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ORIGINAL PAPER

Synthesis, characterization and sensor applications of a new 1,4-naphthoquinone derivative molecule

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Abstract

In this study, a new naphthoquinone derivative molecule was synthesized with a very high yield (99.0%), and its sensor properties were investigated. The characterization of the synthesized molecule was carried out using spectroscopic methods such as ^{1}H-, ^{13}C-NMR and FT-IR. Polymer membrane potentiometric sensors were prepared using this molecule as an ionophore, and these newly prepared sensors exhibited selective behavior toward barium(II) ions. The one of barium(II)-selective potentiometric sensors developed had a low detection limit of 3.51×10^{-6} mol L^{-1} in a wide concentration range of 1.0×10^{-1}–1.0×10^{-5} mol L^{-1} and had also a near-Nernstian behavior. The proposed barium(II) selective sensor was shown to have good reproducibility, fast response time (< 5 s), wide pH working range (5.0–10.0) and low cost production. Besides, it could detect barium(II) ions in various water samples with high recoveries; and based on its advantages, it can be proposed as a new alternative in the analysis of barium(II) ions.

Keywords Naphthoquinones · Barium(II) · Potentiometry · Ion-selective electrodes · Synthesis

Introduction

Naphthoquinones are one of the important groups of molecules found in nature, and they are frequently produced by bacteria, fungi, and higher plants (Khan et al. 2023). 1,4-naphthoquinone is a p-quinone derived from naphthalene in which two hydrogens are replaced with two ketone groups (C-1 and C-4) (Leechaisit et al. 2024; Angulo-Elizari et al. 2024). 1,4-naphthoquinone derivative molecules have a versatile spectrum of biological activities including anticancer, antifungal, antidiabetic, antioxidant, anti-inflammatory, antiviral, antibacterial, antiallergic and antiplatelet activities (Liu et al. 2020; Navarro-Tovar et al. 2023; Ertik et al. 2024; Enciso-Vargas et al. 2024, Widhalm and Rhodes 2016). Naphthoquinone derivative drugs such as atovaquone, lapachol, parvaquone and buparvaquone, which are used in the treatment of various diseases, are currently available in the market (Patil et al. 2024). In addition to their important biological activities, sensor properties of naphthoquinone derivative molecules have also been proven in previous studies (Mermer et al. 2021; Bhasin et al. 2019; Fu et al. 2018). However, the use of naphthoquinone derivatives as sensor materials in potentiometric sensors is quite limited compared to other analytical methods.

Potentiometric solid contact ion-selective electrodes (SC-ISEs) provide significant advantages such as low cost, low energy consumption, high sensitivity, high selectivity, ease of use, wide concentration range, easy miniaturization, fast response time, low detection limit, good reproducibility, and long lifetime in routine ion analysis (Berkel and Özbek 2024; Özbek et al. 2024; Akyasan et al. 2025; Wardak et al. 2023; Vilasó-Cadre et al. 2024; Elik et al. 2025; Kalay et al. 2025; Moraeska and Wardak 2024). Due to these advantages, they can be considered as important alternatives in the analysis of ionic species compared to different spectroscopic and chromatographic methods (Özbek and Altunoluk 2024; Özbek and Berkel 2023).

Barium, which can be found naturally on earth, is widely used in various fields such as the petroleum industry, glass industry, alloying, electroplating, corrosion protection films and pigments (Grajeda et al. 2017; Modi et al. 2014; Bouklouze et al. 1993; Mizani et al. 2023). Due to its common use

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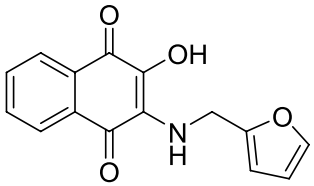


Fig. 1 The chemical structure of the newly synthesized 1,4-naphthoquinone derivative molecule

in the industry, it pollutes soil and water, severely damaging the environment. In addition to its polluting effect, it can also cause various health problems in humans and animals such as loss of reflexes, respiratory failure, rhabdomyolysis and hypophosphatemia (Altunoluk et al. 2024; Zamani et al. 2010; Elmosallamy et al. 2024).

In this study, we synthesized a naphthoquinone derivative molecule (Fig. 1) that exhibits ionophore properties. The newly synthesized molecule showed good selectivity against barium(II) ions. The potentiometric performance properties of the developed sensor were tested under laboratory conditions, and its usability in various real samples was investigated. As a result, we proposed both a new naphthoquinone derivative molecule and a new potentiometric sensor to the literature.

Experimental

Chemicals

All chemicals and solvents used in the ionophore synthesis in the present study were obtained commercially (Sigma-Aldrich and Merck) and used without any further purification. High molecular weight polyvinyl chloride (PVC), plasticizers, anion excluder and tetrahydrofuran (THF) used to prepare the sensor were purchased from Sigma-Aldrich. Barium(II)nitrate (purchased from Sigma-Aldrich) of the proper weight was dissolved in ultrapure water (18.2 MΩ cm^{-1}) (MP Minipure water system, Dest up, 0513957) to obtain 1.0×10^{-1} mol L^{-1} stock Ba^{2+} solution. Other metal solutions were prepared by the same method using nitrate salts of metals (purchased from Sigma-Aldrich, Merck and Fluka). For the preparation of solid contact electrodes, graphite (20 µm particle size), epoxy and hardener were bought from Sigma-Aldrich, Henkel and Bayer AG, respectively.

Apparatus

^{1}H and ^{13}C NMR spectra were recorded with a Bruker Avance DPX-400 spectrometer at 400 MHz (^{1}H) and 100 MHz (^{13}C). IR spectra were recorded on a Jasco FT/IR 430 instrument. Melting points was determined with a Thomas-Hoover capillary melting point apparatus. Thin layer chromatography (TLC) was carried out on silica-gel coated aluminum plates (ALUGRAM® Xtra SILG /UV_{254}, Macherey Nagel). Potentiometric measurements (Medisen Medical Ltd. Şti., Türkiye) were made using a two-electrode system with a solid state barium(II)-selective sensor and an Ag/AgCl reference electrode (Thermo Scientific Orion 900100) which contains 3.0M KCl filling liquid.

