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ORIGINAL RESEARCH

Synthesis and Sensor Properties of a Phenol Derivative Molecule: Potentiometric Determination of Silver(I) Ions

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Abstract

Herein, we developed a novel potentiometric sensor that exhibits high selectivity towards Ag^+ ions, using a newly synthesized phenol derivative **(4)** molecule as an electroactive material (ionophore). The sensor was prepared by coating the surface of a conductive solid contact by a membrane containing bis(2-ethylhexyl)sebacate (BEHS) as plasticizer, poly (vinly chloride) (PVC) as a polymeric matrix, electroactive material **(4),** and potassium tetrakis(4-chlorophenyl)borate (KT*p*ClPB) as an additive. The developed sensor exhibited a wide linear concentration range of 1.0×10^{-6}–1.0×10^{-1} mol L^{-1} and a lower detection limit of 5.87×10^{-7} mol L^{-1}. The sensor exhibited quite good selectivity over other cationic species, and its potential response remained unaffected of pH in the range of 3.0–7.0. In addition, the developed sensor had a short response time of 8 s, good repeatability, and stability. Finally, the proposed sensor was used in the direct determination of Ag^+ in different water samples, and as an indicator electrode for the end point determination in the potentiometric titration of Ag^+ ions against sodium chloride.

Keywords Phenol derivatives · Synthesis · Sensor · Silver(I) · Potentiometry

Introduction

Silver is a naturally occurring metal that is widely used in a variety of current applications such as electrical and electrical equipment, alloys, explosives, jewelery, photography, dental, and medicine [1, 2]. Silver compounds are used to purify swimming pool and drinking water due to their bacteriostatic properties [3]. Silver is known to be toxic to humans at concentrations higher than 0.9 µM in drinking water [4]. In addition, it was reported to be toxic to fish and microorganisms when the concentration of silver in water is higher than 1.6 nM [5]. Therefore, it is important to determine the silver ion in various media. There are numerous analytical methods for the measurement of silver ions in different samples such as flame atomic absorption spectrometry (FAAS) [6], inductively coupled plasma mass spectrometry (ICP–MS) [7], spectrophotometry [8], reversed phase high-performance liquid chromatography (RP–HPLC) [9], and fluorescence spectroscopy [10]. Although these methods are the most widely used methods for the routine analysis of different ions in various samples, they have disadvantages such as the need for the pretreatment of samples, high cost, complexity, and need for trained personnel and laboratory [11–13].

Electrochemical analysis techniques are frequently used for the determination of ions in various samples [14–16]. Potentiometric ion–selective electrodes (ISEs) or sensors have been the focus of attention of researchers working in this field since the day they were defined, due to the unique advantages they provide. These methods provide important benefits such as wide linear concentration range, good selectivity, ease of preparation, low cost, short response time, low detection limit, ease of miniaturization, and low-energy consumption in areas such as routine laboratory analysis, environmental monitoring, various ions, and industrial analysis [17–21].

Ionophores, which are in the composition of ion-selective electrodes and interact directly with the analyte, are very

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important in the production of electrodes that exhibit selectivity towards different ions. It is possible to obtain commercially available ionophores that exhibit selectivity for various ions. However, commercial ionophores are chemicals with high cost. Therefore, there is a need for ionophores that can replace them [22]. In this study, a novel phenol derivative molecule (Fig. 1) with ionophore properties was synthesized and showed high selectivity towards silver(I) ions. We investigated the potentiometric properties of the synthesized molecule and proposed a novel silver(I)-selective sensor.

Materials and Methods

Reagents and Chemicals

All reagents used in the ionophore synthesis were obtained from Sigma-Aldrich and Merck, and used as purchased from commercial suppliers without further purification. The isolation of the products was performed by column chromatography using silica gel Merck 60 (230–400 mesh, 0.04–0.063 mm). Graphite, epoxy (Macroplast Su 2227), and hardener (Desmodur RFE) which were used in the preparation of all–solid–state contact were obtained from Sigma-Aldrich, Henkel (Istanbul, Turkey), Bayer AG (Darmstadt, Germany), respectively. Poly (vinyl) chloride (PVC) of high molecular weight, bis(2-ethylhexyl)sebacate (BEHS), *o*-nitrophenyloctylether (*o*-NPOE), bis(2-ethylhexyl)adipate (DEHA), potassium tetrakis(*p*-chlorophenyl)borate (KT*p*-ClPB), and tetrahydrofurane (THF) used in the preparation of the silver(I)-selective sensor were purchased from Sigma-Aldrich. The nitrate salts of related cations used for the preparation of stock solutions were also obtained from Sigma-Aldrich. Sodium hydroxide (NaOH) and nitric acid (HNO_3) used for pH adjustment were obtained from Merck and Sigma-Aldrich, respectively. Finally, sodium chloride (NaCl) used in the potentiometric titration step was obtained from Sigma-Aldrich.

