ISSN1027-5495. Functional Materials, 32, No.1 (2025), p. 126-133
doi:http://dx.doi.org/10.15407/fm32.01.126 © 2025 — STC "Institute for Single Crystals"

Indolenine-based semisquaraine dye for visual detection and sensing of mercury (II)

R. P. Svoiakov, O. G. Kulyk, I. V. Hovor, H. S. Vlasenko, A. L. Tatarets, O. S. Kolosova

Institute of Functional Materials Chemistry of SSI "Institute for Single Crystals" of NAS of Ukraine, 60 Nauky Ave., 61072 Kharkiv, Ukraine

Received October 22, 2025

Mercury is a highly toxic pollutant that poses significant risks to the environment and human health. Despite the availability of various methods for detecting Hg^{2+} ions, there is a high demand for the development of small molecule sensors that are simple, rapid, cost-effective, selective and sensitive. Here, we examine the application of indolenine-based semisquaraine dye **SqS** as a chemosensor for the mercury detection in an aqueous and organic (alcoholic) media. The addition of Hg^{2+} ions to the **SqS** solution induces a noticeable color change from light pink to yellow, while other metal cations, including Li^{+}, Ni^{+}, Na^{+}, K^{+}, Ba^{2+}, Mg^{2+}, Ca^{2+}, Cu^{2+}, Co^{2+}, Fe^{3+}, Al^{3+}, Pb^{2+}, and Cd^{2+} do not cause any significant change in color or absorption spectra. The limit of Hg^{2+} detection under proposed measurement conditions was determined to be 38 nM. The analysis of the binding characteristics of **SqS** using Job's and molar ratio methods, along with mass spectrometry, indicates that the stoichiometry of the **SqS**–Hg^{2+} complex is 1:1 and 2:1. This chemosensor can be used for the selective colorimetric detection of mercury ions in environmental samples, such as water sources, and in biological systems, contributing to pollution monitoring and safety assessments.

Keywords: squaraine, mercury, chemosensor, determination, spectrum parameters, absorbance, Job's plot, molar ratio method, aqueous solution.

Семіскваратіновий барвник напівкваратін на основі індоленіну для візуального виявлення та визначення ртуті (II). *Р.П. Свояков, О.Г. Кулик, І.В. Говор, Г.С. Власенко, А.Л. Татарець, О.С. Колосова*

Високий рівень токсичності ртуті становить серйозну загрозу для навколишнього середовища та здоров'я людини. Незважаючи на наявність різних методів для виявлення іонів Hg^{2+}, існує великий попит на розробку хемосенсорів на основі малих органічних молекул, які забезпечують простий, швидкий, економічно вигідний, селективний та чутливий спосіб детекції ртуті. У цій роботі ми досліджуємо застосування семіскваратінового барвника **SqS** на основі індоленіну як сенсора для виявлення ртуті в водних та органічних середовищах. Додавання іонів Hg^{2+} до розчину барвника **SqS** спричиняє помітну зміну кольору зі світло-рожевого на жовтий, тоді як інші катіони металів, включаючи Li^{+}, Ni^{+}, Na^{+}, K^{+}, Ba^{2+}, Mg^{2+}, Ca^{2+}, Co^{2+}, Fe^{3+}, Al^{3+}, Pb^{2+} та Cd^{2+}, не викликають жодних помітних змін у кольорі чи спектрах поглинання. Межа виявлення Hg^{2+} у запропонованих умовах аналізу становить 38 нМ. Аналіз характеристик зв'язування **SqS** за допомогою методів Джоба та мольного співвідношення, а також мас-спектрометрії вказує на те, що комплекс **SqS**–Hg^{2+} утворюється зі стехіометрією 1:1 та 2:1. Цей хемосенсор можна використовувати для селективного колориметричного виявлення іонів ртуті в екологічних зразках, таких як водні ресурси, а також у біологічних системах, що сприятиме більш ефективному моніторингу забруднень і оцінці безпеки.