Method

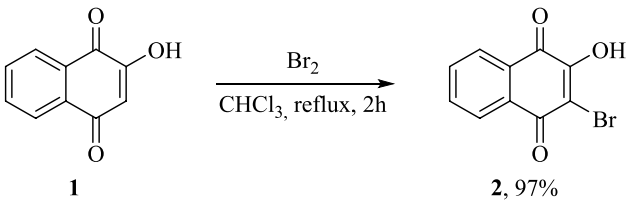
Synthesis of 2-bromo-3-hydroxynaphthalene-1,4-dione (2)

Molecular bromine (1.758 g, 0.011 mol) solution in chloroform (10 mL) at reflux temperature was added dropwise to a stirred solution of 2-hydroxynaphthalene-1,4-dione (**1**) (1.742 g, 0.01 mol) in chloroform (50 mL) in a two-necked flask equipped with a reflux condenser and dropping funnel. The reaction mixture was stirred in the dark at reflux temperature for 2 h. The reaction mixture was washed with a saturated aqueous solution of $Na_2S_2O_5$ (20 mL). The organic layer was dried over Na_2SO_4, and the solvent was removed with a vacuum. The crude product was recrystallized from dichloromethane-hexane (50:5 mL) to give **2** (Scheme 1).

Yellow powder (2.45 g, 99%), mp 203–205 °C (lit. 203–205 °C) (Louvis et al. 2016). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23 (m, 1H), δ 8.16 (m, 1H), 7.86 (s, 1H, OH), 7.86–7.75 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 178.8, 178.0, 155.2, 135.5, 133.7, 132.3, 128.8, 127.9, 127.1, 111.4

Synthesis of 2-((furan-2-ylmethyl) amino)-3-hydroxynaphthalene-1,4-dione (3)

To the solution of 2-bromo-3-hydroxynaphthalene-1,4-dione (**2**) (0.4 g, 1.581 mmol) in dichloromethane (30 mL), furfuryl amine (0.169 g, 1.74 mmol) was added dropwise at room temperature while stirring. The reaction was then stirred at room temperature for 10 min. The reaction was monitored by TLC, and a red precipitate was finally obtained. This precipitate was filtered and then washed with dichloromethane to



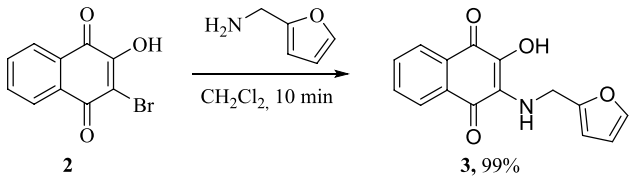
Scheme 1 Synthesis of 2-bromo-3-hydroxynaphthalene-1,4-dione (**2**)

obtain 2-((furan-2-ylmethyl)amino)-3-hydroxynaphthalene-1,4-dione (**3**) (Scheme 2).

Red powder (422 mg, 99%), mp 152–153 °C. ^{1}H NMR (400 MHz, DMSO–d_6) δ 8.22 (bs, 2H, NH and OH), 7.91 (dd, J = 8, 1.2 Hz, 1H), 7.80 (dd, J = 8, 1.2 Hz, 1H), 7.76 (d, J = 1.2 Hz, 1H), 7.67 (td, J = 1.6, 7.5 Hz, 1H), 7.55 (td, J = 1.2, 7.4 Hz, 1H), 6.55–6.51 (m, 2H), 4.11 (s, 2H, CH_2). ^{13}C NMR (100 MHz, DMSO–D_6) δ 184.2, 174.3, 168.1, 148.1, 144.1, 135.5, 134.2, 131.1, 130.9, 126.1, 126.0, 111.4, 110.7, 106.1, 35.7. IR (ν_{max}, cm^{-1}): 3253–2540, 3038, 2987, 2726, 2645, 1677, 1594, 1493, 1472, 1441, 1372, 1321, 1306, 1269, 1222, 1147, 1115, 1064, 1015, 986, 962, 927, 871, 816, 784, 744, 725, 676, 660, 597, 585, 548, 490, 448, 411.

Preparation of potentiometric sensors

PVC membrane sensors, in which the synthesized naphthoquinone derivative molecule was used as an ionophore, were prepared in two stages, as reported in our previous studies (Çakmak et al. 2025; Özbek and Ölcenoglu 2023; Akyasan et al. 2025):



Scheme 2 Synthesis of 2-((furan-2-ylmethyl)amino)-3-hydroxynaphthalene-1,4-dione **(3)**

First, conductive solid contact electrodes were prepared. For this purpose, approximately 3 mL THF was added to a mixture containing graphite (50.0%), epoxy (35.0%) and hardener (15.0%), and mixed until the solution becomes homogeneous. Copper wires with one open end were dipped into this mixture several times when it reached a certain viscosity. The completely coated copper wires were left to dry for 24 h in the dark at room conditions. Then, PVC membrane ion-selective sensors were prepared by dissolving and mixing ionophore, plasticizers, PVC, KT*p*ClPB in approximately 3 mL THF in the ratios given in Table 1. Previously prepared solid contact electrodes were dipped into the homogeneous membrane mixture several times, and their surfaces were coated. The coated electrodes were left to dry in the dark at room conditions for approximately 12 h. Thus, twelve sensors with various compositions given in Table 1 were prepared, and their potentiometric performance properties were tested using Ba^{2+} ion solutions. Among all the prepared sensors, Sensor II, which have a composition of 3.0% ionophore, 32.0% PVC, 64.0% BEHS and 1.0% KT*p*ClPB, had a lower detection limit, a wide working range and the highest R^2 value compared to the other sensors. Therefore, sensors with this composition were used in all subsequent stages of the study. The experimental steps of the study are summarized in Fig. 2.

