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A New Indole Substituted Biphenyldiamine Derivative Schiff Base: A New Sensor Application for the Selective Detection of Hg(II) Ions

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Abstract—A new indole-based biphenyldiamine derivative was synthesized, characterized and a Hg(II) cations sensing application was performed. Within the possible competing cations, our probe gives a selective fluorescence-quenching response towards Hg(II) cation. The limit of detection was found as 169 nM. Time dependent-DFT calculation was also performed to understand the sensing mechanism.

Keywords: sensor, Hg(II) cations, Schiff base, fluorescence, TD-DFT, fluorescence turn-off

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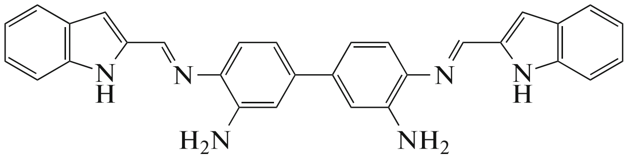
INTRODUCTION

Because of the growing global population, mankind faces new struggles for survival every day. Most of the main threats to life on earth are industrial waste which causes serious environmental problems as a result of their toxic substances released in the industrial processes [1]. Heavy metals, which are poisonous and non-degradable, are a major environmental contaminant and hence tending to build up through the food chain in animals and humans [2–4]. According to WHO's list concerning human health released in 2017, four heavy metals, including plum, cadmium, mercury and arsenic are listed as ten dangerous chemical substances or a combination of chemical products [5]. Among the heavy metals, mercury, with its high toxicity and bio-accumulative dissemination, is the most dangerous pollutant to be considered, because, Hg(II) damage the central nervous system, DNA, mitotic and endocrine system by blocking proteins, enzymes and membranes [6–8]. Mercury emission is caused by a variety of natural factors, including oceanic, volcanic, and anthropogenic influences such as gold mining and waste and fossil fuel combustion [9]. Today, techniques such as titrimetric, voltammetric, potentiometric, and chromatographic approaches which need the use of advanced instrumentation methods are used to detect mercury ions. Because of its serious hazardous effects on human health and the environment, there is a strong need to establish a simple and inexpensive method to determine mercury. Here we report a one-pot synthesized and selective fluorescence-quenched sensor for mercury ion (**I**), its structure is shown in Scheme 1.



I

Scheme 1.

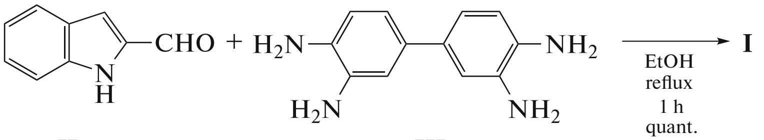
EXPERIMENTAL

All reagents were purchased from Sigma-Aldrich and ACROS and used without further purification. Analytical thin-layer chromatography (TLC) was performed on Kieselgel F-254 precoated aluminum sheet TLC plates purchased from Merck. Visualization was performed under an ultraviolet lamp. Column chromatography was carried out with silica gel (60, 230–400 mesh). HRMS data were recorded by Agilent Technologies, 6224 TOF LC/MS-T1200 Series, applying the electrospray technique. The NMR spectra were recorded on a Bruker Instrument Avance Series-Spectrospin DPX-400 Ultrashield instrument in $CDCl_3$, and DMSO-d_6. The chemical shifts are reported in parts per million (ppm) downfield from an internal TMS (trimethylsilane) as the internal reference. Electronic absorption spectra in solution were acquired using a Shimadzu UV-3600 Plus UV–Vis-NIR spectrophotometer. Fluorescence spectra were determined on an Agilent Cary Eclipse fluorescence spectrophotometer.