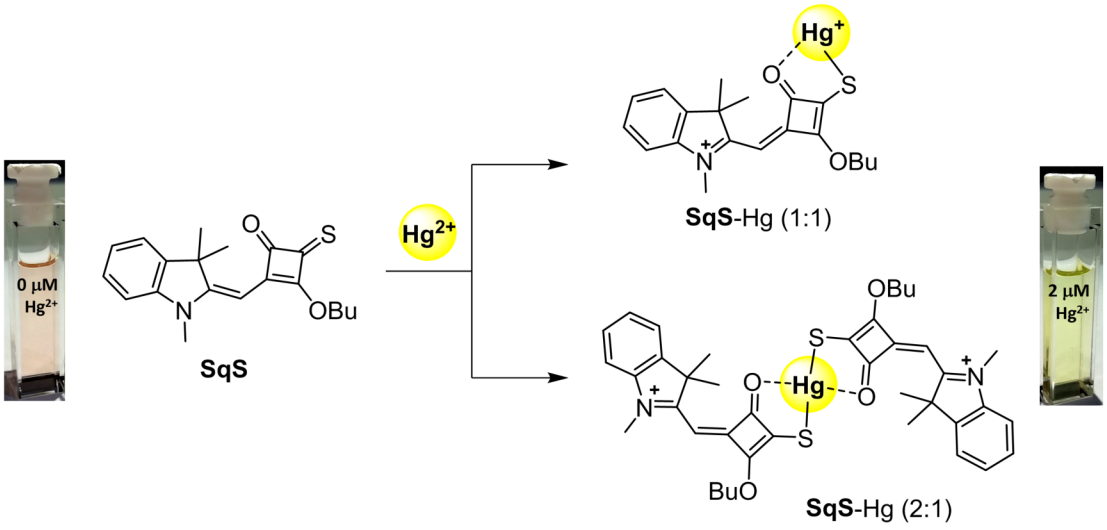
1. Introduction

The rapid development of industry, agriculture, and mining leads to the pollution of our environment with toxic metals, among which mercury (II) is one of the most hazardous metal pollutants [1]. Due to its high affinity for the SH-groups of amino acids, proteins, and enzymes, mercury (II) can be easily accumulated in living organisms, causing irreparable damage to metabolic processes. Since mercury (II) is widely distributed in air, water, soil, and even food, the effective determination of Hg^{2+} ions is an urgent and important task [2,3].

Traditional methods for detecting Hg^{2+} ions include electrochemical analysis, atomic absorption/emission spectroscopy, inductively coupled plasma mass spectrometry, X-ray fluorescence spectrometry, etc. [4–7]. Although each of these methods has certain advantages, their use in Hg^{2+} testing is somewhat limited by factors such as the need for specialized personnel, high instrument costs and maintenance, and complex operational procedures. On the other hand, optical methods such as absorption spectroscopy, which detect changes in absorption spectra or even visual color identification, do not have such problems. As a result, in recent years, more researchers have focused on developing organic small-molecule chemosensors for detecting mercury ions [8–10]. Compared to traditional mercury detection methods, small-molecule chemosensors have gained significant attention due to their numerous advantages. These include their non-invasive nature, portability for field applications, ease of use, and ability to provide rapid real-time detection. Additionally, chemosensors offer superior sensitivity, selectivity, and bioimaging capabilities, making them highly effective for detecting mercury in both environmental and biological systems [8,11–13]. Chemosensors identify mercury ions through specific recognition groups, making the choice of these groups crucial. Among the various options, sulfur-containing recognition groups are often preferred for detecting mercury ions due to their high selectivity, strong reactivity, and favorable photophysical properties [14,15].

Among the diverse small-molecule sensors [10], we focused on polymethine-based ones, as they are increasingly favored for chemosensing due to several key advantages, including high photostability, good solubility, and intense absorption and fluorescence, all of which contribute to enhanced sensitivity [16]. While cyanine [17,18], hemicyanine [19,20], and squaraine [21–23] dyes have been extensively studied, semisquaraine dyes remain relatively underexplored as sensors for mercury detection [24,25].

In this work, we investigate the application of indolenine-based semisquaraine dye **SqS** as a probe for the selective detection of mercury ions (Scheme 1). Our study focuses on the molecular interactions between the dye and mercury ions, examining how these interactions influence spectral properties. The aim of the study is also to develop a new mercury-sensitive sensor based on a small organic molecule.



Scheme 1. The formation of **SqS**-Hg^{2+} complexes: assumed structures with 1:1 and 2:1 stoichiometry.

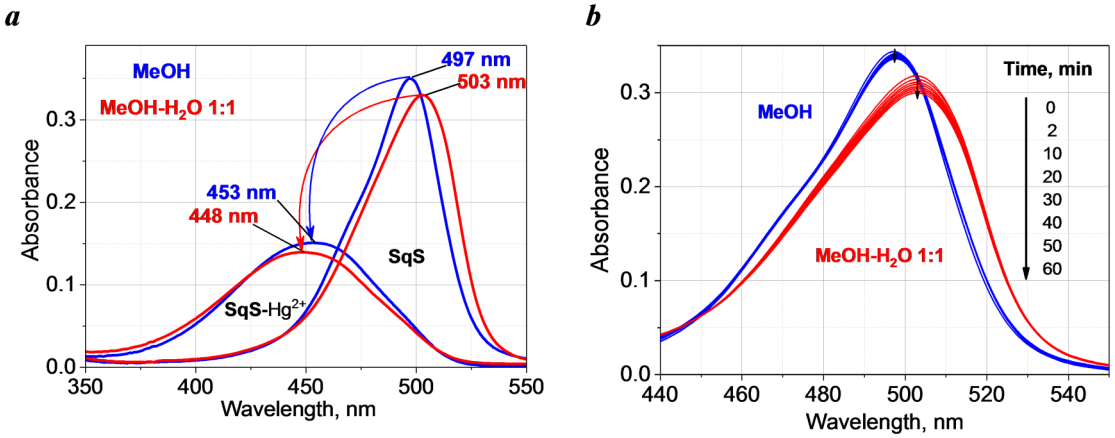


Fig. 1. UV–Vis absorbance spectra of **SqS** (c = 3 μM) solutions in the presence of $Hg(NO_3)_2$ (c = 100 μM) (***a***) and in the presence of HNO_3 (c = 21 mM) (***b***) in MeOH (*blue lines*) and in a mixture of MeOH–H_2O (1:1, v/v) (*red lines*).