Table 1 Components and performance characteristics of the newly developed sensors

No	Membrane composition (*w*/*w*)							Potentiometric Performance			
	PVC	Ionophore	Plasticizers				KT*p*ClPB				
			DEHA	BEHS	DBP	*o*–NPOE		Linear range (mol L^{-1})	Detection limit (mol L^{-1})	Slope (mV decade^{-1})	R^2
1	32.0	2.0	65.0				1.0	1.0×10^{-1}–1.0×10^{-5}	9.37×10^{-6}	14.6 ± 2.35	0.9898
2	**32.0**	**3.0**		**64.0**			**1.0**	$\mathbf{1.0\times10^{-1}}$–$\mathbf{1.0\times10^{-5}}$	$\mathbf{3.51\times10^{-6}}$	**23.3 ± 0.94**	**0.9995**
3	32.0	3.0			64.0		1.0	1.0×10^{-1}–1.0×10^{-4}	8.11×10^{-5}	16.0 ± 3.0	0.9602
4	32.0	3.0				64.0	1.0	1.0×10^{-1}–1.0×10^{-3}	7.50×10^{-4}	23.6 ± 6.5	0.9333
5	32.0	4.0		63.0			1.0	1.0×10^{-1}–1.0×10^{-4}	3.23×10^{-5}	12.3 ± 0.5	0.9860
6	32.0	2.0		65.0			1.0	1.0×10^{-1}–1.0×10^{-5}	8.74×10^{-6}	19.3 ± 3.1	0.9803
7	32.0	5.0		62.0			1.0	1.0×10^{-1}–1.0×10^{-5}	4.20×10^{-6}	19.0 ± 2.9	0.9932
8	30.0	2.0		67.0			1.0	1.0×10^{-1}–1.0×10^{-5}	9.36×10^{-6}	16.0 ± 3.7	0.9740
9	34.0	3.0		62.0			1.0	1.0×10^{-1}–1.0×10^{-5}	9.65×10^{-6}	14.0 ± 2.5	0.9901
10	32.0	3.0	64.0				1.0	1.0×10^{-1}–1.0×10^{-4}	8.66×10^{-5}	16.0 ± 4.8	0.9726
11	32.0	2.0			65.0		1.0	1.0×10^{-1}–1.0×10^{-3}	2.54×10^{-4}	20.0 ± 4.5	0.9480
12	32.0	4.0	63.0				1.0	1.0×10^{-1}–1.0×10^{-4}	9.75×10^{-5}	17.0 ± 2.5	0.9690

DEHA: bis(2–ethylhexyl)adipate, **DBP:** dibutyl phthalate **BEHS:** bis(2–ethylhexyl)sebacate; *o*–**NPOE:** o-nitrophenyl octyl ether

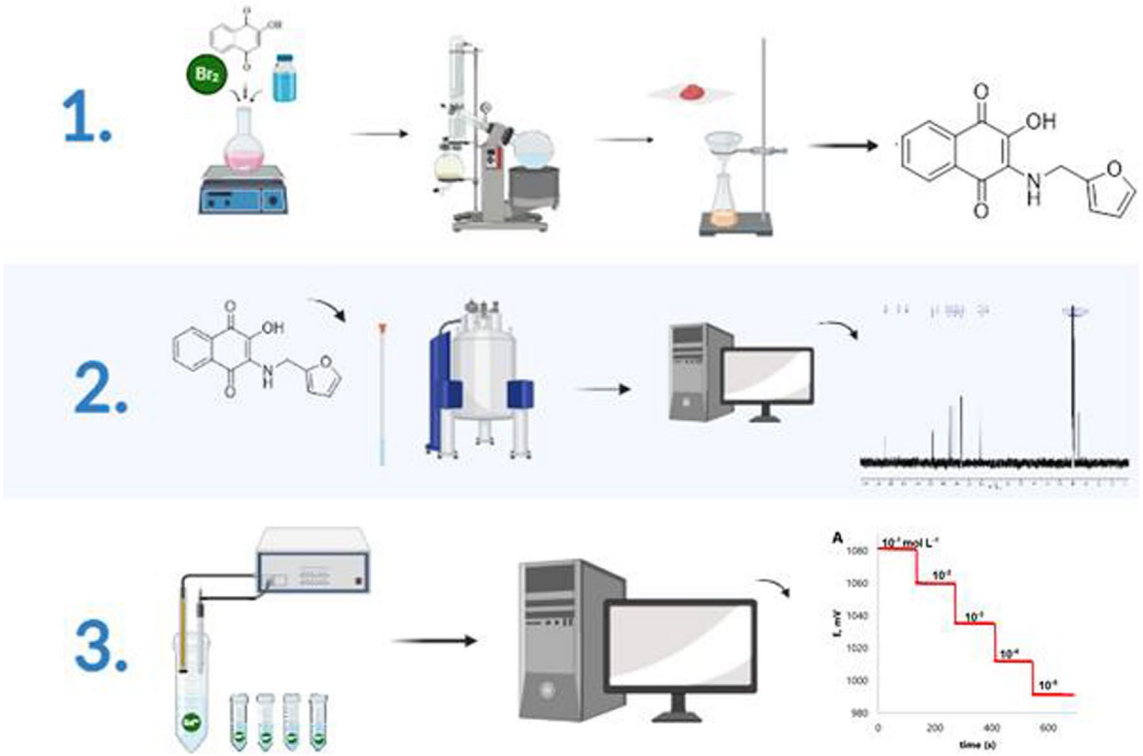


Fig. 2 The experimental steps of the study

Results and discussion

Characterization of 2-((furan-2-ylmethyl) amino)-3-hydroxynaphthalene-1,4-dione (3)

The ^{1}H NMR spectrum confirms the structure of **3** (Fig. 3). The furan ring was characterized by peaks at 7.79 ppm (alpha proton) and 6.54–6.51 ppm (beta protons). 4.11 ppm in the spectrum is attributed to the peak of –N–CH_2–furan ring. Four signals at 8.22 ppm, 9.91 ppm, 7.80 ppm and 7.67 ppm are assigned to –CH– in benzene ring. The peak at 8.22 ppm is a broad singlet integrated into 2 protons which are attributed to –NH and –OH protons. The corresponding ^{13}C NMR spectrum also confirms the structure of **3** (Fig. 4). FT-IR band observed at 3253–2540 cm^{-1} is assigned to O–H and N–H stretching vibrations. The significant broadening of the band can be attributed to the increase in the number of hydrogen bonds due to the presence of O atom of the furan ring, carboxyl, –NH and –OH groups. The strong band at 1677 cm^{-1} belongs to the C=O stretching vibration. The absorption bands in the range of 1594–1147 cm^{-1} can be assigned mainly to the C=C, C–O, and C–N stretching vibrations.