Synthesis of 4,4'-bis((-(1*H*-indol-2-yl)methylene)amino)-[1,1'-biphenyl]-3,3'-diamine (I). 290.3 mg of indole-2-carboxaldehye (**II**) (2 mmol) was dissolved in 15 mL of EtOH and added (214.3 mg of 3,3'-diaminobenzidine (**III**) (1 mmol). The resulting mixture was reflux for refluxed for 1 h. After completion of the reaction (monitored by TLC) light brown precipitate was collected and washed with 5 mL of cold EtOH for three times. The compound **I** was obtained quantitatively as light brown solid. ^{1}H NMR (400 MHz; DMSO; δ, ppm): 5.65 (s., 2H, $-NH_2$), 6.84 (d.d., *J* = 8.3, 2.0 Hz, 1H), 6.99 (d., *J* = 2.2 Hz, 2H), 7.05 (t., *J* = 7.7 Hz, 1H), 7.24 (t., *J* = 7.9 Hz, 1H), 7.36 (d., *J* = 8.3 Hz, 1H), 7.46 (d., *J* = 7.9 Hz, 1H), 7.65 (d., *J* = 7.7 Hz, 1H), 8.76 (s., 1H, imine =CH), 11.67 (s., 1H, indole NH). ^{13}C NMR (100 MHz; DMSO; δ, ppm): 108.5, 112.1, 112.7, 114.8, 116.9, 120.1, 121.9, 124.4, 128.4, 133.4, 137.5, 138.1, 140.2, 145.5, 145.6. IR (ATR, cm^{-1}) 3057 (N–H), 1701 (C=N), 1601 (C=C), 1394 (C–N), 1337 (C–N). HRMS (ESI-TOF) for $C_{30}H_{22}N_6$ $[M-2H]^{2+}$ (*m/z*): 233.0952 (calc.), 233.0927 (found). Δ = 10.7 ppm.

RESULTS AND DISCUSSION

Our present work describes easy and short synthesis of a new indole substituted biphenyldiamine derivative Schiff base (L^1) and its sensor application in acetonitrile solution. For the synthesis of compound L^1, indole-2-carboxaldehyde (L^2) [6] was reacted with [1,1'-biphenyl]-3,3',4,4'-tetraamin (L^3) in EtOH medium. After 1 h reflux, the desired compound L^1 was obtained in quantitative yield (see Scheme 2).



II III

Scheme 2.

After successful synthesis and purification of compound **I**, characterization was performed. Because there is some possible reaction pathway for the formation of more than one product during the reaction. One possible product is the annulation reaction of diamine moiety with the aldehyde functionality yielding to the corresponding benzimidazole rings **V** (Fig. 1). In addition to the benzimidazole ring, tetrasubstituted product in the formation of imines is also possible. One another possible product is compound **I**, resulting from the imine formation reaction. For the imine formation reaction, there are more than one possible product such as symmetric and unsymmetric imines. Thus, to understand the structure of the formed product, advanced characterization processes were required. To clarify the structure of the product, 1D- and 2D-NMR experiments were performed. First, with the help of the ^{1}H NMR spectrum, we could eliminate the tetra-substituted one. In the tetra-substituted case, the must be 2 : 1 integration ratio with the indole and biphenyl aromatic protons (H(2), H(3), H(4) and H(5)). This is not seen in the ^{1}H NMR spectrum. After the elimination of the tetrasubstituted product, our attention was turned to the symmetric and unsymmetric diindole substituted and annulated derivatives. From the point of view of the symmetry, the unsymmetrical product must have two times proton resonance signal numbers to the symmetrical case. As a result, according to the ^{1}H NMR spectrum of the product, the structure must be symmetrical orientation. As for the rest, there are two possible products, symmetric diindole substituted and annulated, benzimidazole ring containing, derivatives. For the determination of the structure 2D-NMR experiments we recorded. With the help of the NMR results, we first assigned all the peaks in ^{1}H and ^{13}C NMR spectra using COSY and HMQC spectra. After successful assignments of all peaks, we then examine the HMBC spectrum to observe the heteronuclear correlation of the H(7) with C(10) and C(11). This correlation can distinguish two possible products from each other. In the case of formation structure **IV** (Fig. 1), there must be a correlation of H(7) with C(10) and no any correlation with C(11). In the case of formation of structure **V**, there must be a correlation of H(7) with C(10) and C(11) in the HMBC spectrum (Fig. 1). According to the HMBC spectrum, H(7) correlates with C(10) but does not correlate with C(11), as a result, the orientation of the product must be in the case of structure **IV** which indicates the reaction yields in the formation of compound **I**.