2. Experimental

All chemicals were purchased from commercial suppliers and used without further purification. The synthesis procedure for **SqS** was previously reported by our research group [26]. To study the formation of a complex between **SqS** and various metal ions, $HgCl_2$ and the standard sample solutions of metal ions were used, *i.e.* 1 mg/mL LiCl in 0.01 M HCl, 1 mg/mL NaCl in water, 1 mg/mL KCl in water, 1 mg/mL $Mg(NO_3)_2$ in 0.1 M HNO_3, 1 mg/mL $Ca(NO_3)_2$ in 0.1 M HNO_3, 1 mg/mL $Ba(NO_3)_2$ in 0.1 M HNO_3, 10 mg/mL $Al(NO_3)_3$ in 1 M HNO_3, 1 mg/mL $Pb(NO_3)_2$ in 1 M HNO_3, 10 mg/mL $Cu(NO_3)_2$ in 1 M HNO_3, 1 mg/mL $AgNO_3$ in 1 M HNO_3, 10 mg/mL $Zn(NO_3)_2$ in 1 M HNO_3, 1 mg/mL $Cd(NO_3)_2$ in 1 M HNO_3, 1 mg/mL $Hg(NO_3)_2$ in 1 M HNO_3, 10 mg/mL $Fe(NO_3)_3$ in 1 M HNO_3, 1 mg/mL $Co(NO_3)_3$ in 1 M HNO_3, 1 mg/mL $Ni(NO_3)_3$ in 1 M HNO_3. All standard sample solutions were purchased from Special design and technological bureau with research production A.V. Bogatsky Physico-Chemical Institute.

All the *absorption spectra* were recorded in 1 cm quartz cells at 25 °C using a PerkinElmer Lambda 35 UV/Vis spectrophotometer. Absorption maxima were determined with an accuracy of ±0.5 nm and were rounded.

Mass spectra were measured on a mixture of MeOH–H_2O (1:1, v/v) with the addition of 0.01% (v/v) formic acid, using a Waters Micromass Quattro Micro API instrument in electrospray ionization (ESI) positive mode.

3. Results and discussion

3.1. Spectral studies of SqS with Hg^{2+}

We first investigated the effect of Hg^{2+} at a relatively high concentration ($c_{Hg(II)}$ = 100 μM) on the spectral properties of **SqS** (c_{Dye} = 3 μM) in MeOH and in a mixture of MeOH–H_2O (1:1, v/v) (Fig. 1a). A mixture of MeOH–H_2O (1:1) was used to assess the potential application of **SqS** in aqueous systems. Many practical applications of chemosensors, such as environmental monitoring, biological assays, or water quality testing, involve detecting analytes in water. When the sensor itself (as in our case) is poorly soluble in water, mixed solvent systems are used.

In methanol, for a 3 μM solution of **SqS** in the presence of 100 μM $Hg(NO_3)_2$ a change in the spectrum parameters was observed, such as a hypsochromic shift of the absorption maximum from 497 nm to 453 nm, accompanied by a decrease in the intensity of the absorption band in 2.3 times (Fig. 1a). In a mixture of MeOH–H_2O (1:1, v/v), the shift occurred from 503 nm to 448 nm, with a decrease in absorption intensity by 2.4 times (Fig. 1a).

These changes in spectrum parameters may also be associated with the presence of nitric acid, which stabilizes Hg^{2+} in the standard solution. To verify that Hg^{2+} is responsible for the observed spectral changes, we also examined the absorbance properties of **SqS** without the addition of Hg^{2+}, but in the presence of the highest concentration of HNO_3 (c = 21 mM) used during our experiments. When the acid was added, the absorption spectrum of **SqS** remained almost unchanged for at least 1 hour in both methanol and a methanol–water (1:1, v/v) mixture (Fig. 1b), indicating that **SqS** shows the spectral response only to Hg^{2+} under the applied conditions.