Membrane composition

In this study, twelve sensors were prepared with different compositions using various plasticizers, and different concentrations of PVC, ionophore, and potassium tetrakis(*p*–chlorophenyl)borate (KT*p*ClPB). According to Table 1, the sensor with composition II had a wide working range, the lowest detection limit and the highest correlation coefficient (R^2) among the prepared sensors. Plasticizers, which have a large proportion in the composition of ISEs, have a significant effect on the sensor behavior. When Table 1 is examined, it was observed that sensors prepared with BEHS exhibited better potentiometric results compared to sensors prepared with other plasticizers. Therefore, the potentiometric behavior of sensors containing BEHS and different proportions of ionophore were further examined in more detail. According to the obtained potentiometric data, it was determined that the mixture containing 3.0% ionophore in its composition have a superior potentiometric response compared to other ionophore ratios. Therefore, the potentiometric performance properties of the sensor II (32.0% PVC, 3.0% ionophore, 64.0% BEHS and 1.0% KT*p*-ClPB) were investigated and reported.

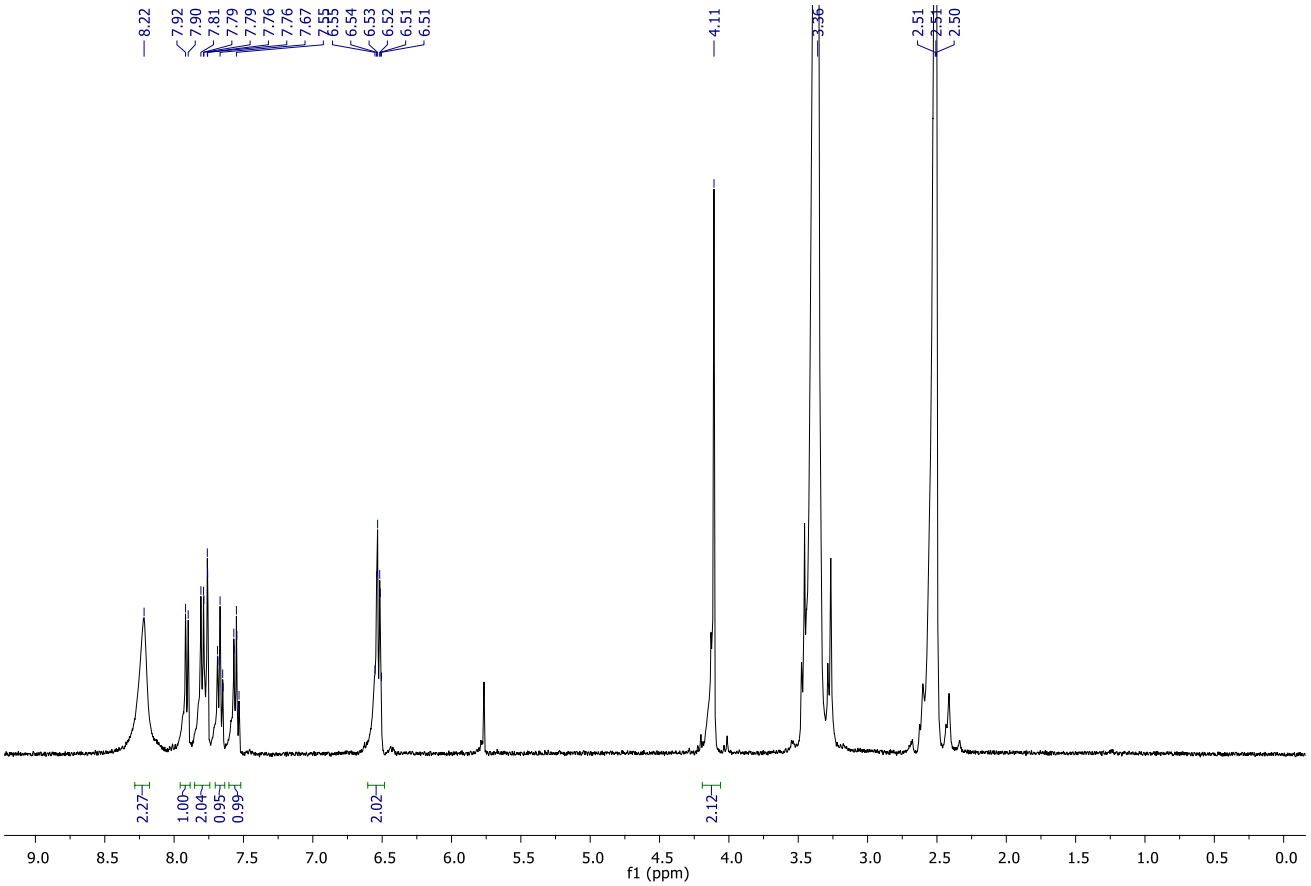


Fig. 3 ^{1}H–NMR spectrum of newly synthesized molecule (**3**)

The use of 1,4-naphthoquinone derivative molecules as ionophore in the determination of various cationic species by ISEs has been demonstrated in literature studies (Hamdan 2010; Gupta et al. 2010; Akyasan et al. 2024). The mechanism of interaction of the new 1,4-naphthoquinone derivative molecule synthesized in this study with analyte ions is proposed as in Fig. 5. It is thought that the interaction between barium(II) ions and the ionophore occurs according to the ion exchange mechanism (Özbek 2023). The ionophore in the membrane structure can retain the barium(II) ion at the interface between the solution and membrane phases (Fig. 5). The partitioning of barium(II) ions between the solution phase and the membrane phase depends on its activity or concentration. Therefore, if the concentrations are not equal at both solution-membrane interfaces, a phase-boundary potential is created in the membrane. When a reference electrode is included in the potentiometric measurement system, the potential difference measured at the two electrodes is the membrane potential.