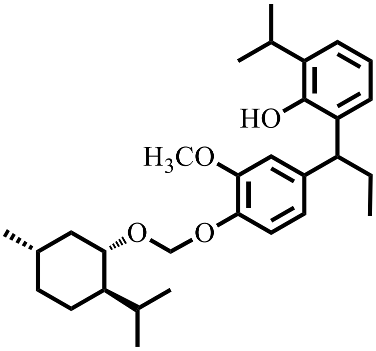


Fig. 1 The chemical structure of ionophore

Apparatus

^{1}H– and ^{13}C– NMR spectra were recorded on a Brucker Advance III instrument (400 MHz). FT–IR spectra was obtained by Jasco FT/IR–4700 spectrometer. Melting points were measured on Electrothermal 9100. As internal standards served TMS (*d* 0.00) for ^{1}H NMR and $CDCl_3$ (*d* 77.0) for ^{13}C NMR spectroscopy *J* values are given in Hz. Potentiometric data were collected by using a computer-controlled multichannel potentiometric system (Medisen Medical Ltd. Sti., Turkey). The system has a lab-made software program. Throughout the potentiometric measurements, Ag/AgCl electrode (purchased from Thermo–Orion) was used as reference electrode.

Method

Synthesis of 4-(1-(2-hydroxy-3-isopropylphenyl)propyl)-2-methoxyphenol (3)

The synthesis of polyphenolic compound (**3**) was achieved according to Friedel–Crafts alkylation method [23]. The reaction of 2-isopropylphenol (**2**) and isoeugenol (**1**) in ratio of 2:1 in the presence of aluminum isopropoxide (Al(O-*i*-Pr)$_3$) as catalyst gave products (**3**) (Scheme 1).

Synthesis of Ionophore (4)

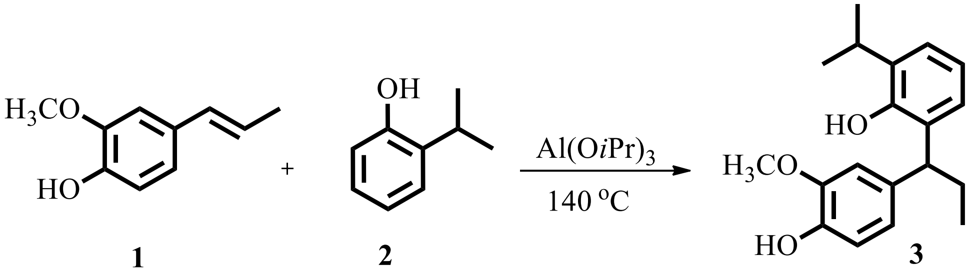
N,*N*-Diisopropylethylamine (DIPEA) (4 mmol) was added to a solution of 4-(1-(2-hydroxy-3-isopropylphenyl)propyl)-2-methoxyphenol (**3**) (1 mmol) in CH_2Cl_2 at room temperature. Chloromethyl methyl ether (1.2 mmol) was added dropwise to the solution, then the resulting mixture was stirred overnight. Reaction mixture was washed with water (3 × 20 mL), and dried over anhydrous Na_2SO_4. The residue was purified through column chromatography (EtOAc/hexane, 1:9) to give **4** as a colorless oil (95%) (Scheme 2).

Preparation of PVC Membrane Silver(I)-selective Sensors

Silver(I)-selective PVC membrane sensor based on newly synthesized a phenol derivative molecule (electroactive component) was prepared by following the general procedure given below:

A mixture of all–solid–state contact consisting of 50.0% (*w*/*w*) graphite, 35.0% (*w*/*w*) epoxy, and 15.0% (*w*/*w*) hardener was thoroughly dissolved in approximately 3 mL of THF. After obtaining the appropriate viscosity, the ends of copper wires were dipped into this mixture several times and covered with conductive solid contact. The coated copper wires were kept in the dark for about 24 h [24, 25]. Then,

Scheme 1 Synthesis of 4-(1-(2-hydroxy-3-isopropylphenyl)propyl)-2-methoxyphenol **(3)**



sensors containing synthesized ionophore, plasticizer, PVC, and conductivity enhancer were prepared by dissolving them in approximately 3 mL of THF. Finally, the surface of the all–solid–contact was coated with this membrane cocktail by dipping them into the prepared membrane mixture for 4–5 times. The PVC membrane coated electrodes were left to dry for approximately 24 h [26, 27].

Result and Discussion

Characterization of Ionophore

Characterization of the synthesized molecule was carried out using spectroscopic methods such as ^{1}H–, ^{13}C– NMR, and FT–IR. Obtained spectroscopic data are compatible with the structure.