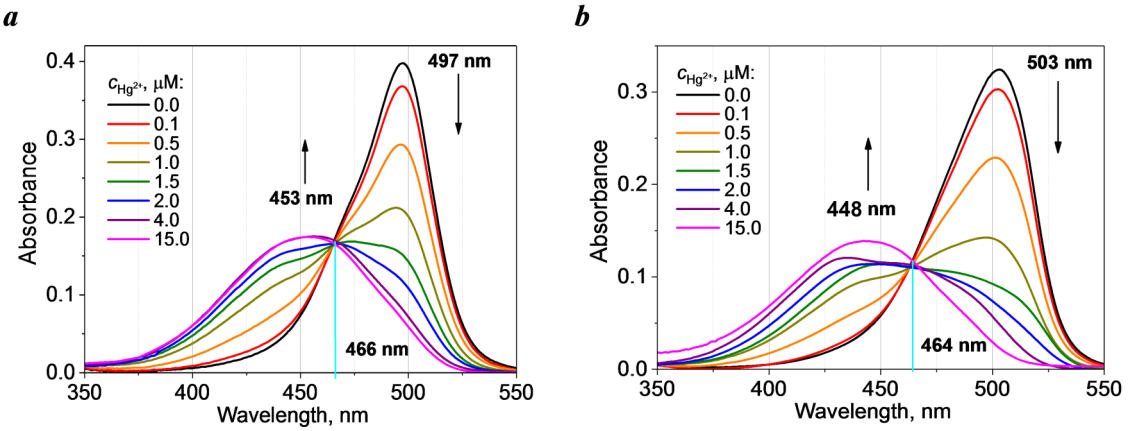


Fig. 2. UV–Vis absorbance spectra of **SqS** (c = 3 μM) solutions containing various concentrations of Hg^{2+} (from 0 μM to 15 μM) in MeOH (***a***) and in a mixture of MeOH–H_2O (1:1, v/v) (***b***).

3.2. Complexation mode

To further investigate the complexation ability of **SqS** and its potential utility as a chemosensing probe, the absorption spectra of **SqS** (c = 3 μM) were measured in the presence of Hg^{2+} at various concentrations in methanol and in a mixture of MeOH–H_2O (1:1, v/v) (Fig. 2). With increasing concentration of Hg^{2+}, we observed a decrease in the absorbance of **SqS** at 497 nm in MeOH (Fig. 2a) with a concomitant increase in absorbance at 453 nm (isosbestic point at 466 nm). This was attributed to the formation of the **SqS**–Hg^{2+} complex. Starting from a certain concentration of Hg^{2+} (*c* = 4 μM) in the solution, the dye **SqS** was almost completely in the complex, as evidenced by the disappearance of the band at 497 nm and the absence of significant changes in the band intensity at 453 nm with a further increase in the concentration of Hg^{2+} ions. Even visually, when adding ~2 μM Hg^{2+} solution, the rapid change in color of the dye solution from light pink to yellow was observed (Scheme 1).

The recognition between **SqS** and Hg^{2+}, studied by absorption spectral titration in MeOH–H_2O (1:1, v/v) (Fig. 2b), revealed a trend similar to MeOH. With the addition of Hg^{2+}, the absorption band at 503 nm gradually decreased, while the absorption at 448 nm increased (isosbestic point at 464 nm). The similar complexation behavior of dyes in methanol and MeOH–H_2O mixture allows us to use only one of these solvent systems. In our further investigations, we preferred to use a mixture of methanol with water.

When analyzing the titration curve, the stoichiometry of binding can also be estimated. The shape and characteristics of the titration curve, such as the inflection points or changes in the slope, provide an indication of how many dye molecules are bound to the target cation. We have plotted the optical absorbance of **SqS** at 503 nm (Fig. 3a) and 448 nm (Fig. 3b) as a function of the Hg^{2+}concentration, obtaining two titration curves, each with its own inflection point: 1.57 μM and 1.76 μM of Hg^{2+}, respectively. Taking into account that the **SqS** concentration was 3 μM, these points correspond to the **SqS**–Hg^{2+} stoichiometry of 1.91:1 and 1.70:1, respectively. This means that more than one dye molecule forms a complex with one Hg^{2+} cation, but the exact stoichiometry cannot be determined from the titration curves. It should be noted that the measurements at a wavelength of 503 nm, turned out to be more accurate than at 448 nm, therefore, we continued measurements only at the 503 nm wavelength.

To determine the stoichiometry of a binding event, Job's plot also known as the continuous variation method was used [27]. The method involves preparing a series of solutions with different ratios of **SqS** and Hg^{2+} while keeping the total concentration constant. By measuring the absorbance, we were able to determine the ratio at which the maximum interaction occurs, corresponding to the stoichiometry of the complex. This ratio corresponds to the break in the linear dependences of optical absorption at 503 nm on molar fraction. The Job plot in Fig. 4a reveals the break at approximately 1.56:1 stoichiometry for the interaction of **SqS** with Hg^{2+}.