Potentiometric response, detection limit and repeatability

The potentiometric response of sensor II with optimum composition was determined using barium(II) ion solutions. It can be clearly seen in Fig. 6a that the developed sensor has a near-Nernstian behavior (23.3 ± 0.94 mV/decade) in the concentration range of 1.0×10^{-1}–1.0×10^{-5} mol L^{-1}. The calibration curve of the sensor is given in Fig. 6b which shows that the sensor has a high R^2 (0.9995) value. The detection limit of ion-selective electrodes is defined as the lowest ion concentration that produces a measurable potential difference across the membrane interface. As seen in Fig. 6b, the calibration graph consists of two linear parts. In potentiometric measurements, the detection limits of ISEs are given as the activity value corresponding to the point where the extrapolations of these two linear regions intersect. The detection limits of the sensors given in Table 1 were calculated according to the rules determined by IUPAC (Buck and Lindner 1994). Thus, the detection limit of the

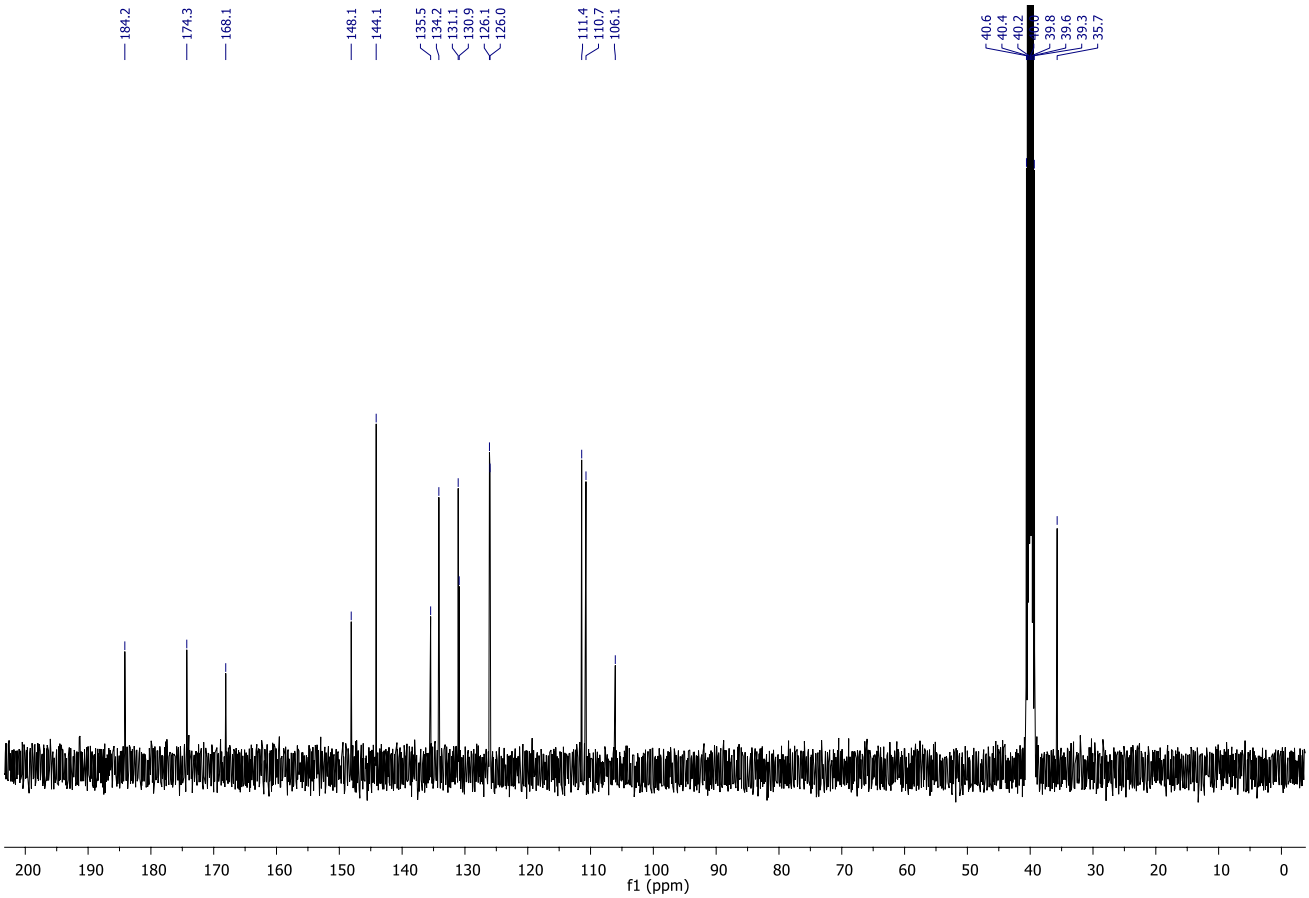


Fig. 4 ^{13}C–NMR spectrum of newly synthesized molecule (**3**)