Viscous oil, yield: 95% **^{1}H NMR** (400 MHz, $CDCl_3$, ppm): $\delta = 7.18–7.12$ (m, 3H), 6.95 (*t*, $J = 8.0$ Hz, 1H), 6.84 (*d*, $J = 8.0$ Hz, 1H), 6.75 (s, 1H), 5.40 (*d*, $J = 8.0$ Hz, 1H), 5.34 (*d*, $J = 8.0$ Hz, 1H), 4.85 (*s*, 1H), 4.18–4.12 (*dd*, $J = 16.0$, 8.0 Hz, 1H), 3.92 (*t*, $J = 8.0$ Hz, 1H), 3.81 (*s*, 3H, $–OCH_3$), 3.61–3.55 (*m*, 1H), 3.23–3.16 (*m*, 1H), 2.18–1.98 (*m*, 5H), 1.68–1.56 (*m*, 2H), 1.39–1.19 (*m*, 8H), 0.97–0.83 (*m*, 12H), 0.56 (*d*, $J = 8.0$ Hz, 3H). **^{13}C NMR** (100 MHz, $CDCl_3$, ppm): $\delta = 151.10$, 149.66, 137.14, 135.21, 130.57, 125.95, 124.19, 120.36, 120.00, 115.36, 111.50, 91.42, 76.76, 60.38, 55.82, 48.25, 46.86, 40.98, 34.41, 31.47, 27.84, 26.90, 25.22, 22.95, 22.86, 22.82, 22.58, 22.54, 22.27, 15.34, 12.63. **FT–IR** (KCl, cm^{-1}): 3489, 2958, 2923, 2865, 1591, 1513, 1452, 1258, 1213, 1138, 1078, 992, 951, 822, 751, 642, 515.

Optimization of Membrane Composition

Potentiometric performance characteristics of ion-selective sensors largely depend on the membrane components. Therefore, in this study, PVC membrane sensors were prepared for the determination of Ag^+ ions and their potentiometric properties were tested under laboratory conditions. The compositions of the sensors prepared using different plasticizers (DEHA, BEHS, and *o*-NPOE), PVC, conductivity enhancer, and newly synthesized ionophore are given in Table 1. As seen in this table, PVC and KT*p*ClPB ratios were kept constant. The potentiometric behavior of the sensors prepared by changing the ratio of ionophore and plasticizer was investigated. In terms of the potentiometric performance characteristics, the developed sensor exhibited the best-wide linear concentration range, highest R^2, and lowest detection limit. Therefore, sensor no I (3.0% ionophore, 32.0% PVC, 1.0% KT*p*ClPB, and 64.0% BEHS) was chosen for further studies.

Working Concentration Range, Detection Limit, and Repeatability

In this study, potentiometric measurements were taken against Ag^+ ions using PVC membrane sensors prepared with sensor I. The potentiometric response of the developed

Scheme 2 Synthesis of ionophore **(4)**

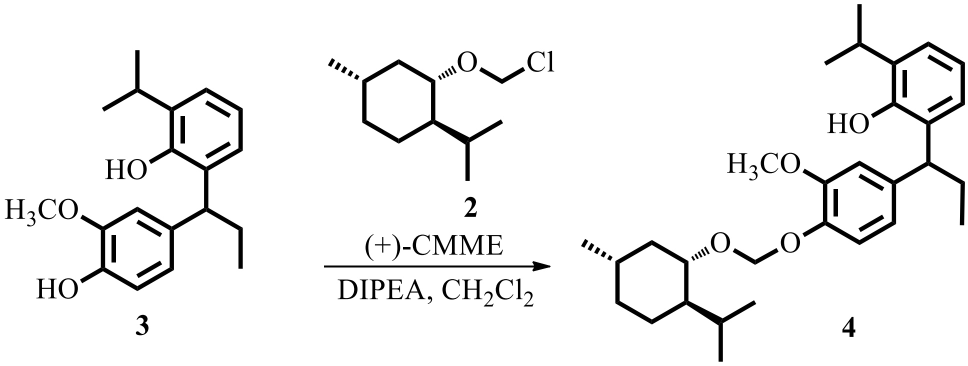


Table 1 The prepared membrane components and potentiometric performance characteristics