Another method that can be used to determine the stoichiometry of a complex, in addition to the Job plot is the molar ratio method [27]. In this method, one component (either ligand or metal ion) is kept constant while the concentration of the other is varied. We measured UV–Vis absorption spectra for the solutions

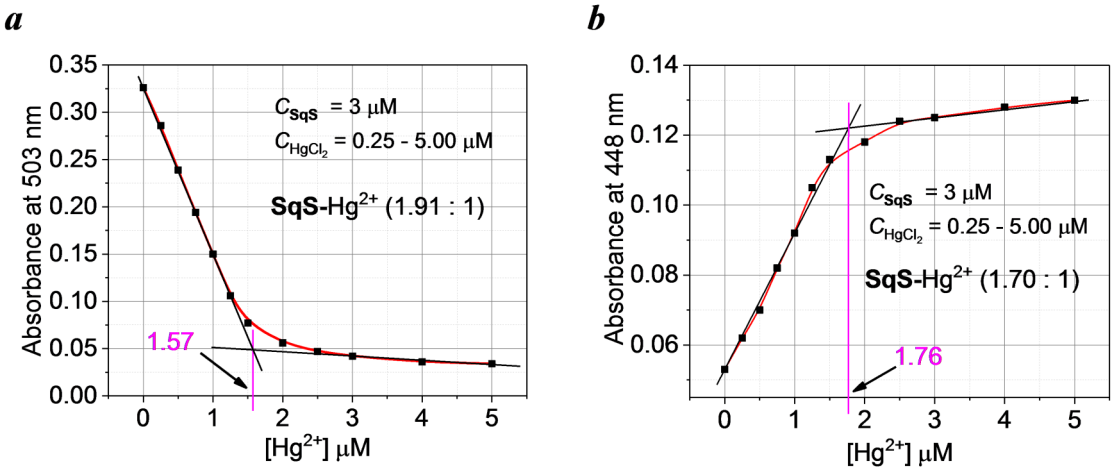


Fig. 3. The absorbance of **SqS**(c = 3 μM) at 503 nm (***a***) and at 448 nm (***b***) *vs.* various concentrations of Hg^{2+}in a mixture of MeOH–H_2O (1:1, v/v).

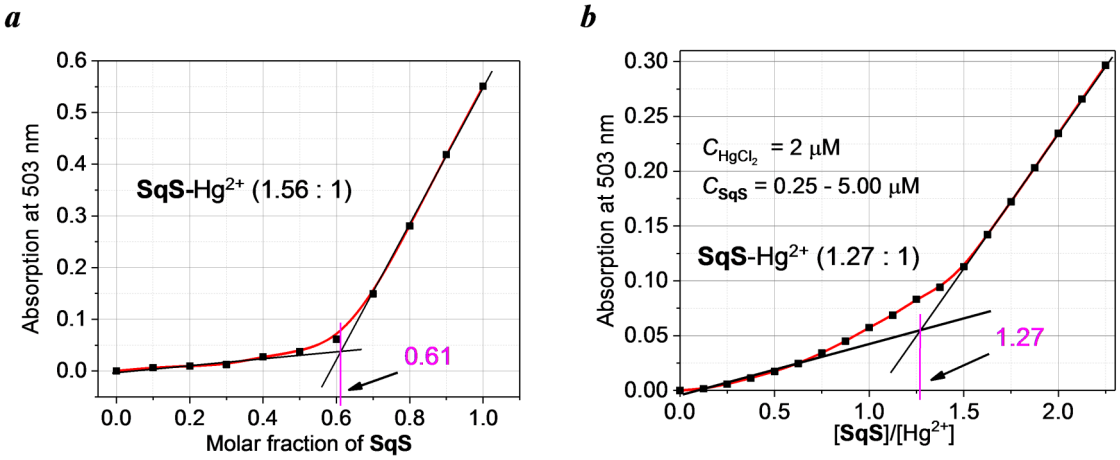
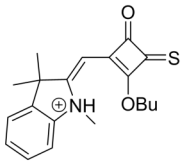
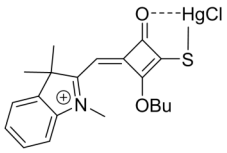
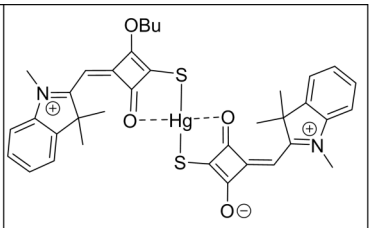
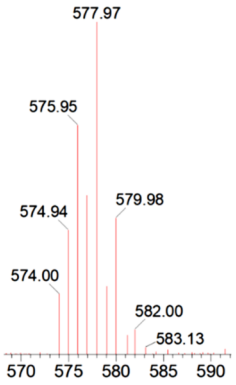
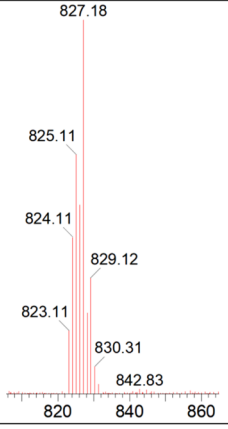