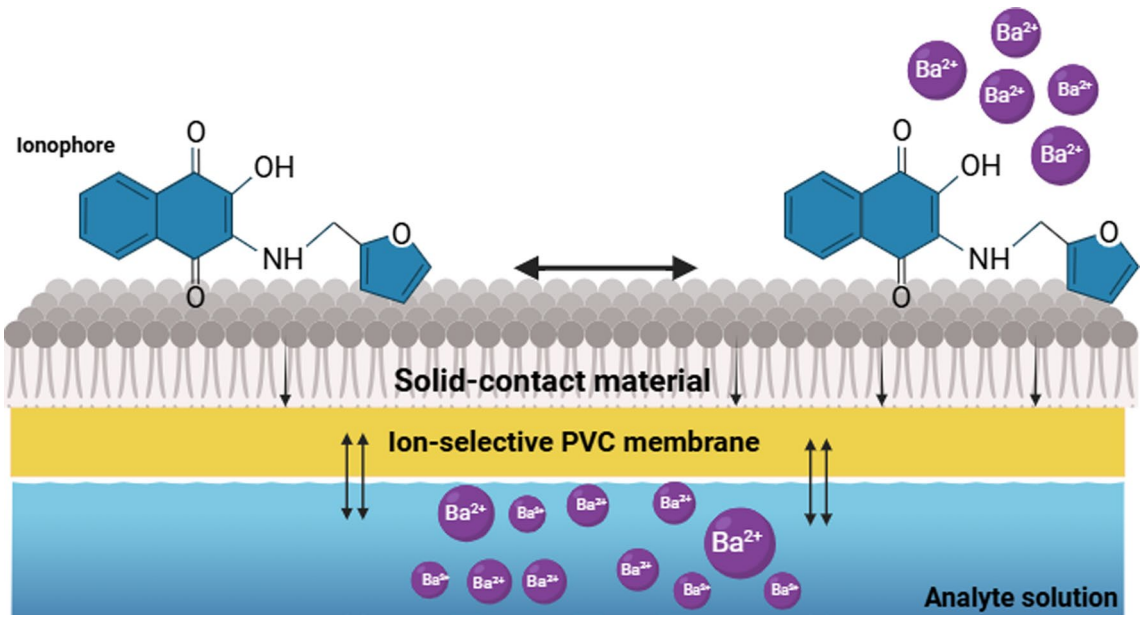


Fig. 5 The proposed mechanism of interaction between ionophore and Ba^{2+} ions

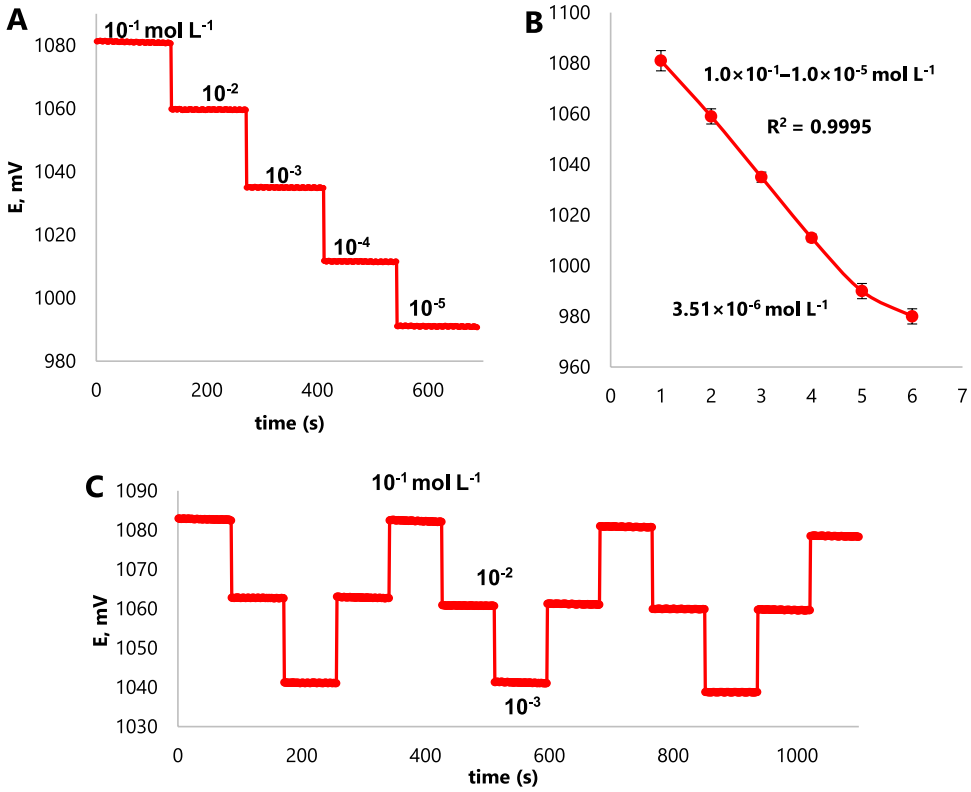


Fig. 6 Potentiometric response (**a**), calibration curve (**b**) and repeatability (**c**) of newly developed barium(II)-selective sensor

Table 2 Repeatability data of barium(II)–selective sensor

Concentration (mol L^{-1})	Potentials (mV)			
	I	II	III	Average (±SD)
1.0×10^{-1}	1082.88	1082.50	1080.94	1082.10 (±0.84)
1.0×10^{-2}	1062.75	1062.94	1061.25	1062.31 (±0.75)
1.0×10^{-3}	1041.19	1041.31	1039.81	1040.77 (±0.68)

proposed new sensor was calculated as 3.51×10^{-6} mol L^{-1}. The repeatability of the prepared sensor was tested using three different barium(II) ion concentrations (10^{-1}, 10^{-2} and 10^{-3} mol L^{-1}). Potentiometric data and standard deviation (±SD) values of the repeatability data obtained from Fig. 6c are given in Table 2. The repeatability graph of the sensor is given in Fig. 6c which proves that the proposed sensor has

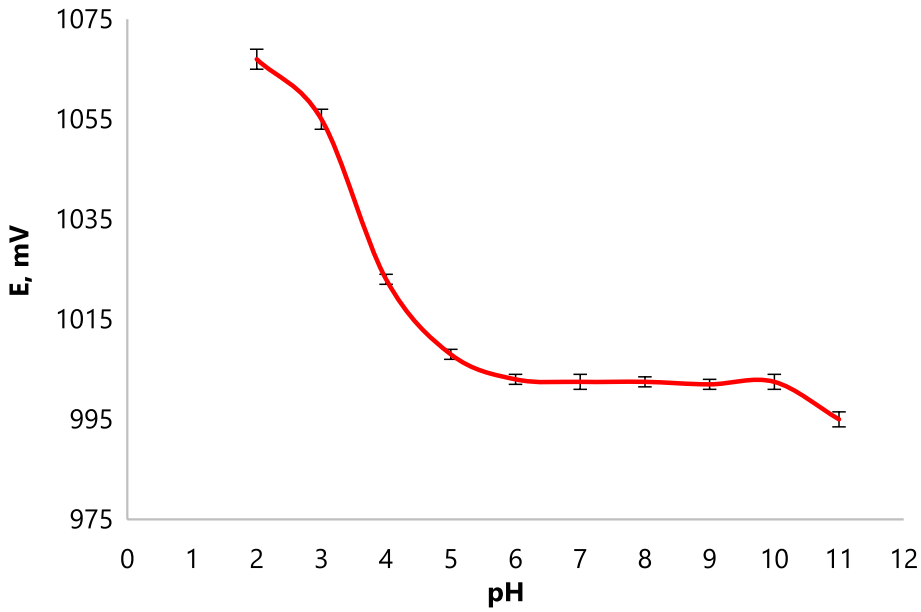


Fig. 7 pH working range of newly developed barium(II)-selective sensor

a repeatable and stable behavior in the specified concentration range.

pH working range

Herein, the pH working range of the developed barium(II) selective sensor was tested using HNO_3 (pH 2.0–7.0) and NaOH (8.0–12.0) solutions. 1.0×10^{-3} mol L^{-1} $Ba(NO_3)_2$ solution was added to the prepared solutions, and potential measurements were then taken. The pH working range of the barium(II) selective sensor is given in Fig. 7. According to data given in this figure, the proposed sensor can work in the pH 5.0–10.0 range without being affected by pH changes. It was thought that the high potential values in the pH < 4.0 range may be due to the presence of hydronium ions, while the low potentials in pH > 10.0 may be due to the formation of $Ba(OH)_2$.

