</sup> and a mean concentration of 1.90 mg kg<sup>-1</sup>.<sup>24</sup>

Currently, the most widely used analytical methods for determining germanium are spectrometric techniques, such as atomic absorption spectroscopy (AAS),<sup>25</sup> inductively coupled plasma mass spectrometry ICP-MS,<sup>26,27</sup> inductively coupled plasma optical emission spectroscopy ICP-OES,<sup>28</sup> high resolution inductively coupled plasma mass spectrometry HRICP-MS,<sup>29</sup> laser ablation inductively coupled plasma mass spectrometry LA-ICP-MS,<sup>30</sup> and spectrophotometry.<sup>31–34</sup> The applicability of certain methods, especially in fieldwork and laboratories within developing nations, may be constrained by factors such as the instrument's initial cost, required technical expertise, expenses for consumables, and equipment maintenance. The spectrophotometric method is preferred in this instance because of its user-friendliness and relatively low costs. In recent years, various newly developed compounds known as optical chemosensors have been studied as analytical agents for the spectrophotometric detection of germanium(IV) ions,<sup>35,36</sup> and other metal ions.<sup>37–39</sup>

Optical chemical sensors (or optodes) provide a simple and cost-efficient method for measuring the concentrations of different cations, anions, and some molecular substances.<sup>40,41</sup> In the last 30 years, optical chemical sensors have been developed with considerable interest.<sup>42–44</sup> Many of them are based on spectrophotometric measurements; however, no optode have been developed for detection of cations of specific elements. Most optodes use reagents to form complexes with metal ions. Various techniques are used to immobilize ion indicators on/in membranes, including covalent bonding to a functionalized support,<sup>45,46</sup> or physical entrapping in a porous polymer matrix or behind a selectively permeable membrane.<sup>47,48</sup> Preferably, the immobilized ionic reagent must remain retained and not leach into the sample solution throughout the analyte measurement process.

This study presents the development of a Ge<sup>4+</sup> optode by immobilization of DMTMP reagent and Aliquat-336 in a CTA membrane that has been plasticized with TEHP. In this study, DMTMP incorporated into the matrix of optode itself did not show any interaction with Ge<sup>4+</sup> ions. However, the presence of Aliquat-336 increases the transport of Ge<sup>4+</sup> in the optode. The

key parameters influencing the design and performance of the sensor shall be systematically assessed and optimized. The influence of different experimental factors—including pH levels, borate ion concentration, and the existence of interfering cations and anions—on the identification of Ge<sup>4+</sup> was examined, along with its preconcentration from large volumes of water and the potential for optode reuse. The optimized optode formulation and adjusted chemical parameters of the aqueous media were used for the quantification of both the Ge<sup>4+</sup> and CH<sub>3</sub>Ge<sup>4+</sup> species. Subsequently, the Ge<sup>4+</sup>-loaded optodes were used to enhance the colorimetric analysis of Ge<sup>4+</sup> in a variety of food and environmental water samples.

## Experimental

### Apparatus

A Fisons (UK) double distiller, made entirely of glass, was employed to prepare deionized water. A Jenway 3505 pH meter (9V AC-powered) was utilized to detect pH values. A digital micrometer (Mitutoyo, Japan) featuring an accuracy of ±0.001 mm was employed to detect the thickness of the membrane samples. Optode samples were placed within a quartz cuvette (dimensions: 3 cm × 1 cm × 1 cm), and their absorbance spectra were measured with a UV-Visible spectrophotometer (model V-530, JASCO, Tokyo, Japan). For each set of samples, blank measurements were conducted. Ge(IV) ion quantification was performed using ICP-AES (PerkinElmer, Germany, 8300).

### Materials

Analytical-grade chemicals including dichloromethane, copper chloride, zinc acetate, lead nitrate, ferrous sulfate, cadmium nitrate, and mercuric chloride were procured from Merck (Mumbai, India; Germany, 8300). Throughout the current studies, deionized water (18 MΩ cm<sup>-1</sup>) was utilized. Aliquat-336 from Sigma-Aldrich (Steinheim, Switzerland) and Cellulose triacetate (molecular weight 72 000–74 000, acetyl value = 43.2%) (CTA), and tri-(2-ethylhexyl) phosphate (TEHP) sourced from Koch-Light Laboratories (Coinbrook Bucks, England) and GeO<sub>2</sub> (spectrometrically pure that was obtained from the Shanghai Third Chemical Factory, Shanghai, China) were used as obtained. Dioctylphthalate (DOP) and *o*-nitrophenyloctyl ether (NPOE) were obtained from Fluka (situated in Busch, Switzerland) and used without additional purification.

A 100.0 µg mL<sup>-1</sup> germanium(IV) stock solution was prepared by gently heating 0.0144 g of high purity GeO<sub>2</sub> in 20.0 mL of 2.00% sodium hydroxide solution until completely dissolved. Hydrochloric acid was added until the solution was colorless, then the solution was transferred to a 100.0 mL standard flask and brought to the volume with water. Standard working solutions of 1.00 µg mL<sup>-1</sup> were obtained by appropriate dilution with water. Fresh dilution preparations were prepared as necessary.

For the assessment of the potential impact of interfering ions, stock solutions (mg L<sup>-1</sup>) of various metal ions were prepared from high-purity nitrate or chloride salts (≥99.99%).



All experiments were conducted using deionized water. A pre-prepared borate buffer, maintaining a pH between 5.65 and 10.50, was used to stabilize the pH of the solutions.<sup>49</sup>

### Synthesis of (DMTMP) schiff base

Initially, 4-amino-3,5-dimercapto-1,2,4-triazole was prepared as described by the published method.<sup>50</sup> Next, two drops of piperidine were introduced to a suspension of 4-amino-3,5-dimercapto-1,2,4-triazole (1.48 g, 10.0 mmol) in absolute ethanol and an equimolar amount of salicylaldehyde (10.0 mmol) in ethanol (10.0 mL). The reflux of the reaction mixture was achieved in 5.00 h by means of a water bath and continuous stirring. After washing the precipitate with warm ethanol, it was filtered, dried on a water bath, recrystallized using bi-distilled water, and finally dried in the air. The product had a melting

point of 287–288 °C. Anal. Cal. For  $C_9H_8N_4OS_2$  (M.wt = 252.31): C, 42.84; H, 3.20; N, 22.21; O, 6.34; S, 25.41%. Found: C, 42.91; H, 3.23; N, 22.24.; O, 6.45; S, 25.40%. The molecular structure of the Schiff base compound has been confirmed by FT-IR spectroscopy and (<sup>1</sup>H-NMR) techniques (Fig. 1). The synthetic route used for the preparation of the Schiff base reagent 2-(((3,5-dimercapto-4*H*-1,2,4-triazole-4-yl)imino)methyl)phenol (DMTMP) is shown in Scheme 1.

### Preparation of optode

CTA (0.10 g) was dissolved in 10 mL dichloromethane. The solution was prepared by the dissolution of TEHP (0.10 g), Aliquat-336 (0.04 g), and DMTMP (0.01 g) in 5.00 mL dichloromethane. The two solutions were combined and ultrasonicated for 2.00 minutes to produce a uniform casting

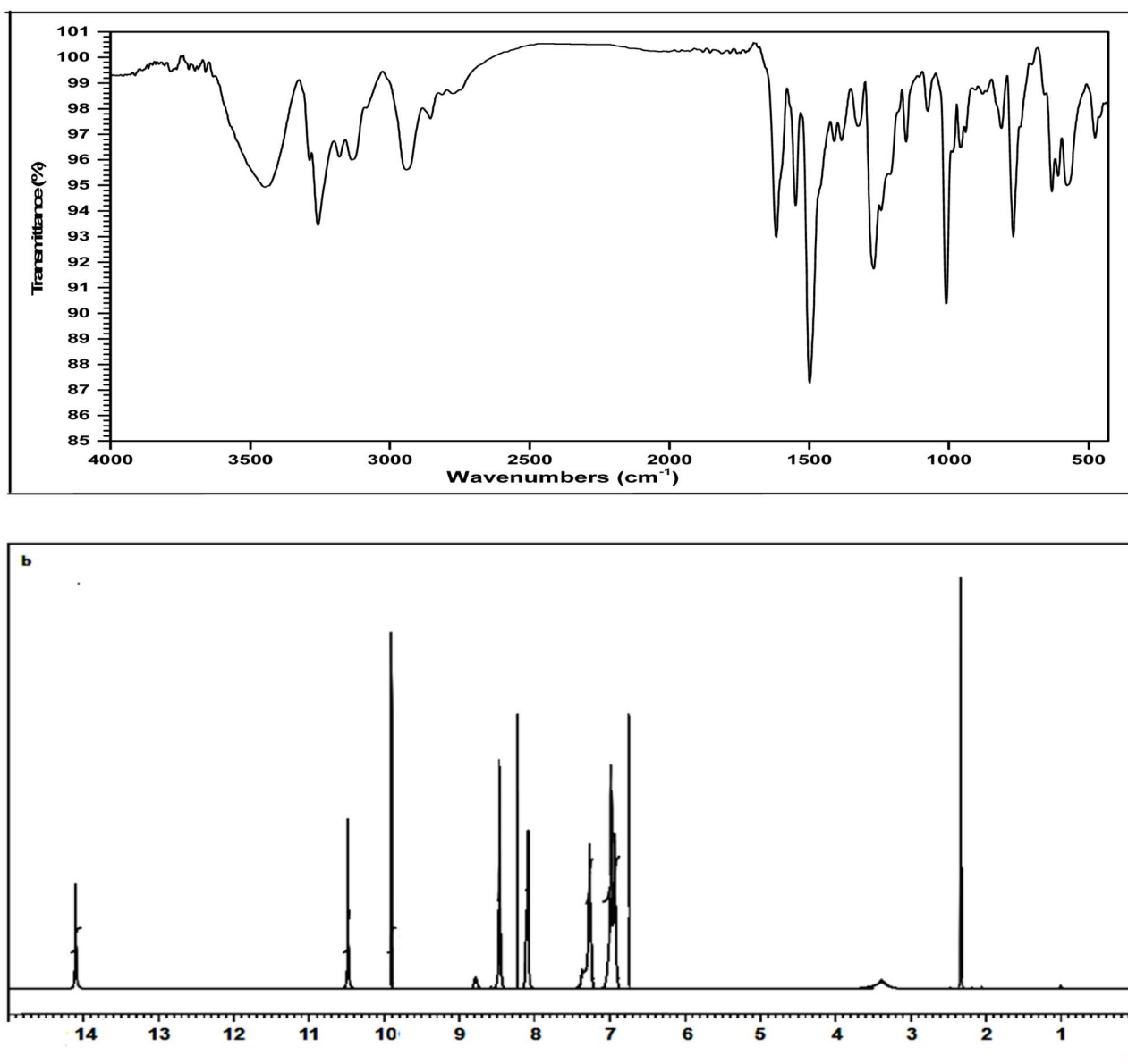
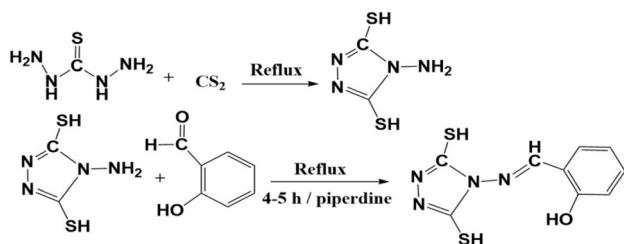


Fig. 1 (a) FT-IR and (b) <sup>1</sup>H-NMR spectra of DMTMP.