Fig. 4. Job's plot (***a***) for different ratios of **SqS** and Hg^{2+} in a MeOH–H_2O (1:1) mixture for absorption measured at 503 nm. Molar ratio plot (***b***) at a constant concentration of Hg^{2+} (c ~ 2 μM) and varying concentration of **SqS** in a mixture of MeOH–H_2O (1:1, v/v) for absorption measured at 503 nm.

with a constant concentration of $Hg^{2+}$and plotted the results as a function of changing **SqS** concentration normalized to the Hg^{2+} concentration. A break between two linear areas was observed at approximately 1.27:1 stoichiometry for the **SqS** interaction with Hg^{2+} (Fig. 4b). Thus, both methods used showed different values for the stoichiometry of the complex with Hg^{2+}, which suggests the formation of several complexes with different stoichiometry in solution.

Mass spectrometry can be used to directly detect the masses of the complexes formed. The peaks in the mass spectrum correspond to different stoichiometry, and their intensities provide information about the relative content of complexes in the mixture. We measured electrospray ionization-mass spectra (MS-ESI) of the **SqS** solution in a mixture of MeOH–H_2O (1:1, v/v) with the addition of $HgCl_2$ in the molar ratio of 1:1. Fig. 5a confirms that the coordination modes of **SqS** with a Hg^{2+} cation were both 1:1 and 2:1, as indicated by their m/z values (Table 1) for positively charged ions. The relative intensity of the 1:1 complex (m/z = 578.1) was 6 times higher than that of the 2:1 complex (m/z = 827.2). When the excess (10 equiv.) of $HgCl_2$ solution was added, the complex **SqS**–Hg^{2+} 2:1 almost disappeared and the 1:1 complex predominated (Fig. 5b). In both spectra, the signal corresponding to the unbound dye (m/z = 342.2) was absent, indicating that all of the dye had formed complexes. From the mass spectrometry data, it can be concluded that an increase in the amount of Hg^{2+} in the solution leads to a redistribution of the composition of the complexes and a greater tendency to form complexes with a 1:1 ratio.

Table 1. — Assumed structures, mass spectra and m/z distribution for **SqS** and **SqS**–Hg^{2+} complexes.

Assumed structure of molecular ion in MS-ESI+			
Mass spectrum measured			
Mass spectrum, calculated m/z values	Chemical Formula: $C_{20}H_{24}NO_2S^+$ Exact Mass: 342.2 m/z: 342.2 (100.0%), 343.2 (21.6%), 344.1 (4.5%), 344.2 (2.2%)	Chemical Formula: $C_{20}H_{23}ClHgNO_2S^+$ Exact Mass: 578.1 m/z: 578.1 (100.0%), 576.1 (74.7%), 575.1 (42.1%), 577.1 (58.8%), 574.1 (24.9%), 580.1 (41.0%), 579.1 (26.6%), 582.1 (5.5%)	Chemical Formula: $C_{36}H_{37}HgN_2O_4S_2^+$ Exact Mass: 827.2 m/z: 827.2 (100.0%), 825.2 (57.7%), 824.2 (42.1%), 826.2 (59.1%), 828.2 (29.0%), 823.2 (24.9%), 829.2 (17.1%), 830.2 (6.7%)

3.3. Characterization of SqS as a chemosensor for Hg^{2+}

To assess the suitability of a dye as an effective chemosensor, several key parameters and properties need to be evaluated. These properties ensure that the dye can selectively, sensitively, and reliably detect the target analyte (such as metal ions, small molecules, or environmental toxins). We checked the major criteria to demonstrate the applicability of **SqS** as a chemosensor for detecting Hg^{2+} ions. The measurements were carried out in a MeOH–H_2O (1:1, v/v) mixture to simulate an aqueous medium.

3.3.1. Selectivity

A highly selective response to the target Hg^{2+} ions compared to other competing metal ions is very important for environmental probes, and essential for their potential application in the analysis of complex samples. We found that the colorimetric changes of **SqS** were specific only for Hg^{2+} ions and no obvious color change or any other significant effect on the spectrum parameters were observed when adding 100 μM other cations, *i.e.* alkali metals (Li^+, Na^+, K^+), alkaline earth metals (Ba^{2+}, Mg^{2+}, Ca^{2+}), transition metals (Ni^{2+}, Cu^{2+}, Co^{2+}, Fe^{3+}, Cd^{2+}) and post-transition metals (Al^{3+}, Pb^{2+}) into the 15 μM **SqS** solution in a mixture of MeOH–H_2O (1:1, v/v) (Fig. 6).