No	Composition (% *w*/*w*)								
	Ionophore	PVC	KT*p*ClPB	BEHS	DEHA	*o*-NPOE	R^2	Linear working concentration (mol L^{-1})	Limit of detection (mol L^{-1})
1	**3.0**	**32.0**	**1.0**	**64.0**	-	-	**0.9930**	$\mathbf{1.0\times10^{-1}–1.0\times10^{-6}}$	$\mathbf{5.87\times10^{-7}}$
2	4.0	32.0	1.0	-	63.0	-	0.9818	$1.0\times10^{-1}–1.0\times10^{-5}$	4.99×10^{-6}
3	4.0	32.0	1.0	63.0	-	-	0.9833	$1.0\times10^{-1}–1.0\times10^{-6}$	6.90×10^{-7}
4	5.0	32.0	1.0	-	-	62.0	0.9922	$1.0\times10^{-2}–1.0\times10^{-6}$	7.96×10^{-7}
5	2.5	32.0	1.0	64.5	-	-	0.9860	$1.0\times10^{-1}–1.0\times10^{-6}$	7.63×10^{-7}
6	3.5	32.0	1.0	63.5	-	-	0.9816	$1.0\times10^{-1}–1.0\times10^{-6}$	6.82×10^{-7}

silver(I)-selective sensor was between 1.0×10^{-8} and 1.0×10^{-1} mol L^{-1} as shown in Fig. 2.

The proposed sensor displayed linear potential response over concentration from 1.0×10^{-7} to 1.0×10^{-1} mol L^{-1} (Fig. 2a). The detection limit is obtained by substituting the potential value corresponding to the intersection point of the extrapolations of the two linear regions in the graph in the linear equation obtained from the calibration curve (Fig. 2b). The detection limit of the proposed sensor was calculated to be 5.87×10^{-7} mol L^{-1}. The potentiometric repeatability of the proposed sensor was investigated using 1.0×10^{-2}, 1.0×10^{-3}, and 1.0×10^{-4} mol L^{-1} Ag^+ solutions. The standard deviations of three replicate measurements at 1.0×10^{-2}, 1.0×10^{-3}, and 1.0×10^{-4} mol L^{-1} Ag^+ concentrations were ± 1.25, ± 0.47, and ± 1.25 mV, respectively (Table 2). The experimental measurements in Fig. 2c and Table 2 show that the proposed sensor had good potentiometric repeatability and stability. In addition, Table 2 shows that the sensor exhibits a Nernstian response of 60.3 (±0.47) mV/decade.

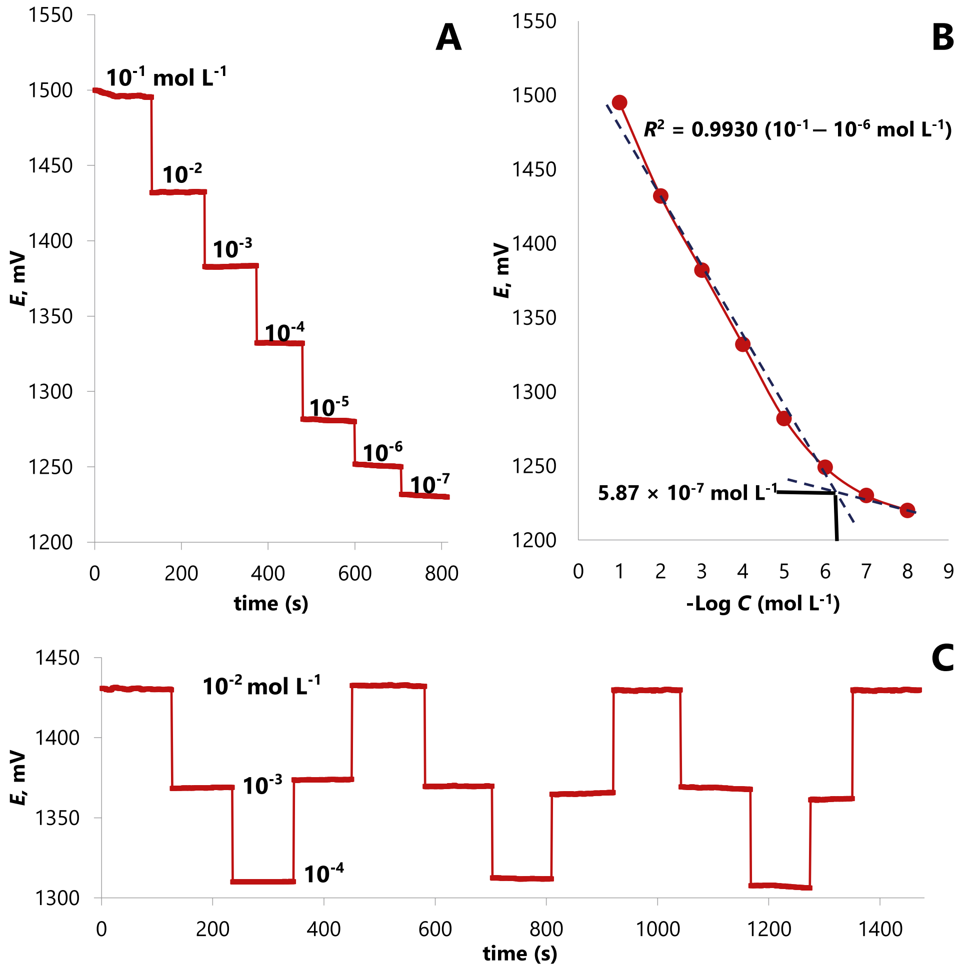


Fig. 2 **a** Potentiometric response, **b** calibration curve, and **c** repeatability of silver(I)-selective sensor