Scheme 1 Synthetic pathway for the preparation of DMTMP Schiff base reagent.

solution. The casting solution was poured into a Petri dish (9 cm inner diameter) placed on a flat, level surface. The lid was partially closed to enable gradual evaporation of  $\text{CH}_2\text{Cl}_2$  from the solution. After two days of evaporation of dichloromethane from the casting solution, the transparent optode was carefully removed from the Petri dish. The resulting optode was self-supporting and showed sufficient mechanical strength for use in stirred aqueous solutions. Consequently, transparent support was not necessary. The prepared optode was then washed thoroughly with water to eliminate any soluble residues which have been present. The measurements showed that the optode membrane is  $38 \pm 5.00 \mu\text{m}$  thick. Optode samples remained at a fixed size of  $2 \text{ cm} \times 1 \text{ cm}$  during the investigation.

### General procedure

The formation of the  $\text{Ge}^{4+}$ -DMTMP complex in the optode sample was spectrophotometrically monitored, with its intensity measured relative to the  $\text{Ge}^{4+}$  concentration in the equilibration solution. The pH of the equilibration solutions (2.50 mL) was maintained at 7.50. The known amount of  $\text{Ge}^{4+}$  (6.00–174 ng mL) was added to the equilibration solution, together with 2.50 mL of borate buffer solution (pH 7.50). Measurements of absorbance for the  $\text{Ge}^{4+}$ -loaded optode samples were taken at

$\lambda_{\text{max}} = 545 \text{ nm}$ . To investigate the kinetics, the optode was immersed in a thoroughly stirred solution containing a defined concentration of  $\text{Ge}^{4+}$  in a borate buffer at pH 7.50. After equilibration for a specified time, the optode was removed from the solution, and its absorbance was recorded at 545 nm. The equilibration of the optode sample was allowed to proceed until a stable absorbance reading was obtained. To study the desorption of  $\text{Ge}^{4+}$ , the optode sample was immersed in 10.0 mL of 0.15 M HCl aqueous solution for a specific time with constant stirring. The release of  $\text{Ge}^{4+}$  from the optode was tracked by measuring the absorbance of the optode sample at 545 nm. Scheme 2 shows a schematic representation of the immobilization process of DMTMP on the membrane and the resulting change in color of the thin film after and prior to exposure to the  $\text{Ge}^{4+}$  solution.

### Determination of stoichiometry

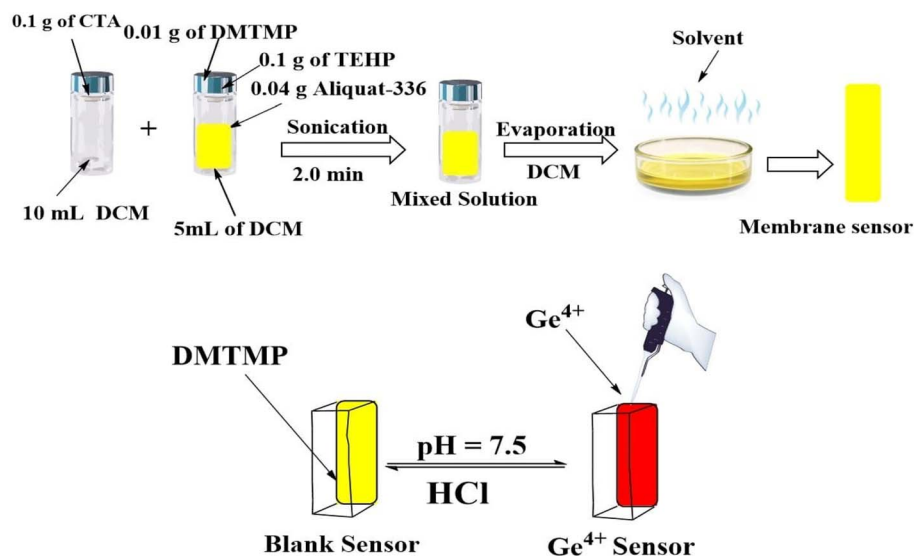
The stoichiometry of the  $\text{Ge}^{4+}$ -DMTMP complex has been investigated using both the mole continuous-variation and ratio methods. The procedures were carried out at pH 7.50 using  $\text{Ge}^{4+}$  and DMTMP at a concentration of  $5.00 \times 10^{-4} \text{ M}$ .

### Interference studies

The effect of various interfering cations, including certain alkali metals, transition elements, and lanthanides, on the uptake of  $\text{Ge}^{4+}$  by the optode was examined by equilibrating optode samples in a borate buffer solution at pH 7.50, each containing a constant concentration of  $\text{Ge}^{4+}$  and varying concentrations of the interfering cations. The absorption of  $\text{Ge}^{4+}$  was determined by comparing the absorbance of solutions before and after the optode samples reached the equilibrium.

### Application to real samples

The proposed method was used to determine  $\text{Ge}^{4+}$  ion concentrations in real soil and water samples obtained from



Scheme 2 Schematic representation for the preparation and complexation of the proposed sensor and the  $\text{Ge}^{4+}$ -DMTMP complex.



industrial sites in and around Quesna and Shoubra. The previously described procedure was used for the analysis of 20.0 mL samples of various water types—including process, natural, seawater, wastewater, and post-oil extraction water—and for an acid-digested soil sample.

### Procedure for soil analysis

Soil specimens were taken from manufacturing areas in the cities of Shoubra and Quesna. These samples were air-dried in a laboratory oven at 70.0 °C, then finely ground and sieved through a 0.25 mm nylon to ensure uniform particle size. A 1.00 g soil sample was subjected to 10.0 mL of concentrated HCl and 3.00 mL of concentrated HNO<sub>3</sub>, and then left to stand overnight.<sup>51</sup> The digested product was pH adjusted to 7.50 using borate buffer solution, and then volumetrically standardized in a 25.0 mL graduated flask. The solutions were further processed as shown in the procedure described above.

### Determination of germanium in foods

All the samples of food and fruit were purchased from supermarkets located in Benha City. Dry ashing and wet digestion are frequently employed for sample decomposition; however, traditional methods of both methods may result in loss of germanium. To mitigate these problems, a reflux setup was chosen for sample digestion. A 5.00 g sample was combined with 20.0 mL of digesting acid (HNO<sub>3</sub>:H<sub>2</sub>SO<sub>4</sub> = 10:1) in a 250 mL calibrated flask fitted with a reflux apparatus. The flask was left to stand overnight, then the mixture was gently heated on an electrical heater. After removing the NO<sub>2</sub>, the stopcock was turned and the sample solution was gently heated for approximately 3.00 to 5.00 minutes until sulfuric acid fumes were visible. Afterward, the solution was allowed to cool with the stopcock open, and then it was closed once more. Subsequently, 5.00 mL of 30.0% hydrogen peroxide was gradually added while maintaining mild heat. The stopcock was closed, and the mixture was concentrated to roughly 10.0 mL. Finally, the contents were transferred to a 25.0 mL volumetric flask and diluted to the mark with distilled water. The volume of 5.00 mL was pH-adjusted to 7.50, and then volumetrically standardized in a 25.0 mL graduated flask. The solutions were further processed as shown in the procedure described above.

## Results and discussion

### Measurement principle

DMTMP, bound to the surface of the triacetylcellulose membrane, has been observed to form a complex with Ge<sup>4+</sup> ions in the borate buffer solution. In this study, DMTMP was incorporated into a CTA matrix which was plasticized using TEHP. No significant color change was observed, when this optode sample was equilibrated with Ge<sup>4+</sup>-containing solutions across a pH range of 3.00 to 10.0. The absorbance readings of the equilibrated optode samples revealed no evidence of Ge<sup>4+</sup> ion uptake in the optode containing only DMTMP. This suggests that the DMTMP, immobilized within the TEHP-plasticized CTA matrix, did not exhibit any interaction with

Ge<sup>4+</sup> ions present in the equilibration medium. Aliquat-336 in the optode was observed to enhance the movement of Ge<sup>4+</sup> from aqueous phase to optode matrix, and its preconcentration as DMTMP-Ge<sup>4+</sup> complex in the optode. Multivariate optimization and contribution of variables are calculated and explained as follows.

### Effect of variable parameters

The selectivity and sensitivity imparted by a given ionophore are known to be strongly influenced by factors such as the membrane composition, nature of the solvent mediator, and the additives used.<sup>52</sup> It was therefore examined in detail the various parameters—including the type of plasticizer, the amount of ionophore, and the incorporation of Aliquat 336—affect the response properties of the membrane.

To determine the optimal DMTMP loading, membranes containing 1.00–8.00 mg of DMTMP were prepared. As the DMTMP amount increased from 1.00 to 4.00 mg, the optodes absorbance increased correspondingly; however, further additions up to 8.00 mg resulted in negligible changes in absorbance (Fig. 2). Therefore, the amount of DMTMP in the optode was set at 4.00 mg for subsequent investigations.

To enhance the optical properties, the quantity of DMTMP incorporated in the optode has been optimized and kept at a constant level. The TEHP-based optode showed more uniformity and superior kinetic performance relative to other plasticizer such as DOP and NPOE. The ratios of TEHP, CTA, and Aliquat-336 within the optode were adjusted to improve uptake efficiency, mechanical strength, response kinetics, and homogeneity. The ideal formulation of the optode was identified as: TEHP = 40.0 wt%, CTA = 40.0 wt%, Aliquat-336 = 16.0 wt%, and DMTMP = 4.00 wt%.

Spectrophotometric analysis was used to investigate the extraction efficiency of Ge<sup>4+</sup> ions from aqueous solutions by means of the developed optode, revealing a quantitative uptake at pH > 6.00. The sorption kinetics of Ge<sup>4+</sup> were significantly faster in deionized water (25.0 min) and a borate buffer solution at pH 7.50 (5.00 min). This is because Ge<sup>4+</sup> may form hydrated

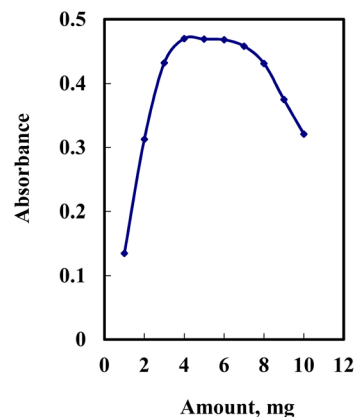
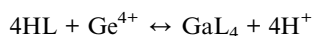


Fig. 2 Absorbance as a function of the amount of DMTMP in the sensor matrix having a fixed proportion of CTA (40.0 mg), TEHP (40.0 mg) and Aliquat 336 (16.0 mg).



species of  $\text{Ge}^{4+}$  or  $\text{GeOH}^{4+}$  in an aqueous phase within a pH interval of 6.00–8.00. The presence of quaternary ammonium salts in the optode matrix would impede the sorption of these  $\text{Ge}^{4+}$  species.  $\text{Ge}^{4+}$  can form either an anionic or neutral complex with borate, which is readily sorbed into the optode matrix. The optode designed in this method is well-suited for analyzing environmental water samples, as they naturally contain borate ions. The effects of different pH-containing borate buffer solutions on the absorbance of the  $\text{Ge}^{4+}$  optode at wavelength 545 nm associated with  $\text{Ge}^{4+}$ -DMTMP complex were further investigated by equilibrating the optode samples for 5.00 min in a solution containing differing levels of buffer and a fixed concentration of  $\text{Ge}^{4+}$  ( $100 \text{ ng mL}^{-1}$ ) at pH 7.50.