Response time and lifetime

The dynamic response time of the proposed sensor was studied by considering the rules specified by IUPAC (Buck and Lindner 1994). The response time of the developed barium(II) selective sensor is given in Fig. 8. It was determined by dipping it from one solution to another at each tenfold concentration change and by recording the time it took to reach the equilibrium. Based on data given in Fig. 8, it was determined that the proposed new sensor reached the equilibrium very quickly and had a response time of less than 5 s. The lifetime of the proposed newly developed sensor was examined in monthly periods. After a period of six months, a decrease in the slope (mV/decade) of the sensor was observed. The lifetime of the sensor was determined as 6 months.

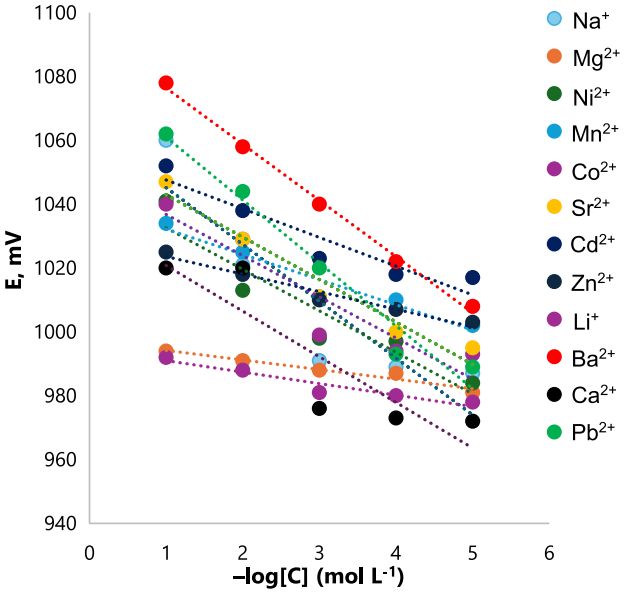


Fig. 9 Potentiometric selectivity of newly developed sensor to various ionic species

Selectivity

Potentiometric ion-selective electrodes can respond to more than one species in the solution medium, but they are selective to only one species. Therefore, one of the most important features of ISEs is to determine the species to which it will be selective. Potentiometric behavior of the prepared PVC membrane sensors was performed using eleven different cationic species. The proposed sensor exhibited selectivity to Ba^{2+} ions among different cationic species. The potential responses of the developed sensor to different cations are shown in Fig. 9, and it shows that the proposed sensor exhibits the highest potential values against Ba^{2+} ions in the concentration range of 1.0×10^{-1}–1.0×10^{-4} mol L^{-1}. At

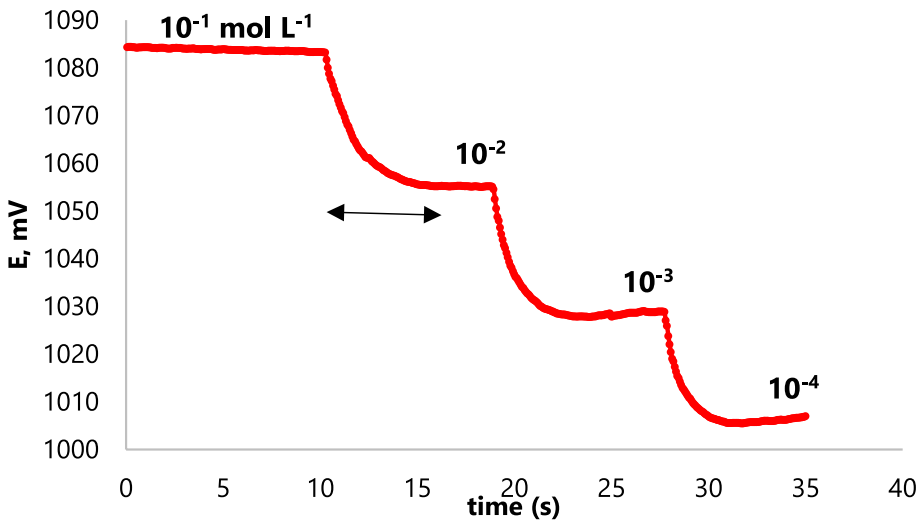


Fig. 8 Dynamic response time of newly developed sensor

low concentration values ($< 10^{-4}$ mol L^{-1}), Cd^{+2} ions were found to interfere. This observation suggests that the newly proposed sensor can interfere with different ions such as Cd^{2+} at low concentrations. The mathematical expression of the ability of an ion-selective sensor to distinguish analyte ions from other ions in solution medium can be explained by calculating selectivity coefficients ($K^{pot}_{A,B}$). In this study, the selectivity coefficients of other cationic species using the potential values corresponding to 1.0×10^{-2} mol L^{-1} concentration were calculated according to the equation by the separate solution method (SSM) recommended by IUPAC (Umezawa et al. 2000). Selectivity coefficients calculated according to IUPAC rules are given in Table 3. Based on the data in Table 3 and Fig. 9, it can be said that the proposed new sensor is highly selective toward barium(II) ions except for the interference of cadmium(II) ion at low concentrations ($< 10^{-4}$ mol L^{-1}).