Table 2 The repeatability data of the silver(I)-selective sensor

Ag^+ solution	Potential (mV)			
	I	II	III	Average (± SD)*
1.0×10^{-2}	1430	1432	1429	1430.3 (± 1.25)
1.0×10^{-3}	1369	1370	1369	1369.3 (± 0.47)
1.0×10^{-4}	1310	1311	1308	1309.7 (± 1.25)

Potentiometric Selectivity

The selectivity of ion-selective sensors is one of the most important performance parameters that determine the behavior of the sensor against the main ion in the presence of other ions. Potentiometric selectivity studies were carried out for sensor I, which exhibits the best potentiometric performance characteristics in terms of concentration range and detection limit. In the study, the potentiometric behavior of twelve different cationic species other than silver(I) in the 1.0×10^{-1} – 1.0×10^{-5} mol L^{-1} concentration range were tested. The potentiometric behavior of these ions is given in Fig. 3.

The selectivity coefficients were determined by the separate solution method (SSM) as suggested by IUPAC [28] and are given in Table 3. The values in Table 3 were calculated by writing the potential value of the ions at 1.0×10^{-2} mol L^{-1} in the equation below:

$$\log K_{A,B}^{pot} = \frac{(E_B - E_A)Z_A F}{RT\ln 10} + \left(1 - \frac{Z_A}{Z_B}\right)\log a_A$$

where $K_{A,B}^{pot}$ = selectivity coefficient, a_A = activity of silver ion, a_B = activity of interfering ion, z_A = charge of silver ion, z_B = charge of interfering ion; R, T, and F have the usual meanings.

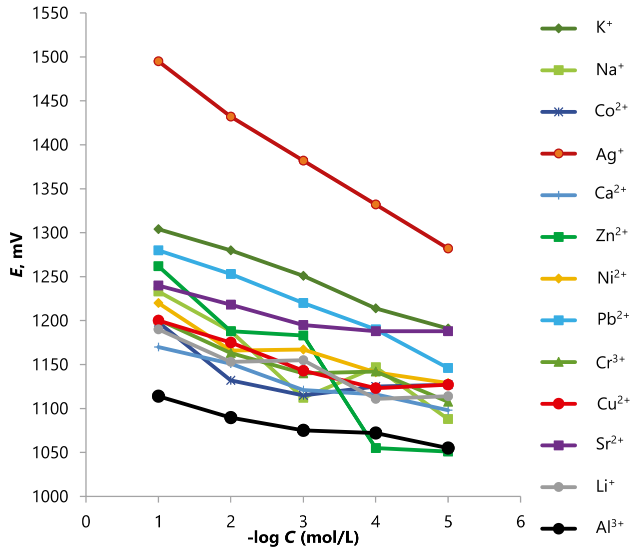


Fig. 3 The potentiometric selectivity of silver(I)-selective sensor

The sensor performed highly selective response to silver(I) ion over the other cations. The sensor response to various cations decreases in the following order:

$$K^+ > Pb^{2+} > Sr^{2+} > Na^+ > Zn^{2+} > Cu^{2+} > Ni^{2+} > Cr^{3+} > Li^+ > Ca^{2+} > Co^{2+} > Al^{3+}$$

pH Effect

The solutions used in the pH-working range of the developed sensor were prepared with HNO_3 for the pH range of 2.0–7.0, and NaOH for the pH range of 8.0–12.0, and determined at 1.0×10^{-2} mol L^{-1} Ag^+ concentration. The results are shown in Fig. 4. As can be seen, the potential remains constant in the pH range of 3.0–7.0. This shows the applicability of the developed sensor in an acidic media. On the other hand, the reason for the decreasing trend at high pH values may be due to the hydrolysis of Ag^+ and the formation of silver hydroxyl in solution.

Response Time and Life-time

In this study, the response time of the developed sensor was determined considering the IUPAC recommendations [29]. For this purpose, we measured the time required to reach equilibrium potential for the sensor which was immersed in one solution from another in this concentration range of 1.0×10^{-1} – 1.0×10^{-5} mol L^{-1}. The response time of the developed sensor is given in Fig. 5. As a result, we determined that the response time of the sensor is less than 8 s. The life-time of the proposed sensor was determined by monitoring the potential behavior in potentiometric measurements taken against silver(I) ions at different times throughout the study. At the end of the study, we determined that the sensor had a life-time of 6 weeks.