The uptake of  $\text{Ge}^{4+}$  in the optode sample increased with the buffer volume in the equilibrating solution, reaching a maximum at 2.50 mL, after which it stable. At pH 7.50 (0.05 M of both boric and sodium borate), DMTMP is expected to be predominantly present in the optode as HL. This species may form an ion pair with Aliquat-336, facilitating  $\text{Ge}^{4+}$  extraction. The uptake mechanism can be described by the following reaction:



where L is the deprotonated form of DMTMP.

Fig. 3 displays the UV-Visible absorption spectra of the blank optode and of optode samples containing different concentrations of  $\text{Ge}^{4+}$  ions. The figure shows that the blank optode exhibits a peak absorbance ( $\lambda_{\text{max}}$ ) at 367 nm, which is attributed to the unbound form of DMTMP. Upon interaction with  $\text{Ge}^{4+}$  ions, the optode samples showed a significant red shift in absorbance, moving from 367 nm (in the absence of  $\text{Ge}^{4+}$ ) to 545 nm, accompanied by an isosbestic point at 453 nm. The absorbance at the maximum wavelength ( $\lambda_{\text{max}} = 545 \text{ nm}$ ) increased in direct correlation to the amount of  $\text{Ge}^{4+}$  accumulated by the optode. This behavior demonstrates that the optodes response is linearly dependent on the concentration of  $\text{Ge}^{4+}$  ions absorbed from the surrounding solution. In order to evaluate the practical usefulness of the optode for the detection

of  $\text{Ge}^{4+}$ , it was subjected to environmental water samples artificially enriched with  $\text{Ge}^{4+}$ .

### Stoichiometric ratio of $\text{Ge}^{4+}$ -DMTMP complex

The absorption spectra of DMTMP and its germanium complex ( $\text{Ge}$ -DMTMP) were documented at the early stages of the investigation, as shown in Fig. 3. The graph shows that DMTMP has its maximum absorption at 367 nm, while the  $\text{Ge}$ -DMTMP complex shows a distinct peak at a much higher wavelength of 545 nm. To determine the exact ratio of DMTMP to  $\text{Ge}^{4+}$  in the complex, we utilized two approaches: the Job's process and the molar ratio process. According to Job's method, the maximum absorption occurred at a DMTMP :  $\text{Ge}^{4+}$  ratio of 4 : 1. Similarly, the molar ratio method showed an intersection point at a mole ratio of 4, which confirmed the result. Both methods consistently indicated a stoichiometric ratio of 1 : 4 between germanium and DMTMP in the  $\text{Ge}$ -DMTMP complex. In addition, by comparing the infrared (IR) spectra of DMTMP and the  $\text{Ge}$ -DMTMP complex, the researchers derived the structural model of the complex, shown in Scheme 3. The conditional formation constant ( $\log K$ ), calculated by Harvey and Manning equation<sup>53</sup> using the data obtained from the above two methods, was found to be 7.35, whereas the true constant was 10.10.

### Effect of stirring

The stirring of the  $\text{Ge}^{4+}$  solution has a significant impact on the sensor's response. Compared to the unstirred solution, stirring resulted in almost three times the improvement. This behavior is attributed to the migration of  $\text{Ge}^{4+}$  ions towards the fixed DMTMP. The stirring process enhances both the interaction between  $\text{Ge}^{4+}$  ions and DMTMP and the diffusion of  $\text{Ge}^{4+}$  ions across the membrane toward DMTMP. In contrast, the absence of stirring, the concentration gradient is the only factor affecting the diffusion of the  $\text{Ge}^{4+}$  ions through the membrane.<sup>52</sup>

### Response time and reusability

The optode's response time to  $\text{Ge}^{4+}$  was observed to vary with the thickness of the optode sample. The period needed for the optode strip ( $2 \text{ cm} \times 1 \text{ cm}$ ) to reach peak absorbance at  $\lambda_{\text{max}} = 545 \text{ nm}$  for the  $\text{Ge}^{4+}$ -DMTMP complex in a well-agitated  $\text{Ge}^{4+}$  solution significantly decreased—from 25.0 minutes to just 5.00 minutes—when the optode thickness was reduced from  $75.0 \mu\text{m}$  to  $38.0 \mu\text{m}$ . A decrease in thickness has been observed with respect to the mechanical strength of the self-supporting optode. The ideal equilibration durations for effective  $\text{Ge}^{4+}$  uptake by the optode sample (with a thickness of  $40.0 \mu\text{m}$ ) were determined to be 25.0 minutes from deionized water and 5.00 minutes from an aqueous solution containing 2.50 mL of borate buffer at pH 7.50. The sorption kinetics of  $\text{Ge}^{4+}$  remained consistent across concentrations spanning from 6.00 to  $174 \text{ ng mL}^{-1}$  in well-mixed aqueous samples.

Since the optode proposed in this study is capable of pre-concentrating  $\text{Ge}^{4+}$  ions from aqueous solutions, several factors influence its detection limit and applicable concentration range

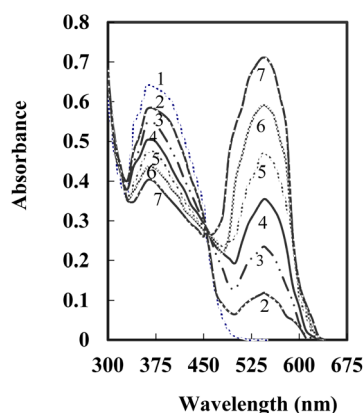
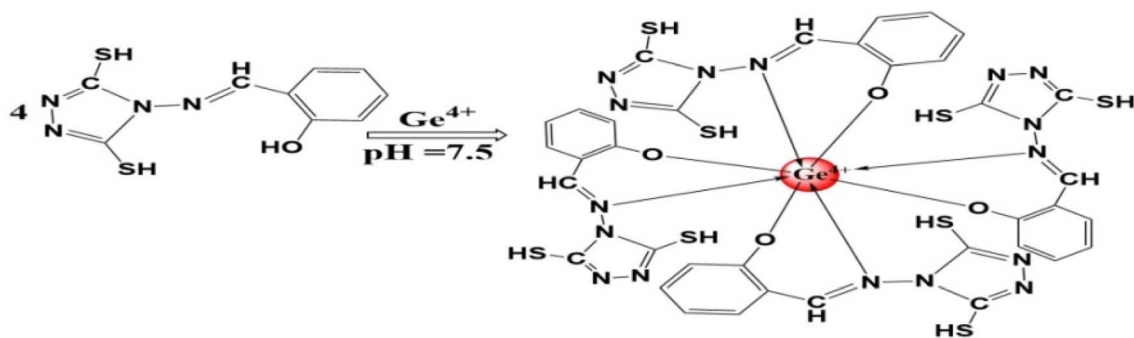


Fig. 3 Absorption spectra of 1-control sensor 2–7 DMTMP optode at 25.0, 50.0, 75.0, 100.0, 125.0 and  $150.0 \text{ ng mL}^{-1}$  at pH 7.50.





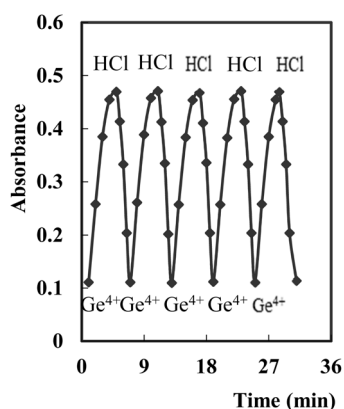
Scheme 3 The stoichiometric ratio of the formed Ge-DMTMP complex.

for the quantitative analysis of  $\text{Ge}^{4+}$ . These include the volume of the solution used during equilibration, the minimum quantity of  $\text{Ge}^{4+}$  needed within the optode matrix to generate a measurable analytical signal, and the sorption capability of the optode toward  $\text{Ge}^{4+}$ . The experimental findings revealed that a  $2\text{ cm} \times 1\text{ cm}$  optode strip could adsorb up to  $88.0\text{ }\mu\text{g}$  of  $\text{Ge}^{4+}$  ions. The lowest detectable concentration of  $\text{Ge}^{4+}$  required for a measurable response was determined to be  $12.0\text{ }\mu\text{g}$ .

A direct linear correlation was observed between the absorbance at  $545\text{ nm}$  and the  $\text{Ge}^{4+}$  concentration in the aqueous solution, ranging from  $6.00$  to  $174\text{ ng mL}^{-1}$ . Detection capabilities were established through statistical evaluation of blank measurements, where LOD ( $3\sigma/s$ ) and LOQ ( $10\sigma/s$ ) were found to be  $1.75$  and  $5.75\text{ ng mL}^{-1}$ , respectively, with  $\sigma$  denoting blank signal variability and  $s$  representing the calibration curve's slope.<sup>54</sup> A comparable response was achieved after  $5.00$  minutes of equilibration in the presence of borate buffer. The absorbance measurements for optode samples exposed to a constant amount of  $\text{Ge}^{4+}$  exhibited reproducibility within a margin of  $1.00$ – $2.00\%$ . The stability tests of the sensor under different conditions such as atmospheric storage, extreme pH and high-salinity conditions showed that the sensor membrane was not affected the determination  $\text{Ge}^{4+}$  ions, which further strengthens the reliability of the sensor in real-world environments.

The optode's reusability was evaluated by performing five consecutive cycles of  $\text{Ge}^{4+}$  sorption and desorption. The desorption of  $\text{Ge}^{4+}$  from the optode was performed using a  $0.15\text{ M HCl}$  solution. Both the sorption and desorption processes were examined by measuring absorbance at  $545\text{ nm}$ . Fig. 3 shows the patterns observed over five successive cycles of  $\text{Ge}^{4+}$  sorption and desorption. Fig. 4 shows that the sorption profile lasted for  $5.00$  minutes, whereas  $\text{Ge}^{4+}$  was quantitatively desorbed from the optode in just  $2.00$  minutes when equilibrated in a well-stirred  $2.50\text{ mL}$  aqueous solution of  $0.15\text{ M HCl}$ . This demonstrates the reusability of the optode in the proposed method. A schematic representation of the preparation, complexation and regeneration of the proposed sensor and the  $\text{Ge}^{4+}$ -DMTMP complex is described in Scheme 2 for SI to improve reproducibility.