Analytical applications

The applications of the newly developed naphthoquinone-based barium(II)-selective sensor in real samples were carried out using different water samples. Barium(II) ion was added to water samples that do not contain barium(II) ions in the amounts given in Table 4, and the Ba^{2+} ion concentration in the water samples was determined using the newly developed sensor. According to the data in Table 4, it is clearly seen that the proposed barium(II)-selective potentiometric sensor can detect barium(II) ions in various water samples with quite high recovery. Based on these findings, the newly produced sensor can be proposed as a new alternative to other analytical methods used in Ba(II) ion analyses.

Table 3 The selectivity coefficient of newly developed sensor for different interfering ions

Interfering ions	$log\ K^{pot}_{Ba(II),M^{n+}}$	$K^{pot}_{Ba(II),M^{n+}}$
Pb^{2+}	−0.65	0.224
Cd^{2+}	−0.79	0.162
Co^{2+}	−1.08	8.3×10^{-2}
Sr^{2+}	−1.12	7.6×10^{-2}
Mn^{2+}	−1.18	6.6×10^{-2}
Na^{+}	−1.32	4.8×10^{-2}
Ca^{2+}	−1.35	4.5×10^{-2}
Zn^{2+}	−1.42	3.8×10^{-2}
Ni^{2+}	−1.59	2.6×10^{-2}
Mg^{2+}	−2.37	4.27×10^{-3}
Li^{+}	−2.43	3.72×10^{-3}

Comparison study

In this study, a new 1,4-naphthoquinone derivative molecule was synthesized. The synthesized molecule exhibited selectivity to barium(II) ions and was used as an ionophore. Considering the increasing costs of commercial ionophores, the synthesized molecule is important for the production of an economical sensor. On the other hand, the performance characteristics of the proposed sensor were compared with some barium(II)-selective potentiometric sensors in the literature. As seen in Table 5, the proposed sensor has relatively similar properties to its counterparts in terms of linear range, detection limit and pH working range. In addition, the developed sensor has the fastest response time compared to its counterparts in Table 5. As a result, the fact that the ionophore in the composition of the developed sensor is not included in the literature and has a very fast response time compared to its counterparts is an important indicator of superiority.

Conclusion

The limited availability and increasing cost of commercial ionophores have limited sensor research. Therefore, researchers have turned to the synthesis of ionophores to produce more economical sensors. Nowadays, many molecules exhibiting ionophore properties have been synthesized by sensor researchers and more economical sensors have been produced. In this study, we investigated the sensor properties of a novel naphthoquinone derivative molecule. For this purpose, following the synthesis of a new naphthoquinone derivative molecule with a very high yield, we characterized it using various spectroscopic methods. Then, we prepared ISEs using the synthesized molecule as an ionophore and developed a new sensor selective to barium(II) ions. The developed sensor was also shown to have a wide

Table 4 Determination of Ba^{2+} ions in various water samples with the newly developed sensor

Real samples	Ba^{2+} quantity, (mol L^{-1})		
	Added Ba^{2+}	Found (±SD) with sensor*	% Recovery
Bottled water	1.0×10^{-3}	$1.02\ (\pm0.12)\times10^{-3}$	102.0
Purification drinking water	1.0×10^{-3}	$9.92\ (\pm0.17)\times10^{-4}$	99.2
Purification water	1.0×10^{-3}	$9.89\ (\pm0.13)\times10^{-4}$	98.9
Tap water (Tokat, Türkiye)	1.0×10^{-3}	$9.55\ (\pm0.21)\times10^{-4}$	95.5

*Average value ($n=3$)

Table 5 Comparison of the proposed new sensor with its counterparts in the literature

Ionophore	Linear range (mol L^{-1})	Limit of detection (mol L^{-1})	pH working range	Response time (s)	References
Barium(II)–Rose Bengal	5.0×10^{-5}–1.0×10^{-1}	2.5×10^{-6}	4.5–10.0	20	Othman and El-Shahawi (2006)
2,3,4-pyridine-1,3,5,7,12-pentaazacyclopentadeca-3-ene	1.41×10^{-6}–1.0×10^{-1}	Not reported	2.5–7.0	18	Singh et al. (2005)
4–4′-methylenediantipyrine	1.0×10^{-6}–1.0×10^{-2}	5.2×10^{-7}	3.4–10.6	15	Abedi and Zamani (2008)
Thiosemicarbazone derivative molecule	1.0×10^{-6}–1.0×10^{-1}	5.54×10^{-7}	6.0–9.0	< 10	Altunoluk et al. (2024)
3-deoxy-D-erythro-hexos-2-ulose bis (thiosemicarbazone)	1.0×10^{-6}–1.0×10^{-2}	5.6×10^{-7}	2.6–11.0	15	Zamani et al., (2010)
1,2-bis(diarylphosphine oxide) naphthalene	1.0×10^{-5}–1.0×10^{-1}	5.0×10^{-6}	3.0–11.0	60	Saleh (2000)
Dimethyl-4,4-dimethoxy-5,6,5,6-dimethylene dioxy biphenyl-2,2-dicarboxylate	1.0×10^{-5}–1.0×10^{-1}	5.0×10^{-6}	4.0–9.0	Not reported	Hassan et al. (2003)
Dibenzo-24-crown-8	1.0×10^{-6}–1.0×10^{-3}	6.1×10^{-7}	4.1–9.0	< 10	Negi et al. (2015)
4-aminobenzoic acid 2-diethylaminoethyl ester	1.0×10^{-5}–1.0×10^{-1}	4.23×10^{-6}	5.0–11.0	8	Özbek et al. (2025)
2-((furan-2-ylmethyl)amino)-3-hydroxynaphthalene-1,4-dione	1.0×10^{-5}–1.0×10^{-1}	3.51×10^{-6}	5.0–10.0	< 5	This work

concentration range, a low detection limit, a fast response time, good reproducibility and a wide pH working range. The sensor, which was shown to be successfully applied in real samples, can be used in the determination of barium(II) ions. Combined, the data in the present study suggests that naphthoquinone derivative molecules can be used as sensor materials in the routine analysis of various ions, and this study can be used as a guide by researchers studying the development of new ionophores.

Author contributions Oguz Özbek was involved in investigation, analysis, writing—review & editing. Onur Cem Altunoluk, Kıymet Berkil Akar, Ömer Isildak done investigation and analysis.

Declarations

Conflict of interest The authors declare no conflict of interest.

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