Analytical Applications

Potentiometric Titration

In the first analytical application of the developed silver(I)-selective sensor, we investigated its usability as an indicator electrode by potentiometric titration. For this purpose, we added 5 mL of 1.0×10^{-2} mol L^{-1} NaCl solution to 50 mL of 1.0×10^{-2} mol L^{-1} silver(I) solution and recorded the potential obtained after each addition. A total of 70 mL of NaCl was added and, the titration end point was

Table 3 The potentiometric selectivity coefficients of the silver(I)-selective sensor

Interfering ions	Selectivity coefficient		Interfering ions	Selectivity coefficient	
	log $K^{\mathrm{pot}}_{\mathrm{Ag}^+,M^{n+}}$	$K^{\mathrm{pot}}_{\mathrm{Ag}^+,M^{n+}}$		log $K^{\mathrm{pot}}_{\mathrm{Ag}^+,M^{n+}}$	$K^{\mathrm{pot}}_{\mathrm{Ag}^+,M^{n+}}$
K^+	−2.57	2.69×10^{-3}	Ni^{2+}	−4.50	3.16×10^{-5}
Pb^{2+}	−3.03	9.33×10^{-4}	Cr^{3+}	−4.55	2.82×10^{-5}
Sr^{2+}	−3.62	2.40×10^{-4}	Li^+	−4.72	1.91×10^{-5}
Na^+	−4.13	7.41×10^{-5}	Ca^{2+}	−4.75	1.78×10^{-5}
Zn^{2+}	−4.14	7.24×10^{-5}	Co^{2+}	−5.07	8.51×10^{-6}
Cu^{2+}	−4.35	4.47×10^{-5}	Al^{3+}	−5.78	1.66×10^{-6}

determined as 50 mL. The graph of potential (E)-added NaCl (mL) created with the obtained data is sigmoid as seen in Fig. 6. The sharp decrease in the turning point in the graph shows that the developed sensor can be used as an indicator electrode.

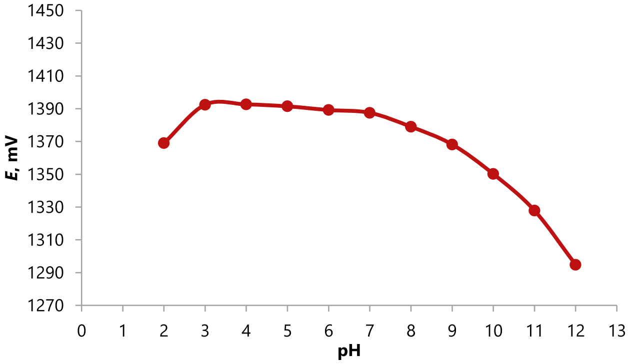


Fig. 4 The pH effect on the silver(I)-selective sensor at 1.0×10^{-2} mol L^{-1} Ag^+

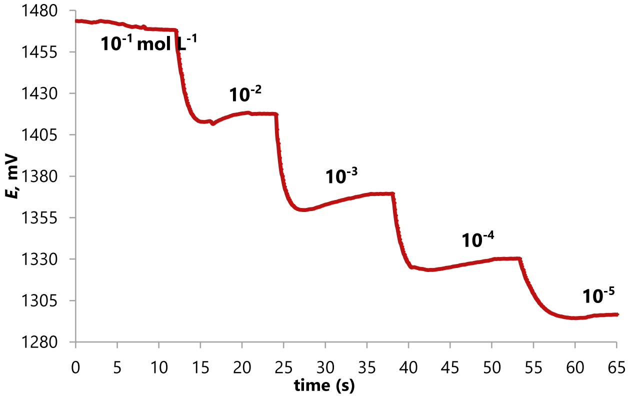


Fig. 5 Response time of silver(I)-selective sensor

Real Sample Applications

In another analytical application of the sensor, we performed silver(I) analysis in different water samples with the direct potentiometry. Silver nitrate solution was added to the water samples in the amounts indicated in Table 4, and direct measurements were taken with the developed sensor. The amount of silver(I) was calculated by using the linear equation with the obtained potential values. When the amount of silver(I) added and the amount found with the sensor is evaluated, it can be stated that the sensor can detect silver(I) ions with very high recoveries (Table 4).