Finally, the optode was used for analyzing environmental water samples spiked with different concentrations of  $\text{Ge}^{4+}$ . Some samples in a volume of  $2.50\text{ mL}$  had  $\text{Ge}^{4+}$  a concentration exceeding the analytical range's upper limit. Two sets of experiments were conducted to address this: one employing the samples as obtained and another with 10-fold diluted samples. The pH of the liquid samples was adjusted to  $7.50$ , followed by the addition of  $2.50\text{ mL}$  borate buffer solution. The optode samples were then equilibrated with agitation for  $5.00$  minutes. The mean levels of  $\text{Ge}^{4+}$  detected in five distinct surface water samples ranged between  $12.1$  and  $30.7\text{ ng mL}^{-1}$ , with relative standard deviations ranging from  $1.75\%$  to  $2.15\%$ .

Fig. 4 Reversibility of the sensor exposed  $100.0\text{ ng mL}^{-1}\text{ Ge}^{4+}$  and  $0.15\text{ M HCl}$ .

### Lifetime and stability

The refined membrane retained structural integrity after three weeks of inactivation and showed excellent stability with less than a  $1.00\%$  variation in dynamic range during  $\text{Ge}^{4+}$  ion solution measurements. For the next two months, the optode was exposed daily for one hour to a  $\text{Ge}^{4+}$  solution ( $100.0\text{ ng mL}^{-1}$ ), during which the optical membrane exhibited only a slight absorbance variation, not exceeding  $3.25\%$ . A straightforward rinse with distilled water effectively restored the membrane function. It is noteworthy that no ligand leaching was detected in the solution during the analysis of the samples at this time. This increased stability is probably due to the high lipophilicity of DMTMP and its electron delocalization, both of



Table 1 Impact of interfering ions on the estimation of 100.0 ng mL<sup>-1</sup> Ge<sup>4+</sup> at pH 7.50 borate buffer solution

Foreign ions	Added as	Amount tolerated	Foreign ions	Added as	Amount tolerated
K <sup>+</sup>	KCl	15 000	La <sup>3+</sup>	LaCl <sub>3</sub>	2000
Na <sup>+</sup>	NaNO <sub>3</sub>	13 500	Ti <sup>2+</sup>	TiCl <sub>2</sub>	1750
Li <sup>+</sup>	LiCl	12 000	Mn <sup>2+</sup>	MnCl <sub>2</sub> ·4H <sub>2</sub> O	1500
Ag <sup>+</sup>	AgNO <sub>3</sub>	11 000	Sc <sup>3+</sup>	Sc(NO <sub>3</sub> ) <sub>3</sub>	1300
Ca <sup>2+</sup>	CaCl <sub>2</sub>	10 000	Y <sup>3+</sup>	YCl <sub>3</sub>	1200
Ba <sup>2+</sup>	BaCl <sub>2</sub> ·2H <sub>2</sub> O	9250	Cr <sup>3+</sup>	CrCl <sub>3</sub>	1100
Mg <sup>2+</sup>	MgCl <sub>2</sub>	8500	Se <sup>4+</sup>	Na <sub>2</sub> SeO <sub>3</sub>	1000
Cd <sup>2+</sup>	CdCl <sub>2</sub>	8000	Zr <sup>4+</sup>	ZrCl <sub>4</sub>	925
Co <sup>2+</sup>	CoCl <sub>2</sub> ·6H <sub>2</sub> O	7500	Pt <sup>4+</sup>	PtCl <sub>4</sub>	850
Cu <sup>2+</sup>	CuCl <sub>2</sub> ·6H <sub>2</sub> O	7000	Te <sup>4+</sup>	Na <sub>2</sub> TeO <sub>3</sub>	825
Zn <sup>2+</sup>	ZnCl <sub>2</sub>	6500	Sn <sup>4+</sup>	SnCl <sub>2</sub> ·2H <sub>2</sub> O	800
Sn <sup>2+</sup>	SnCl <sub>2</sub> ·2H <sub>2</sub> O	6000	Th <sup>4+</sup>	ThCl <sub>4</sub>	800
Fe <sup>2+</sup>	FeSO <sub>4</sub>	5500	UO <sub>2</sub> <sup>2+</sup>	UO <sub>2</sub> (NO <sub>3</sub> ) <sub>2</sub>	800
Sr <sup>2+</sup>	SrCl <sub>2</sub>	5000	Ce <sup>4+</sup>	Ce(NO <sub>3</sub> ) <sub>4</sub>	800
Pb <sup>2+</sup>	PbSO <sub>4</sub>	4500	V <sup>5+</sup>	V <sub>2</sub> O <sub>5</sub>	800
Pd <sup>2+</sup>	PdCl <sub>2</sub>	4000	Cr <sup>6+</sup>	K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	775
Ni <sup>2+</sup>	Ni(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	3500	Mo <sup>6+</sup>	(NH <sub>4</sub> ) <sub>2</sub> Mo <sub>7</sub> O <sub>24</sub> ·2H <sub>2</sub> O	775
Hg <sup>2+</sup>	HgCl <sub>2</sub>	3000	W <sup>6+</sup>	Na <sub>2</sub> WO <sub>4</sub>	775
Al <sup>3+</sup>	AlCl <sub>3</sub>	2500	Os <sup>8+</sup>	OsO <sub>4</sub>	750
Fe <sup>3+</sup>	FeCl <sub>3</sub>	2250			

which increase the durability of the system when complexed with Ge<sup>4+</sup> ions.

#### Inter-day and intra-day precision

Reproducibility, assessed over several days, and repeatability, assessed over one day, were assessed by performing five

consecutive extraction and determination procedures with 100 ng mL<sup>-1</sup> of Ge<sup>4+</sup>. For the intra-day assessment, the tests were conducted within the same day, while for inter-day assessment the tests were spread over three consecutive days. Both assays produced satisfactory results, with a relative standard deviation

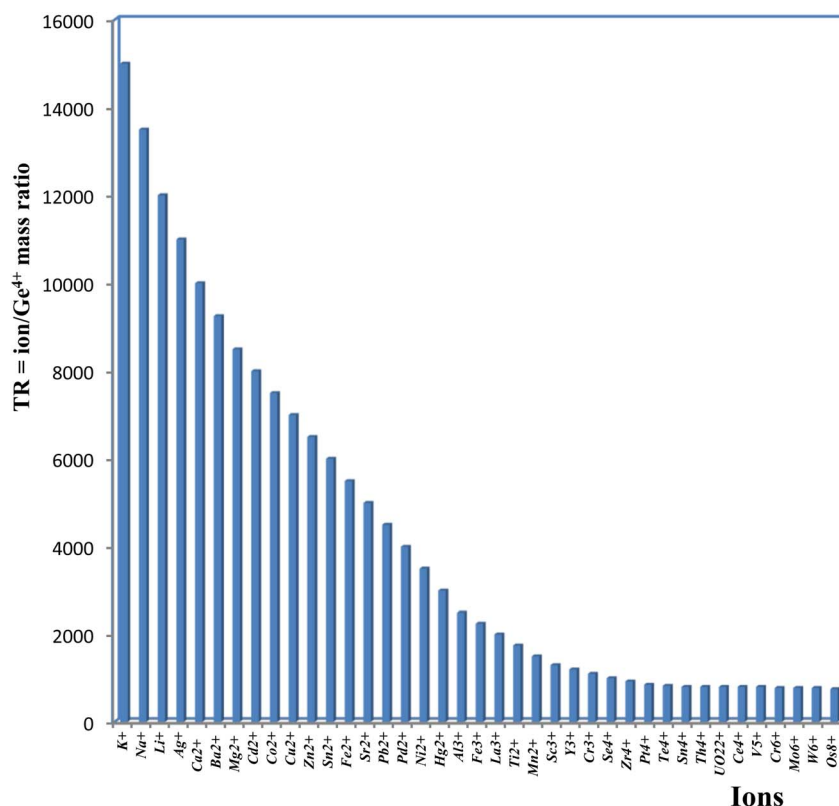


Fig. 5 Tolerance ratio for various interfering ions in the determination of 100.0 ng mL<sup>-1</sup> of Ge<sup>4+</sup>.



(%RSD) of 1.93 for intra-day and 2.25 for the inter-day measurements, respectively.

### Accuracy/recovery

Assessment of accuracy is necessary to validate any analytical procedure. In this context, samples like distilled water and

municipal water, which were initially free of Ge<sup>4+</sup>, were enriched with the analyte to measure the accuracy. The Results from different applications of the proposed procedure consistently ranged from 98.70% to 101.80%. This consistency confirms the procedures accuracy and underscores its lack of interference from other ions.

Table 2 Survey of spectrometric methods applied for the determination of germanium