Additionally, these cations were checked for interference with the detection of Hg^{2+}. We observed changes in the absorption spectra only upon the addition of 2 μM Hg^{2+} to a solution of 2 μM **SqS** that contained 100 μM of other metal ions. Thus, the presence of above-mentioned cations did not interfere with the determination of Hg^{2+}, which proves the high selectivity of the **SqS** probe with respect to Hg^{2+}.

3.3.2. Calibration curve

The concentration range over which the sensor response varies linearly with the analyte concentration is known as the linear response range. The linearity within this range

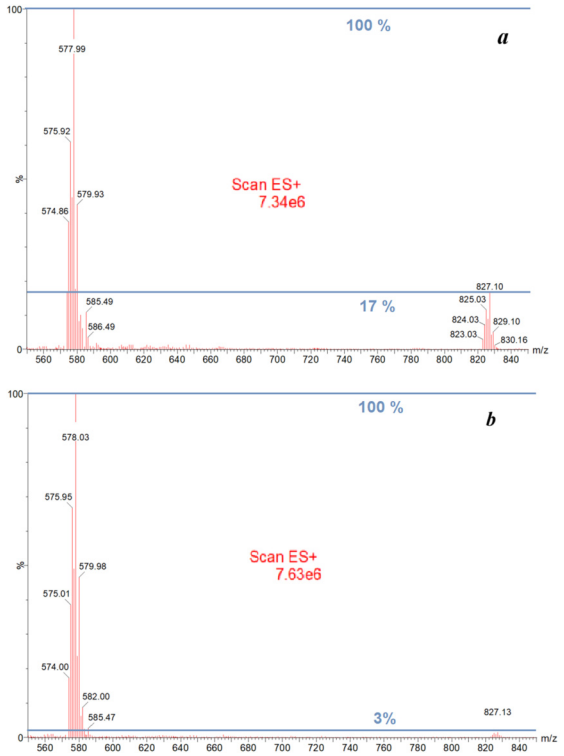


Fig. 5. Mass spectra of the complexes formed in a solution of **SqS** in a MeOH–H_2O (1:1, v/v) mixture with the addition of 1 (***a***) and 10 (***b***) equiv. of $HgCl_2$.

indicates the ability to produce responses that are directly proportional to the concentration of the analyte. As demonstrated in Fig. 3a, the linearity is observed in the region of 0–1.50 μM Hg^{2+}, suggesting that within this interval the **SqS** probe (3 μM) can provide reliable and consistent results for Hg^{2+} determination. To establish the key analytical parameters of the proposed procedure, the absorption spectra of **SqS** (c_{Dye} = 3 μM) were measured for various Hg^{2+} concentrations (0, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50 μM). By plotting the absorbance at 503 nm versus the Hg^{2+} concentration, a linear calibration curve was obtained with the regression equation $y = a + bx$, where y is the signal response, a is the y-intercept, x is the analyte concentration, and b is the slope of the calibration line (Fig. 7).

Thus, we obtained the equation $y = 0.329\pm0.002 - 0.175\pm0.003\times x$, which allows the unknown concentrations of Hg^{2+} to be determined by interpolation the measured absorbance value. Taking into account the R^2 value of 0.998, which is very close to 1, we can conclude that the linear relationship between the Hg^{2+} concentration and the measured response is very strong. This indicates that the calibration model fits the data extremely well and the technique used for quantification is highly reliable.

3.3.3. Limit of detection (LOD), limit of quantification (LOQ) and dynamic range

The limit of detection (LOD) is the lowest concentration of an analyte that can be reliably detected, though not necessarily quantified, under the experimental conditions. It is determined as the concentration corresponding to a signal that is 3.3 times higher than the noise level and is calculated using the formula: LOD = 3.3×σ/b, where σ is the standard deviation of the response at 0 μM Hg^{2+} concentration, which is equal to the standard deviation of the Y-axis intercept. The LOQ is the lowest concentration at which the analyte can be quantitatively determined with acceptable precision and accuracy. It is calculated as: LOQ = 10×σ/b. In our experiments under the proposed measurements conditions, the LOD was calculated to be 0.038 μM and the LOQ was 0.114 μM.

The dynamic range, defined as the range of concentrations over which the analyte can be accurately quantified, spans from the LOQ to the point where the calibration curve begins to deviate from linearity. In our case, this range extends from 0.11 to 1.50 μM Hg^{2+}.

Fig. 6. Photograph of **SqS** (c = 15 μM) solutions in a mixture of MeOH–H_2O (1:1, v/v) in the presence of various metal ions (c = 100 μM).