Comparison Study

We compared the new silver(I)-selective sensor we developed with the potentiometric silver(I)-selective sensors previously reported in the literature in terms of linear-working range, response time, detection limit, and pH working

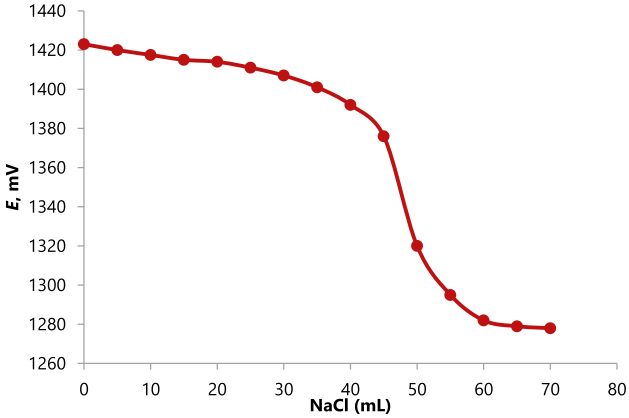


Fig. 6 Potentiometric titration curve of Ag^+ ion (1.0×10^{-2} mol L^{-1}, 50.0 mL) with NaCl (1.0×10^{-2} mol L^{-1}), using the developed sensor as an indicator electrode

Table 4 Analysis of silver(I) ions in different water samples by use of the developed sensor

Real sample	Ag^+ quantity, (mol L^{-1})		
	Added Ag^+	Mean (± SD) found with sensor*	% Recovery
Tap water (Zonguldak, Turkey)	1.00×10^{-3}	$9.37\ (\pm0.169)\times10^{-4}$	93.70
Purification water	1.00×10^{-3}	$9.84\ (\pm0.244)\times10^{-4}$	98.40
Commercial water	1.00×10^{-3}	$9.70\ (\pm0.069)\times10^{-4}$	97.10

*Average value ($n=3$)

Table 5 Comparison of the developed sensor with the existing sensors in literature

Ionophore	Lineer concentration range (mol L^{-1})	Limit of detection (mol L^{-1})	pH working range	Response time (s)	Ref
Without ionophore	1.0×10^{-5}–1.0×10^{-1}	4.25×10^{-6}	0.7–7.0	5–30	[30]
N,N-Dibenzyl-dibenzo-diaza-18-crown-6	7.0×10^{-6}–1.0×10^{-1}	3.0×10^{-6}	4.0–7.0	<10	[31]
5,11,17,23-tetra-*tert*-butyl-25,27-dihydroxy-calix[4]arene-thiacrown-4	1.0×10^{-6}–1.0×10^{-2}	8.0×10^{-7}	2.0–6.0	5–10	[32]
Schiff base-*p*-*tert*-butylcalix[4]arene	1.0×10^{-5}– 1.0×10^{-1}	3.0×10^{-6}	1.0–5.6	20	[33]
Dilaktam Crown ether	1.0×10^{-5}–1.0×10^{-1}	6.8×10^{-6}	5.1–7.2	~20	[34]
2,c-8,c-14,c-20-tetrabutyl-4,6,10,12,16,18,22,24-octaacetyl-resorc[4]arene	1.0×10^{-5}–1.0×10^{-1}	3.0×10^{-6}	1.5–6.0	<20	[35]
Schiff-base-p-tert-butylcalix[4]arene	1.0×10^{-5}–1.0×10^{-1}	6.31×10^{-6}	1.0– 6.0	30	[36]
Phenol derivative molecule	1.0×10^{-6}–1.0×10^{-1}	5.87×10^{-7}	3.0–7.0	<8	This work

range. When the data in Table 5 is evaluated, the sensor we have developed has a wider linear-working range, a lower detection limit, and a faster response time than its counterparts. In addition, very close results were obtained in the pH working range parameters.

Conclusions

In this study, a novel phenol derivative compound was synthesized and its potentiometric properties were tested. After completing the characterization of the synthesized compound using spectroscopic methods, it was directly used as an electroactive component in the production of sensors. As a result of the potentiometric studies, it was determined that the synthesized molecule exhibited a highly selective behavior towards silver(I) ions. The sensor we have developed can be prepared very easily and offers extremely low-cost analysis because the electroactive component is produced in our laboratory. In addition, the sensor exhibits linear behavior over a wide concentration range and has a very low detection limit. Its fast response time and successful analytical applications clearly demonstrate that the sensor can be a new alternative for the determination of silver(I) ions in various samples.

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Declarations

Conflict of Interest The authors declare no competing interests.