Spectrophotometric reagent	Beer's law ( $\mu\text{g mL}^{-1}$ )	LOD <sup>a</sup> ( $\mu\text{g mL}^{-1}$ )	Selectivity	Analyzed sample	Ref.
Phenylfluorone and zephiramine <sup>b</sup>	47.5	0.10	Sn <sup>2+,4+</sup> , Sb <sup>3+</sup> , Ta <sup>5+</sup> , Nb <sup>5+</sup> , W <sup>6+</sup> , Mo <sup>6+</sup>	Ground water	55
Nano-sized TiO <sub>2</sub> <sup>c</sup>	43.0		Sr <sup>2+</sup> , Zn <sup>2+</sup> , PO <sub>4</sub> <sup>3-</sup> , F <sup>-</sup>	Water	56
Nano-TiO <sub>2</sub> (salicyl fluorone in the presence of cetyltrimethylammonium bromide) <sup>b</sup>	0.0–0.24	0.072	Si <sup>4+</sup> , Sn <sup>4+</sup> , Al <sup>3+</sup> , Fe <sup>3+</sup>	Water; certified reference material	57
Preconcentration on an organic solvent-soluble membrane and determination with <i>o</i> -nitrophenylfluorone in presence of sodium dodecyl sulfate <sup>b</sup>	0.02–0.36	0.004	Pb <sup>2+</sup> , Mo <sup>6+</sup>	Chinese herb, waters, and urine sample	58
Phenylfluorone <sup>b</sup>			Sb <sup>3+</sup> , Sb <sup>5+</sup> , Sn <sup>2+</sup> , Mo <sup>6+</sup> , Ti <sup>4+</sup>	Lignite ashes	59
Phenylfluorone <sup>b</sup>	0.01–0.06	0.005	In <sup>3+</sup> , Fe <sup>2+</sup> , Te <sup>4+</sup> , Tl <sup>+</sup> , Sn <sup>4+</sup>		60
TiO <sub>2</sub> nanoparticles (salicyl fluorone in the presence of cetyltrimethylammonium bromide) <sup>b</sup>			Cu <sup>2+</sup> , Ba <sup>2+</sup> , Cd <sup>2+</sup> , Co <sup>2+</sup> , Ni <sup>2+</sup> , Se <sup>4+</sup> , Sr <sup>2+</sup> , Li <sup>+</sup> , Si <sup>4+</sup>		61
9-( <i>o</i> -Chlorophenyl)-2,6,7-trihydroxyxanthen-3-one (cetyltrimethyl ammonium bromide) <sup>b</sup>	0.0–200		Ba <sup>2+</sup> , Pb <sup>2+</sup> , Ga <sup>3+</sup> , Sb <sup>3+</sup> , V <sup>5+</sup> , Cr <sup>6+</sup> , W <sup>6+</sup> , Mo <sup>6+</sup>	Minerals & ores	60
Coprecipitation of germanium in the presence of Mg <sup>2+</sup> , Ga <sup>3+</sup> , Ca <sup>2+</sup> and HCO <sub>3</sub> <sup>-d</sup>		0.006		Sea-, surface- and ground-waters	64
Precipitation with Fe(OH) <sub>3</sub> and determination with trimethoxyphenylfluorone <sup>b</sup>	0.0–0.24	0.021	Sr <sup>2+</sup> , Pb <sup>2+</sup> , Zr <sup>4+</sup> , Ti <sup>4+</sup> , Mo <sup>6+</sup>	Foods	32
The separation was done by an isocratic elution <sup>e</sup>	0.05–5.0			Tonic oral liquids	65
Catechol violet and cetyltrimethylammonium bromide <sup>b</sup>	0.1–1.0		Sn <sup>4+</sup> , Fe <sup>3+</sup> , Bi <sup>3+</sup> , V <sup>5+</sup> , Cr <sup>6+</sup> , Mo <sup>6+</sup> , Sb <sup>3+</sup>		65
Mercapto-modified silica gel <sup>e</sup>	0.01–0.20	0.008	Co <sup>2+</sup> , Cu <sup>2+</sup> , Ni <sup>2+</sup>		66
Cloud point methodology, triton X-114 <sup>f</sup>	10–300	0.59	As <sup>4+</sup> , Te <sup>4+</sup> , Sb <sup>4+</sup>	water samples	12
Chitosan functionalized with di-2-propanolamine <sup>g</sup>	50	0.002		Seawater samples	67
Modified copolymer styrene-maleic anhydride, (bis(2,3,4-trihydroxyphenyl-azo) benzidine in the presence of heterocyclic amines)	0.0–90	0.18	Cu <sup>2+</sup> , Fe <sup>3+</sup>	Seawater obtained after oil pumping	68
(Methybenzeneazosalicylfluorone) using ultrasound-assisted leaching <sup>b</sup>	2.75	0.007	Cr <sup>3+</sup> , Hg <sup>2+</sup> , Ti <sup>4+</sup> , U <sup>6+</sup> , As <sup>3+</sup> , Bi <sup>3+</sup> , Se <sup>4+</sup> , Te <sup>4+</sup> , Pt <sup>4+</sup> , Pt <sup>2+</sup> , Pd <sup>2+</sup> , Ln <sup>3+</sup> , Ru <sup>4+</sup> , Au <sup>3+</sup>	Certified reference materials	34
Anionic resin (IRA-900), catechol <sup>h</sup>				Fly ash	69
Kelex-100, [7-(4-ethyl-1-methyloctyl)-8-hydroxyquinoline] functional sol gel <sup>i</sup>			As <sup>3+</sup> , Sb <sup>3+</sup> , Zn <sup>2+</sup> , Ni <sup>2+</sup>	Water	70
Preconcentration/separation procedure (spectrophotometric reagent) pyrogallol <sup>i</sup>	12–90	0.018	As <sup>3+</sup> , Sn <sup>4+</sup>	Ore	71
2-Amino-4-( <i>m</i> -tolylazo)pyridine-3-ol at pH 3.5-Triton X-100 and KCl, immobilized on chitosan <sup>j</sup>	0.5–75	0.017		Water	72
(DMTMP) sensor <sup>b</sup>	0.00175	0.006–0.174	Highly selective	Water and food	This work

<sup>a</sup> LOD: Limit of detection technique. <sup>b</sup> spectrophotometry. <sup>c</sup> Graphite furnace atomic absorption. <sup>d</sup> Hydride generation-atomic. <sup>e</sup> High-performance ion-exclusion chromatography. <sup>f</sup> Hydride generation flame atomic absorption spectrometry. <sup>g</sup> Inductively coupled plasma mass spectrometry. <sup>h</sup> Atomic absorption spectrometry. <sup>i</sup> Adsorptive stripping voltammetric; spectrometry; emission spectrometry. <sup>j</sup> Flow injection hydride generation atomic fluorescence spectrometry.



## Robustness and ruggedness

The robustness of the techniques was assessed by measuring absorbance values at different wavelengths. At the same time, method ruggedness was confirmed by having two different researchers perform the procedure and by a single analyst using two different cuvettes. The consistent results achieved from these tests fell within an acceptable range, underscoring the reliability and stability of the procedures.

## Interferences study

To evaluate the influence of competing cations, calibration curves for the membrane were generated in the occurrence of potential interfering ions, like  $K^+$ ,  $Ag^+$ ,  $Na^+$ ,  $Li^+$ ,  $Pb^{2+}$ ,  $Cd^{2+}$ ,  $Ni^{2+}$ ,  $Cu^{2+}$ ,  $Sr^{2+}$ ,  $Zn^{2+}$ ,  $Mg^{2+}$ ,  $Ba^{2+}$ ,  $Fe^{3+}$ ,  $Al^{3+}$ ,  $Cr^{3+}$ ,  $La^{3+}$ ,  $Cr^{3+}$ ,  $Sc^{3+}$ ,  $Se^{4+}$ ,  $Te^{4+}$ ,  $Th^{4+}$ , and  $UO_2^{2+}$ . Table 1 and Fig. 5 collectively highlight that the optode shows minimal interference from other ions, while displaying a pronounced sensitivity specifically to  $Ge^{4+}$ .

Selectivity describes the sensor's preference for responding to the target ion over other potentially interfering ions. Table 1 demonstrates the film's selectivity for the maximum tolerance ratio to  $Ge^{4+}$  ion, at 15 000-fold higher concentration of interfering ions compared to the primary ion ( $Ge^{4+}$  at 100.0 ng

$mL^{-1}$ ). According to the table, all the tested ions show acceptable tolerance levels, at a concentration of 750 times (for  $Os^{8+}$ ) higher than that of  $Ge^{4+}$  in the solution.

## Comparison with other studies

In contrast to earlier approaches for the preconcentration and spectro-photometric detection of  $Ge^{4+}$  (Table 2), the proposed optode provides greater simplicity, faster analysis, and lower detection limit. Although the method described<sup>68</sup> in—employing a modified styrene-maleic anhydride copolymer along with bis(2,3,4-trihydroxyphenyl-azo) benzidine in the occurrence of heterocyclic amines and spectrophotometric detection—exhibits similar selectivity, the proposed procedure offers lower detection limits and a narrower determination range. The proposed method offers greater advantages in terms of sensitivity and interference resistance. To the best of our knowledge, this study represents the first reported use of DMTMP as a chromogenic reagent for the preconcentration and optical sensor-based determination of  $Ge^{4+}$ .

Compare the advantages of the proposed method to existing optical sensors, the present method provides a simple and cost-effective method for preconcentrating, extracting and determining the concentrations of  $Ge^{4+}$  ions without interference

Table 3 Results of the determination of  $Ge^{4+}$  in various water samples ( $n = 6$ ;  $P = 0.95$ )

Sample	$Ge^{4+}$ added $ng mL^{-1}$	Proposed method		ICP-AES method		$t$ -test <sup>b</sup>	$F$ -test <sup>c</sup>
		Found <sup>a</sup>	Recovery (%)	Found <sup>a</sup>	Recovery (%)		
Process water	0.00	—	—	—	—	—	—
	40.0	39.8 ± 0.56	99.6	40.6 ± 1.76	101.5	1.06	—
	80.0	80.5 ± 0.73	100.6	79.0 ± 1.49	98.8	—	2.11
	120.0	121.2 ± 0.47	101.0	118.2 ± 1.52	98.5	0.72	—
Natural water	0.00	—	—	—	—	—	—
	60.0	60.4 ± 0.81	100.7	59.3 ± 1.36	98.8	—	3.76
	120.0	119.0 ± 0.39	99.2	121.8 ± 1.84	101.5	1.76	—
	180.0	—	—	183.2 ± 1.71	101.8	—	—
Waste water	0.00	—	—	—	—	—	—
	35.0	35.4 ± 0.74	101.1	34.4 ± 1.28	101.2	1.35	—
	70.0	69.1 ± 0.61	98.7	70.9 ± 1.53	101.3	—	3.59
	140.0	141.6 ± 0.93	101.1	138.3 ± 1.75	98.8	1.81	—
Sea water <sup>d</sup>	0.00	12.1	—	12.0	—	—	—
	25.0	36.8 ± 0.81	99.2	38.2 ± 1.97	103.2	—	2.66
	50.0	63.2 ± 0.97	101.8	60.9 ± 1.42	98.2	0.82	—
	60.0	71.4 ± 0.90	101.0	73.4 ± 1.48	101.9	—	1.98
Water obtained after oil pumping <sup>e</sup>	0.00	30.7	—	30.5	—	—	—
	15.0	45.2 ± 0.87	101.4	44.5 ± 1.66	97.8	—	3.13
	30.0	60.0 ± 0.91	98.8	61.4 ± 1.48	101.5	1.66	—
	45.0	76.1 ± 1.38	100.5	74.1 ± 1.74	98.2	—	3.73
Soil <sup>f</sup>	0.00	26.5	—	26.2	—	—	—
	40.0	65.8 ± 0.65	98.9	67.8 ± 1.81	102.4	1.90	—
	80.0	108.2 ± 0.87	101.6	104.9 ± 1.48	98.5	—	3.75
	120.0	145.0 ± 1.02	99.0	148.3 ± 1.77	101.4	1.87	—
Soil <sup>g</sup>	0.00	12.3	—	12.4	—	—	—
	20.0	31.9 ± 0.76	98.8	33.0 ± 1.84	101.9	—	3.67
	40.0	52.8 ± 0.92	101.0	51.6 ± 1.43	98.5	1.95	—
	60.0	71.7 ± 0.81	99.3	73.3 ± 1.29	101.2	—	3.83

<sup>a</sup> Mean ± relative standard deviation ( $n = 6$ ). <sup>b</sup> Tabulated  $t$ -value for five degrees of freedom at  $P(0.95)$  is 2.57. <sup>c</sup> Tabulated  $F$ -value at  $P(0.95)$  is 5.05.

<sup>d</sup> Mediterranean sea from Alexandria. <sup>e</sup> Water obtained after oil pumping (Red sea from El-Ghardaka). <sup>f</sup> Obtained from Shoubra City. <sup>g</sup> Obtained from Quesna City.



from most cations and anions present in the real samples. The comparative data show significant improvements in the performance of the current sensor, in particular in terms of its faster response time, reduced interference susceptibility, improved qualitative, and diagnostic capability, extended linear range, and more efficient processing compared to previous designs.