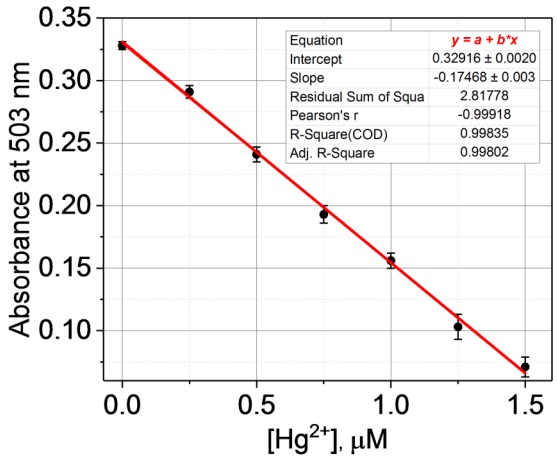


Fig. 7. Calibration curve of **SqS** (c = 3 μM) absorbance at 503 nm versus corresponding Hg^{2+} concentrations

4. Conclusions

We explored the potential of using the indolenine-based semisquaraine dye **SqS** as a sensor for mercury detection by investigating its complexation with Hg^{2+} in aqueous media.

1. Addition of Hg^{2+} to a **SqS** solution causes changes of spectrum parameters, namely a hypsochromic shift in the absorption band, as well as a decrease in its intensity by more than two times. The accompanying noticeable color change from light pink to yellow allows visual detection of Hg^{2+}.

2. The binding characteristics of **SqS** examined using Job's plot, molar ratio methods, and mass spectrometry, revealed the formation of both 1:1 and 2:1 **SqS**–Hg^{2+} complexes in solution.

3. The investigated probe **SqS** can serve as an effective sensor for the selective and reliable colorimetric and spectroscopic detection of mercury ions in environmental samples, with a dynamic range from 0.11 to 1.50 μM Hg^{2+} and a detection limit (LOD) of 38 nM under proposed measurement conditions.

Acknowledgments

This work was supported by the project of National Academy of Sciences of Ukraine "New supramolecular extraction systems for analytical separation, concentration and determination of transition metals".

References

1. Natasha, M. Shahid, S. Khalid et al., *Sci. Total Environ.*, **711**, 134749 (2020).
2. B. Gworek, W. Dmuchowski, A. H. Baczewska-Dąbrowska, Environ. *Sci. Eur.*, **32**, 128 (2020).
3. L. Wang, D. Hou, Y. Cao et al., *Environ. Int.*, **134**, 105281 (2020).
4. G. Xu, P. Song, L. Xia, *Nanophotonics,* **10**, 4419 (2021).
5. K. E. Kristian, S. Friedbauer, D. Kabashi et al., J. Chem. Educ., 92, 698 (2015).
6. J. Švehla, R. Žídek, T. Ružovič et al., *Spectrochim. Acta Part B At. Spectrosc.*, **156**, 51 (2019).
7. K. Pytlakowska, K. Kocot, B. Hachuła et al., *Spectrochim. Acta Part B At. Spectrosc.,* **167**, 105846 (2020).
8. R. Iftikhar, I. Parveen, Ayesha et al., *J. Environ. Chem. Eng.,* **11**, 109030 (2023).
9. D. Udhayakumari, *J. Incl. Phenom. Macrocycl. Chem.*, **102**, 451 (2022).
10. S. Chakraborty, K. Das, S. Halder, *Inorganica Chim. Acta*, **566**, 122026 (2024).
11. L. Wang, Y. Ma, W. Lin, *J. Hazard. Mater.*, **461**, 132604 (2024).
12. Y. Wang, L. Zhang, X. Han et al., *Chem. Eng. J.*, **406**, 127166 (2021).
13. H. Shuai, C. Xiang, L. Qian et al., *Dyes Pigm.*, **187**, 109125 (2021).
14. L. Ma, C. Liu, H. Zhu et al., *Dyes Pigm.*, **220**, 111595 (2023).
15. G. Bjørklund, G. Crisponi, V. M. Nurchi et al., *Molecules*, **24**, 3247 (2019).
16. M. Matsui, in: Progress in the Science of Functional Dyes, Springer Singapore, Singapore (2021), p. 3–19.
17. Y. Li, Y. Qi, Z. Xu et al., *Color. Technol.*, **138**, 427 (2022).
18. G. Li, Y. Guan, F. Ye et al., *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.*, **239**, 118465 (2020).
19. S. Fang, L. Zhang, Y. Zhao et al., *Sens. Actuators B Chem.*, **411**, 135768 (2024).
20. Y. Wang, X. Hou, Z. Li et al., *Dyes Pigm.*, **173**, 107951 (2020).
21. C. V. Esteves, J. Costa, H. Bernard et al., *New J. Chem.*, **44**, 6589 (2020).
22. H. Zhu, J. Fan, H. Chen et al., *Dyes Pigm.*, **113**, 181 (2015).
23. K. Ilina, W. M. MacCuaig, M. Laramie et al., *Bioconjug. Chem.*, **31**, 194 (2020).
24. R. R. Avirah, K. Jyothish, D. Ramaiah, *Org. Lett.*, **9**, 121 (2007).
25. J.-S. Bae, Y.-A. Son, S.-H. Kim, *Fibers Polym.*, **10,** 403 (2009).