References

1. K. Xu, C. Pérez-Ràfols, M. Cuartero, G.A. Crespo, Electrochim. Acta **374**, 137929 (2021)
2. O. Isildak, N. Deligönül, O. Özbek, Turk. J. Chem. **43**, 1149–1158 (2019)
3. M.A. Karimi, S.Z. Mohammadi, A. Mohadesi, A. Hatefi-Mehrjardi, M. Mazloum-Ardakani, L.S. Korani, A.A. Kabir, Sci. Iran **18**, 790–796 (2011)
4. H.M. Abu-Shawish, S.M. Saadeh, H.M. Dalloul, B. Najri, H. Al Athamna, Sens. Actuators B Chem. **182**, 374–381 (2013)
5. T. Zhang, Y. Chai, R. Yuan, J. Guo, Mater. Sci. Eng. C **32**, 1179–1183 (2012)
6. J.N. Bianchin, E. Martendal, E. Carase, J. Anal. Methods. Chem. **2011**, 1–7 (2011)
7. F. Valverde, M. Costas, F. Pena, I. Lavilla, C. Bendicho, Chem. Speciat. Bioavailab. **20**, 217–226 (2008)
8. R.K. Saha, Orient. J. Chem. **32**, 499–507 (2016)
9. Q. Hu, G. Yang, Y. Zhao, J. Yin, Anal. Bioanal. Chem. **375**, 831–835 (2003)
10. B.H. Zhang, L. Qi, F.Y. Wu, Microchim. Acta **170**, 147–153 (2010)

11. M.E.B. Mohamed, E.Y. Frag, M.H. El Brawy, Microchem. J. **164**, 106065 (2021)
12. Ö. Isildak, O. Özbek, M.B. Gürdere, J. Anal. Test. **4**, 273–280 (2020)
13. O. Özbek, Ö. Isildak, C. Berkel, J. Incl. Phenom. Macrocycl. Chem. **98**, 1–9 (2020)
14. S.P. Akanji, O.A. Arotiba, D. Nkosi, Electrocatalysis **10**, 643–652 (2019)
15. T. Tamji, A. Nezamzadeh-Ejhieh, Electrocatalysis **10**, 466–476 (2019)
16. G. Kuzu Çelik, A.F. Üzdürmez, A. Erkal, E. Kılıç, A.O. Solak, Z. Üstündağ, Electrocatalysis **7**, 207–214 (2016)
17. O. Özbek, Ö. Isildak, M.B. Gürdere, A. Cetin, Org. Commun. **14**, 228–239 (2021)
18. Ö. Isildak, O. Özbek, Crit. Rev. Anal. Chem. **51**, 218–231 (2021)
19. C. Topcu, Talanta **161**, 623–631 (2016)
20. Ö. Isildak, O. Özbek, K.M. Yigit, Int. J. Environ. Anal. Chem. **101**, 2035–2045 (2021)
21. O. Özbek, C. Berkel, Ö. Isildak, I. Isildak, Clin. Chim. Acta **524**, 154–163 (2022)
22. C. Topcu, Investigation of usage of recently synthesized Schiff bases as active components in chemical sensors. MSc Thesis, Ondokuzmayis University, Samsun, Turkey (2009)
23. E. Findik, M. Ceylan, M. Elmastaş, Eur. J. Med. Chem. **46**, 4618–4624 (2011)
24. Ö. Isildak, O. Özbek, K.M. Yigit, Bulg. Chem. Commun. **52**, 448–452 (2020)
25. O. Özbek, Ö. Isildak, ChemistrySelect **7**, e202103988 (2022)
26. O. Özbek, Ö. Isildak, I. Isildak, Biochem. Eng. J. **176**, 108181 (2021)
27. Ö. Isildak, O. Özbek, J. Chem. Sci. **132**, 29 (2020)
28. Y. Umezawa, P. Bühlmann, K. Umezawa, K. Tohda, A.S. Amemiya, Pure Appl. Chem. **72**, 1851–2082 (2000)
29. R.P. Buck, E. Lindner, Pure Appl. Chem. **66**, 2527–2536 (1994)
30. D.M. Sejmanović, B.B. Petković, M.V. Budimir, S.P. Sovilj, V.M. Jovanović, Electroanal. **23**, 1849–1855 (2011)
31. I. Isildak, M. Yolcu, O. Isildak, N. Demirel, G. Topal, H. Hosgoren, Microchim. Acta **144**, 177181 (2004)
32. A. Demirel, A. Doğan, G. Akkuş, M. Yılmaz, E. Kılıç, Electroanal. **18**, 1019–1027 (2006)
33. R.K. Mahajan, M. Kumar, V. Sharma, I. Kaur, Analyst **126**, 505–507 (2001)
34. M. Masrournia, H. Zamani, H. Mohammedzadeh, S.M. Seyedi, M.R. Ganjali, H.A. Eshghi, J. Chil. Chem. Soc. **54**, 63–67 (2009)
35. M. Mazloum, M.S. Niassary, S.H. Mirhoseini Chahooki, M.K. Amini, Electroanal. **14**, 376–381 (2002)
36. R.K. Mahajan, I. Kaur, V. Sharma, M. Kumar, Sensors **2**, 417–423 (2002)