### Reproducibility and repeatability

The main key characteristics of a sensor are its reproducibility and repeatability. The sensor membrane's repeatability was evaluated by submerging it multiple times in solutions with 100.0 ng mL<sup>-1</sup> Ge<sup>4+</sup> ions. After ten measurements, the relative standard deviation of the absorbance values recorded at  $\lambda = 545$  nm in the Ge<sup>4+</sup> solution was around 1.93%, demonstrating consistent performance of the sensor.

The reproducibility of the sensor membranes was assessed by determining the absorbance of a 100.0 ng mL<sup>-1</sup> Ge<sup>4+</sup> solution through six different membranes. The relative standard deviation of the absorbance values recorded at  $\lambda = 545$  nm in the Ge<sup>4+</sup> solution was around 2.25%. These results confirm the excellent reproducibility and repeatability of the sensor membrane.

### Analytical applications

The optode developed for Ge<sup>4+</sup> detection was used for the analysis of water and seawater samples collected post oil extraction. The results, when compared to results obtained with the standard ICP-AES technique, demonstrated the proposed method's high precision and accuracy (Table 3). The studied water samples contained germanium at concentrations of several tens of ng L<sup>-1</sup>.<sup>11</sup>

Germanium concentration was increased by a factor of 200 during the treatment process. In addition to, known quantities of Ge<sup>4+</sup> were spiked into the water samples prior to pretreatment. There was strong agreement among the estimated and added amounts of Ge<sup>4+</sup>, and excellent recoveries were achieved, demonstrating the sorbent's effectiveness for selectively extracting germanium from different water samples. The effectiveness of the suggested method was evaluated by determining the *t*-value (for accuracy) and conducting an *F*-test (for precision) in comparison to the ICP-AES technique. The average values were derived using Student's *t*-tests and *F*-tests with a 95.0% confidence level and five degrees of freedom.<sup>73</sup> The results showed that the calculated values (Table 3) were within the theoretical limits. Compared to the alternative method, the proposed approach shows superior accuracy, wider detection

Table 4 The results of the determination of germanium in food and fruit samples

Samples	Spiked (ng g <sup>-1</sup> )	Ge content <sup>a</sup> (ng g <sup>-1</sup> )		Recovery (%)		<i>t</i> -test <sup>b</sup>	<i>F</i> -test <sup>c</sup>
		Proposed	ICP-AES	Proposed	ICP-AES		
Bean	—	71.3 ± 0.16	70.9 ± 0.87	—	—	1.78	3.53
	20.0	90.7 ± 0.32	92.5 ± 1.16	99.3	101.8		
	40.0	111.0 ± 0.27	113.0 ± 1.21	99.7	101.9		
Rice	—	11.2 ± 0.31	11.0 ± 1.23	—	—	1.88	3.92
	35.0	46.5 ± 0.45	45.4 ± 1.49	100.7	98.7		
	70.0	80.8 ± 0.58	83.4 ± 1.62	99.5	103.0		
Egg	—	53.5 ± 0.09	53.8 ± 1.05	—	—	1.67	3.74
	15.0	69.1 ± 0.16	67.7 ± 1.17	100.9	98.4		
	30.0	84.5 ± 0.28	85.3 ± 1.25	101.3	101.8		
Cornmeal	—	16.0 ± 0.24	15.7 ± 1.47	—	—	1.53	3.77
	50.0	65.2 ± 0.37	67.5 ± 1.54	98.8	102.7		
	100.0	118.4 ± 0.41	114.7 ± 1.37	102.1	99.1		
Apple	—	13.2 ± 0.39	13.5 ± 1.29	—	—	1.79	4.04
	60.0	73.8 ± 0.31	71.9 ± 1.46	100.8	97.8		
	120.0	135.7 ± 0.22	131.6 ± 1.39	101.9	98.6		
Chicken	—	25.6 ± 0.13	26.0 ± 1.56	—	—	1.85	3.97
	25.0	50.0 ± 0.33	51.8 ± 1.71	98.8	101.6		
	50.0	76.5 ± 0.13	75.4 ± 1.82	101.2	99.2		
Sunflower oil	—	43.3 ± 0.25	43.7 ± 1.63	—	—	1.66	3.49
	27.5	71.7 ± 0.09	69.7 ± 1.15	101.3	97.9		
	55.0	99.9 ± 0.16	99.4 ± 1.07	101.6	100.7		
Peach	—	21.6 ± 0.42	21.5 ± 0.93	—	—	1.71	3.68
	70.0	90.8 ± 0.24	92.8 ± 1.35	99.2	101.4		
	140.0	160.3 ± 0.31	163.2 ± 1.62	99.2	101.1		
Tea	—	14.1 ± 0.26	14.0 ± 1.33	—	—	1.95	4.22
	65.0	80.0 ± 0.37	67.9 ± 1.67	101.1	98.4		
	130.0	143.6 ± 0.44	145.7 ± 1.38	99.7	101.2		
Butter	—	21.7 ± 0.11	21.5 ± 1.46	—	—	1.78	3.82
	55.0	77.4 ± 0.19	75.6 ± 1.53	100.9	98.8		
	110.0	133.0 ± 0.30	129.9 ± 1.71	101.0	98.8		

<sup>a</sup> Mean ± S.D. (*n* = 6). <sup>b</sup> Tabulated *t*-value for five degrees of freedom at *P* (0.95) is 2.57. <sup>c</sup> Tabulated *F*-value at *P* (0.95) is 5.05.



range, enhanced stability, and reduced time requirements, highlighting its overall benefits.

### Determination of germanium in food and fruit samples

The practical application of the fabricated optode has been demonstrated by the detection of trace levels of Ge<sup>4+</sup> in various samples of food and fruit. To confirm the method's accuracy, spiking tests and separate analytical procedures were conducted, and the findings are summarized in Table 4. For comparison, AAS was used as a reference process, with its results also presented in Table 4. The recovery of spiked samples showed reasonable accuracy, which was further confirmed by the standard addition method, demonstrating the system's effectiveness in ion detection. A strong correlation between the spiked and detected amounts of the analyte was observed. As shown in Tables 3 and 4, the germanium concentrations determined using the developed method closely matched those obtained by ICP-AES. Recovery rates for the added standards consistently surpassed 95.0%, strongly supporting the method's precision and its reliability regardless of matrix interferences.

## Conclusions

The color-changing optode for detection of Ge<sup>4+</sup> ions in aqueous samples was produced by immobilization of DMTPM and the liquid ion-exchanger Aliquat-336 in a matrix of tri-(2-ethylhexyl) phosphate-plasticized cellulose triacetate. The optode showed a linear response after a 5.00 minute equilibration period in a well-stirred borate medium, as well as under comparable conditions in deionized water. The adsorbed ions of Ge<sup>4+</sup> in the optode matrix can be quantified by visual colorimetry. The developed optode showed its reusability by releasing Ge<sup>4+</sup> ions after equilibration in a 0.15 M HCl solution for 2.00 minutes. The presence of cations such as Zn<sup>2+</sup>, Fe<sup>2+</sup>, Cu<sup>2+</sup>, and Pb<sup>2+</sup> did not significantly interfere with the uptake of Ge<sup>4+</sup> ions in the optode sample or the subsequent color development. A marked alteration in color and an absorbance exceeding 3σ of the blank were observed in aqueous samples (tap water) containing 11.0 ng in 100 mL (0.11 ng mL<sup>-1</sup>) after 25.0 minutes of equilibration.

## Author contributions

Mostafa Nassar, conceptualization, validation, methodology, investigation, data curation, validation, methodology, formal analysis. Alaa Amin:supervision, conceptualization, validation, writing – review & editing, writing – original draft.

## Conflicts of 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 authors declare that the data supporting the findings of this study are available within the article.

## Acknowledgements

This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [Grant No. KFU254754]. The authors also gratefully acknowledge Benha University for its support.

## References

- O. I. Sobolev, B. V. Gutyj, S. V. Soboliea, O. O. Borshch, I. M. Kushnir, R. A. Petryshak, O. S. Naumyuk, V. I. Kushnir, O. Y. Petryshak, M. M. Zhelavskiy, V. B. Todoruk, H. V. Sus, N. D. Levkivska, A. O. Vysotskij and N. V. Magrelo, A review of germanium environmental distribution, migration and accumulation, *Ukr. J. Ecol.*, 2020, **10**, 200–208, DOI: [10.15421/2020\\_86](https://doi.org/10.15421/2020_86).
- R. A. Reddeman, R. Glavits, J. R. Endres, T. S. Murbach, G. Hirka, A. Vertesi, E. Beres and I. P. Szakonyine, A Toxicological Evaluation of Germanium Sesquioxide (Organic Germanium), *J. Toxicol.*, 2020, **1**, 6275625, DOI: [10.1155/2020/6275625](https://doi.org/10.1155/2020/6275625).
- L. G. Menchikov and A. V. Popov, Physiological activity of trace element germanium including anticancer properties, *Biomed.*, 2023, **11**, 1535–1542, DOI: [10.3390/biomedicines11061535](https://doi.org/10.3390/biomedicines11061535).
- L. Li, T. Ruan, Y. Lyu and B. Wu, Advances in effect of germanium or germanium compounds on animals—A Review, *J. Biosci. & Med.*, 2017, **5**, 56–73, DOI: [10.4236/jbm.2017.57006](https://doi.org/10.4236/jbm.2017.57006).
- L. S. Keith, N. Maples-Reynolds in *Handbook on the Toxicology of Metals Chapter 13 - Germanium Volume II: Specific Metals*, Academic press, Elsevier, 5th edn, 2022, pp. 289–316, DOI: [10.1016/B978-0-12-822946-0.00012-X](https://doi.org/10.1016/B978-0-12-822946-0.00012-X).
- B. Robertz, J. Verhelle and M. Schurmans, The Primary and secondary production of germanium: A life-cycle assessment of different process alternatives, *JOM*, 2015, **67**, 412–424, DOI: [10.1007/s11837-014-1267-6](https://doi.org/10.1007/s11837-014-1267-6).
- M. Frenzel, C. Mikolajczak, M. A. Reuter and J. Gutzmer, Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium, *Resour. Policy*, 2017, **52**, 327–335, DOI: [10.1016/j.resourpol.2017.04.008](https://doi.org/10.1016/j.resourpol.2017.04.008).
- R. Olivier and L. Béatrice, Germanium isotope geochemistry, *Rev. Min. & Geochem.*, 2017, **82**, 601–656, DOI: [10.2138/rmg.2017.82.14](https://doi.org/10.2138/rmg.2017.82.14).
- D. Sellì, I. A. Baburin, R. Martonák and S. Leoni, Novel metastable metallic and semiconducting germaniums, *Sci. Rep.*, 2013, **3**, 01466, DOI: [10.1038/srep01466](https://doi.org/10.1038/srep01466).
- R. Pillarisetty, Academic and industry research progress in germanium nanodevices, *Nature*, 2011, **479**, 324–328, DOI: [10.1038/nature.10678](https://doi.org/10.1038/nature.10678).
- S. Akiyama, A. Miyaji, Y. Hayashi, M. Hiza, Y. Sekiguchi, T.-R. Koyama, A. Shiga and T. Baba, Selective conversion of ethanol to 1,3-butadiene using germanium talc as catalyst, *J. Catal.*, 2018, **359**, 184–197, DOI: [10.1016/j.jcat.2018.01.001](https://doi.org/10.1016/j.jcat.2018.01.001).



- 12 A. E. Boyukbayram and M. Volkan, Cloud point preconcentration of germanium and determination by hydride generation atomic absorption spectrometry, *Spectrochim. Acta (B)*, 2000, **55**, 1073–1080, DOI: [10.1016/S0584-8547\(00\)00233-0](https://doi.org/10.1016/S0584-8547(00)00233-0).
- 13 M. Yellishetty, D. Huston, T. E. Graedel, T. T. Werner, B. K. Reck and G. M. Mudd, Quantifying the potential for recoverable resources of gallium, germanium and antimony as companion metals in Australia, *Ore. Geol. Rev.*, 2017, **82**, 148–159, DOI: [10.1016/j.oregeorev.2016.11.020](https://doi.org/10.1016/j.oregeorev.2016.11.020).
- 14 A. Isildar, E. R. Rene, E. D. van Hullebusch and P. N. L. Lens, Electronic waste as a secondary source of critical metals: Management and recovery technologies, *Resour. Conserv. Recycl.*, 2018, **135**, 296–312, DOI: [10.1016/j.resconrec.2017.07.031](https://doi.org/10.1016/j.resconrec.2017.07.031).
- 15 A. Julander, L. Lundgren, L. T. Skare, M. Grander and B. Palm, Electronic waste as a secondary source of critical metals: Management and recovery technologies, Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden, *Environ. Int.*, 2014, **73**, 243–251, DOI: [10.1016/j.envint.2014.07.006](https://doi.org/10.1016/j.envint.2014.07.006).
- 16 D. N. Perkins, M. N. Brune Drisse, T. Nxele and P. D. Sly, E-waste: a global hazard, *Ann. Glob. Health*, 2014, **80**, 286–295, DOI: [10.1016/j.aogh.2014.10.001](https://doi.org/10.1016/j.aogh.2014.10.001).
- 17 M. Jabłońska-Czapla and K. Grygoyć, Selected technology-critical elements as indicators of anthropogenic contamination of surface water and suspended solids on the example of the Biała Przemsza River (Poland), *Chemosphere*, 2022, **307**, 135801, DOI: [10.1016/j.chemosphere.2022.135801](https://doi.org/10.1016/j.chemosphere.2022.135801).
- 18 M. Jabłońska-Czapla, K. Grygoyć, M. Rachwał, A. Fornalczyk and J. Willner, Technology-critical elements (TCE) in soils in the areas around waste electrical and electronic equipment (WEEE) recycling plant, *10<sup>th</sup> Nordic Conference on Plasma Spectrochemistry*, 2022, Loen, Norway, p. 74.
- 19 J. Wojcieszek, J. Szpunar and R. Lobinski, Speciation of technologically critical elements in the environment using chromatography with element and molecule specific detection, *Trends Anal. Chem.*, 2017, **104**, 1–12, DOI: [10.1016/j.trac.2017.09.018](https://doi.org/10.1016/j.trac.2017.09.018).
- 20 P. Nuss and G. A. Blengini, Towards better monitoring of technology critical elements in Europe: coupling of natural and anthropogenic cycles, *Sci. Total Environ.*, 2018, **613–614**, 569–578, DOI: [10.1016/j.scitotenv.2017.09.117](https://doi.org/10.1016/j.scitotenv.2017.09.117).
- 21 A. Cobelo-Garcia, M. Filella, P. Croot, C. Frazzoli, G. Du Laing, N. Ospina-Alvarez, S. Rauch, P. Salaun, J. Schäfer and S. Zimmermann, COST action TD1407: network on technology-critical elements (NOTICE) from environmental processes to human health threats, *Environ. Sci. Pollut. Res.*, 2015, **22**, 15188–15194, DOI: [10.1007/s11356-015-5221-0](https://doi.org/10.1007/s11356-015-5221-0).
- 22 W. Kui, *Trace Elements in Life Science*, Chinese Measurement Press, Peking, 1991, pp. 525.
- 23 O. Wiche, B. Szekely, C. Moschner and H. Helmeier, Germanium in the soil-plant system—a review, *Environ. Sci. Pollut. Res.*, 2018, **25**, 31938–31956, DOI: [10.1007/s11356-018-3172-y](https://doi.org/10.1007/s11356-018-3172-y).
- 24 O. Wiche, V. Zertamni, W. Hentschel, R. Achtziger and P. Midula, Germanium and rare earth elements in topsoil and soil-grown plants on different land use types in the mining area of Freiberg (Germany), *J. Geochem. Explor.*, 2017, **175**, 120–129, DOI: [10.1016/j.gexplo.2017.01.008](https://doi.org/10.1016/j.gexplo.2017.01.008).
- 25 G. A. Hambrick, P. N. Froelich, M. O. Andreae and B. L. Lewis, Determination of methylgermanium species in natural waters by graphite furnace atomic absorption spectrometry with hydride generation, *Anal. Chem.*, 1984, **56**, 421–424, DOI: [10.1021/ac00267a027](https://doi.org/10.1021/ac00267a027).
- 26 C. Delvigne, B. Angeletti, A. Guihou, I. Basile-Doelsch and J. D. Meunier, Reliable determination of Ge in solid environmental samples using a chemical preparation procedure developed for Si isotopes and ICP-MS analysis, *Geostand. Geoanal. Res.*, 2017, **42**, 139–149, DOI: [10.1111/ggr.12197](https://doi.org/10.1111/ggr.12197).
- 27 P. U. Okoroafor, L. Mann, K. A. Ngu, N. Zaffar, N. L. Monei, C. Boldt, T. Reitz, H. Heilmeyer and O. Wiche, Impact of soil inoculation with bacillus amyloliquefaciens FZB42 on the phytoaccumulation of germanium, rare earth elements, and potentially toxic elements, *Plants*, 2022, **11**, 341, DOI: [10.3390/plants.11030341](https://doi.org/10.3390/plants.11030341).
- 28 (a) E. Rosenberg, Environmental speciation of germanium, *Ecol. Chem. Eng.*, 2007, **14**, 707–732; (b) E. Rosenberg, Germanium: environmental occurrence, importance and speciation, *Rev. Environ. Sci. Biotechnol.*, 2009, **8**, 29–57, DOI: [10.1007/s11157-008-9143-x](https://doi.org/10.1007/s11157-008-9143-x).
- 29 C. Delvigne, S. Opfergelt, D. Cardinal, B. Delvaux and L. André, Distinct silicon and germanium pathways in the soil-plant system: evidence from banana and horsetail, *J. Geophys. Res.*, 2009, **114**, G02013, DOI: [10.1029/2008JG000899](https://doi.org/10.1029/2008JG000899).
- 30 R. Belissant, M. C. Boiron, B. Luais and M. Cathelineau, LA-ICP-MS analyses of minor and trace elements and bulk Ge isotopes in zoned Ge-rich sphalerites from the Noailhac-Saint-Salvy deposit (France): insights into incorporation mechanisms and ore deposition processes, *Geochim. Cosmo-chim. Acta.*, 2014, **126**, 518–540, DOI: [10.1016/j.gca.2013.10.052](https://doi.org/10.1016/j.gca.2013.10.052).
- 31 M. Soylak and S. Yigit, Preconcentration-separation of germanium at ultra trace levels on polysulfone membrane filter and its determination by spectrophotometry, *J. Ind. Eng. Chem.*, 2015, **24**, 322–325, DOI: [10.1016/j.jiec.2014.10.003](https://doi.org/10.1016/j.jiec.2014.10.003).
- 32 L. Zaijun, P. Jiaomai and T. Jan, Spectrophotometric method for determination of germanium in foods with new color reagent trimethoxyl-phenylfluorone, *Anal. Chim. Acta*, 2001, **445**, 153–159, DOI: [10.1016/S0003-2670\(01\)01259-4](https://doi.org/10.1016/S0003-2670(01)01259-4).
- 33 Z. Xia, L. Zaijun, Y. Rui and L. Huizhen, A novel room temperature ionic liquid extraction spectrophotometric determination of trace germanium in natural water with methybenzeneazosalicylfluorone, *Anal. Lett.*, 2006, **39**, 863–877, DOI: [10.1080/00032710600605766](https://doi.org/10.1080/00032710600605766).
- 34 L. Zaijun, Z. Xia, L. Huizhen and Y. Rui, Novel spectrophotometric method for determination of trace



- germanium in soils with methybenzene-azosalicyl-fluorone using ultrasound-assisted leaching, *Commun. Soil Sci. & Plant Anal.*, 2008, **39**, 461–474, DOI: [10.1080/00103620701826597](https://doi.org/10.1080/00103620701826597).
- 35 S. Keawwangchai, N. Morakot and T. Keawwangchai, Novel selective and sensitive optical chemosensor based on phenylfluorone derivative for detection of Ge(IV) ion in aqueous solution, *Spectrochim. Acta (A)*, 2018, **202**, 290–300, DOI: [10.1016/j.saa.2018.05.063](https://doi.org/10.1016/j.saa.2018.05.063).
- 36 L. Zaijun, Z. Xia, L. Huizen and P. Jiaomai, Development of spectrophotometric method for determination of germanium, *Rev. Anal. Chem.*, 2011, **26**, 23–42, DOI: [10.1515/REVAC.2007.26.1.23](https://doi.org/10.1515/REVAC.2007.26.1.23).
- 37 E. M. I. Moustafa, A. S. Amin and E. R. Darwish, Optical chemical sensor of Gd(III) based on 5-(2'-bromophenylazo)-6-hydroxypyrimidine-2,4-dione immobilized on poly(methyl methacrylate) and 2-nitrophenyl octyl ether matrix, *RSC Adv.*, 2022, **12**, 26090–26098, DOI: [10.1039/D2RA03729G](https://doi.org/10.1039/D2RA03729G).
- 38 A. S. Amin, S. M. El-Bahy and A. M. E. Hassan, Construction of an optical sensor for molybdenum determination based on a new ionophore immobilized on a polymer membrane, *J. King. Saud. Univ.-Sci.*, 2023, **35**, 102592, DOI: [10.1016/j.jksus.2023.102592](https://doi.org/10.1016/j.jksus.2023.102592).
- 39 M. Aish, R. F. Alshehri, A. S. Amin and E. R. Darwish, Exploring the design and performance of a tellurium optical sensor utilizing a plasticizer-free polymer inclusion membrane, *Food Chem.*, 2024, **439**, 138112, DOI: [10.1016/j.foodchem.2023.138112](https://doi.org/10.1016/j.foodchem.2023.138112).
- 40 A. A. Ensafi and M. Fouladgar, Development a simple PVC membrane bulk optode for determination of lead ions in water samples, *Sens. Lett.*, 2009, **7**, 1135, DOI: [10.1166/sl.2009.1029](https://doi.org/10.1166/sl.2009.1029).
- 41 E. R. Darwish, A. O. Babalghith, A. O. S. Bahathiq, A. S. Amin and M. A. El-Attar, Synergistic optical sensing: selective colorimetric analysis of copper in environmental and biological samples, *Spectrochim. Acta (A)*, 2024, **314**, 124202, DOI: [10.1016/j.saa.2024.124202](https://doi.org/10.1016/j.saa.2024.124202).
- 42 Z. Al-Mallah and A. S. Amin, Utilization of a triacetylcellulose membrane to immobilize 5-(2',4'-dimethyl-phenylazo)-6-hydroxypyrimidine-2,4-dione for erbium determination in real sample, *J. Ind. & Eng. Chem.*, 2018, **63**, 281–287, DOI: [10.1016/j.jiec.2018.02.027](https://doi.org/10.1016/j.jiec.2018.02.027).
- 43 A. S. Amin, S. El-Bahy and H. H. El-Feky, Utility of 5-(2',4'-dimethyl-phenylazo)-6-hydroxy-pyrimidine-2, 4-dione in PVC membrane for a novel green optical chemical sensor to detect zinc ion in environmental samples, *Anal. Biochem.*, 2022, **643**, 114579, DOI: [10.1016/j.ab.2022.114579](https://doi.org/10.1016/j.ab.2022.114579).
- 44 R. F. Alshehri, A. S. Amin and E. R. Darwish, Introducing an innovative immobilized optode based on PVC-ETH-5294 matrix for environmentally friendly sensing of lead ions, *Talanta Open*, 2024, **9**, 100285, DOI: [10.1016/j.talo.2023.100285](https://doi.org/10.1016/j.talo.2023.100285).
- 45 A. M. E. Hassan, R. F. Alshehri, S. M. El-Bahy, A. S. Amin and M. Aish, A modified selective optical sensor for selenium determination based on incorporating xlenol orange in a poly(vinyl chloride) membrane, *RSC Adv.*, 2023, **13**, 34618–34629, DOI: [10.1039/d3ra05308c](https://doi.org/10.1039/d3ra05308c).
- 46 R. F. Alshehri, M. Hemdan, A. O. Babalghith, A. S. Amin and E. R. Darwish, An innovative approach in titanium determination based on incorporating of 2-amino-4-(4-nitrophenyl)diazanylpyridine-3-ol in a PVC membrane, *RSC Adv.*, 2024, **14**, 712–724, DOI: [10.1039/d3ra06679g](https://doi.org/10.1039/d3ra06679g).
- 47 M. Aish, R. F. Alshehri and A. S. Amin, Construction of an optical sensor for copper determination in environmental, food and biological samples based on the covalently immobilized 2-(2-benzothiazolylazo)-3-hydroxy-phenol in agarose, *RSC Adv.*, 2023, **13**, 24777–24788, DOI: [10.1039/d3ra04249a](https://doi.org/10.1039/d3ra04249a).
- 48 R. F. Alshehri, A. S. Amin and E. R. Darwish, Ultrasensitive and highly selective detection of nickel ion by two novel optical sensors, *Anal. & Bioanal. Chem.*, 2023, **415**, 5695–5707, DOI: [10.1007/s00216-023-04845-x](https://doi.org/10.1007/s00216-023-04845-x).
- 49 J. A. Dean, *Analytical Chemistry Handbook*, McGraw-Hill, New York, 1995, pp. 1430–1434.
- 50 J. Sandstrom, Cyclizations of thiocarbohydrazide and its mono-hydrazone part II. Reactions with dialkyl trithiocarbonates, *Acta Chim.*, 1960, **14**, 1295–1302.
- 51 D. L. Sparks, *Environmental Soil Chemistry*, Academic Press, New York, 1995.
- 52 M. Ahmad and R. Narayanaswamy, Optical fiber Al(III) sensor based on solid surface fluorescence measurement, *Sens. & Actuators (B)*, 2002, **81**, 259–266, DOI: [10.1016/S0925-4005\(01\)00961-3](https://doi.org/10.1016/S0925-4005(01)00961-3).
- 53 A. S. Amin and A. S. Al-Attas, Study of the solid phase extraction and spectrophotometric determination of nickel using 5-(4'-chlorophenylazo)-6-hydroxypyrimidine-2, 4-dione in environmental samples, *J. Saudi Chem. Soc.*, 2012, **16**, 451–459, DOI: [10.1016/j.jscs.2011.02.018](https://doi.org/10.1016/j.jscs.2011.02.018).
- 54 IUPAC, Nomenclature, symbols, units and their usage in spectrochemical analysis–II. Data interpretation analytical chemistry division, *Spectrochim. Acta (B)*, 1978, **33**, 241–245.
- 55 Y. Inukai, Y. Kaida and S. Yasuda, Selective separation of germanium(IV) by iminodiacetic acid-type chitosan chelating resin, *Anal. Sci.*, 1997, **13**, 339–344, DOI: [10.2116/analsci.13.339](https://doi.org/10.2116/analsci.13.339).
- 56 R. R. Moskalyk, Review of germanium processing worldwide, *Miner. Eng.*, 2004, **17**, 393–402, DOI: [10.1016/j.mineng.2003.11.014](https://doi.org/10.1016/j.mineng.2003.11.014).
- 57 L. Zhang, X. Guo, H. Li, Z. Yuan, X. Liu and T. Xu, Separation of trace amounts of Ga and Ge in aqueous solution using nano-particles micro-column, *Talanta*, 2011, **85**, 2463–2469, DOI: [10.1016/j.talanta.2011.07.096](https://doi.org/10.1016/j.talanta.2011.07.096).
- 58 Y. Chen, R. Zhu, H. Qiong, F. Ji and X. Gu, Determination of trace germanium by spectrophotometry after preconcentration on an organic solvent-soluble membrane, *Microchem. J.*, 2000, **64**, 93–97, DOI: [10.1016/S0026-265X\(99\)00020-X](https://doi.org/10.1016/S0026-265X(99)00020-X).
- 59 J. Aznarez, P. Moneo, J. C. Vidad and F. Palacios, Extraction-spectrophotometric determination of germanium with phenylfluorone in N,N-dimethyl-form amide, *Analyst*, 1985, **110**, 747–749, DOI: [10.1039/AN9851000747](https://doi.org/10.1039/AN9851000747).



- 60 J. D. Burton and J. P. Riley, The spectrophotometric determination of germanium with phenylfluorone, *Mikrochim. Acta*, 1978, **47**, 586–591, DOI: [10.1007/BF01221668](https://doi.org/10.1007/BF01221668).
- 61 L. Zhang, H. Li, X. Liu and P. Kang, Sorption behavior of germanium(IV) on titanium dioxide nanoparticles, *Russ. J. Inorg. Chem.*, 2012, **57**, 622–628, DOI: [10.1134/S003602361204016X](https://doi.org/10.1134/S003602361204016X).
- 62 H. Shen, Z. Wang and G. Xu, Spectrophotometric determination of trace amounts of germanium in minerals and ores with 9-(o-chlorophenyl)-2,6,7-trihydroxy-xanthen-3-one in the presence of cetyltrimethylammonium bromide, *Analyst*, 1987, **112**, 887–889, DOI: [10.1039/AN9871200887](https://doi.org/10.1039/AN9871200887).
- 63 I. D. Brindle, M. E. Brindle and X. C. Le, Pre-concentration by coprecipitation. Part 1. Rapid method for the determination of ultra-trace amounts of germanium in natural waters by hydride generation–atomic emission spectrometry, *J. Anal. Atom. Spect.*, 1991, **6**, 129–132, DOI: [10.1039/JA9910600129](https://doi.org/10.1039/JA9910600129).
- 64 Q.-C. Chen, S.-F. Mou, Y. Yan and Z.-M. Ni, Separation and determination of inorganic germanium and  $\beta$ -carboxyethylgermanium sesquioxide by high-performance ion-exclusion chromatography, *J. Chromatogr. (A)*, 1997, **789**, 403–412, DOI: [10.1016/S0021-9673\(97\)00451-2](https://doi.org/10.1016/S0021-9673(97)00451-2).
- 65 C. L. Leong, Spectrophotometric determination of germanium with catechol violet and cetyltrimethylammonium bromide, *Talanta*, 1971, **18**, 845–848, DOI: [10.1016/0039-9140\(71\)80137-6](https://doi.org/10.1016/0039-9140(71)80137-6).
- 66 G. Göktürk, M. Delzende and M. Volkan, Preconcentration of germanium on mercapto-modified silica gel, *Spectrochim. Acta (B)*, 2002, **55**, 1061–1069, DOI: [10.1016/j.jfca.2006.04.009](https://doi.org/10.1016/j.jfca.2006.04.009).
- 67 A. Sabarudin, T. Umemura and S. Motomizu, Chitosan functionalized with di-2-propanolamine: its application as solid phase extractant for the determination of germanium in water samples by ICP-MS, *Microchem. J.*, 2011, **99**, 34–39, DOI: [10.1016/j.microc.2011.03.004](https://doi.org/10.1016/j.microc.2011.03.004).
- 68 K. T. Mahmudov, R. A. Aliyeva, S. Z. Hamidov, F. M. Chyragov, S. R. Mardanova, M. N. Kopylovich and A. J. L. Pombeiro, Preconcentration of germanium(IV) on styrene-maleic anhydride copolymer modified with aminobenzoic acids and its spectrophotometric determination with bis(2,3,4-trihydroxyphenylazo) benzidine, *Am. J. Anal. Chem.*, 2012, **3**, 790–799, DOI: [10.4236/ajac.2012.312105](https://doi.org/10.4236/ajac.2012.312105).
- 69 F. A. Torralvo and C. Fernandez-Pereira, Recovery of germanium from real fly ash leachates by ion-exchange extraction, *Miner. Eng.*, 2011, **24**, 35–41, DOI: [10.1016/j.mineng.2010.09.004](https://doi.org/10.1016/j.mineng.2010.09.004).
- 70 H.-J. Park and L. L. Tavlarides, Germanium (IV) adsorption from aqueous solution using a Kelex-100 functional adsorbent, *Ind. & Eng. Chem. Res.*, 2009, **48**, 4014–4021, DOI: [10.1021/ie801733d](https://doi.org/10.1021/ie801733d).
- 71 C. Q. Sun, Q. Gao and L. L. Liu, Adsorptive stripping measurements of germanium (IV) in the presence of pyrogallol, *Talanta*, 1995, **42**, 881–884, DOI: [10.1016/0039-9140\(95\)01501-2](https://doi.org/10.1016/0039-9140(95)01501-2).
- 72 I. M. I. Moustafa, Z. AL-Mallah and A. S. Amin, Spectrophotometric quantification of germanium (IV) in environmental samples using chemically modified chitosan sorbent and optimized cloud phase extraction method, *J. Ind. Environ. Chem.*, 2018, **2**, 1–8.
- 73 J. N. Miller and J. C. Miller, *Statistics and Chemometrics for Analytical Chemistry*, Prentice-Hall, London, 2005.