After elucidation of the structure of compound **I**, our attention was turned to the examination of the ion sensing application. To see the ion affinity of compound **I**, we first prepared a 10 μM solution of compound **I** in acetonitrile. Then, we tested the compound with a broad range of 33.3 μM solution of perchlorate salts of cations, such as Ag, Al, Cd, Co, Cr, Cu, Fe(II), Fe(III), Hg, Mn, Ni, Pb, and Zn ions. According to the spectroscopic analysis, the compound **I** gives response only towards the Hg ion detected in the UV–Vis spectrometer (Fig. 2a). But the

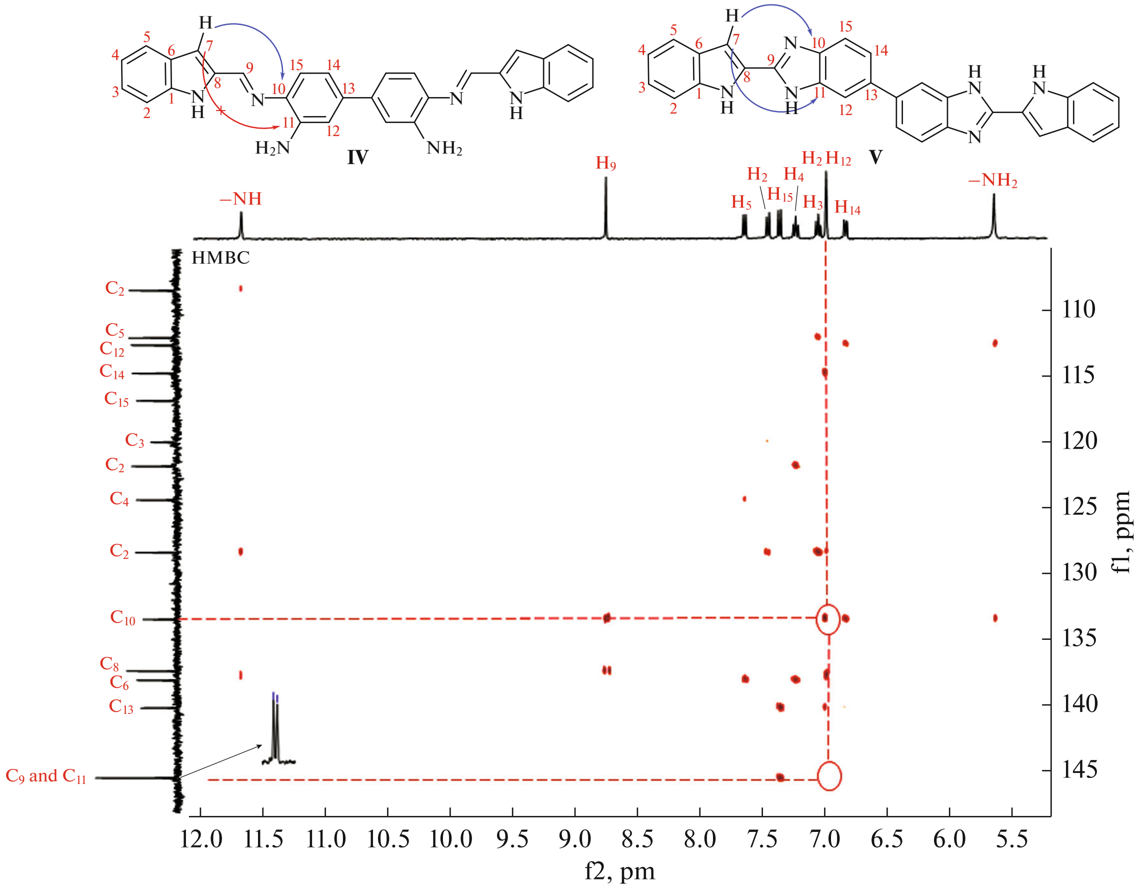


Fig. 1. HMBC spectrum of compound **I**.

fluorescence measurements showed the additional response towards the Pb cation among the 13 cations series (Fig. 2b). As a result, compound **I** gives selectively fluorescence-quenching response to the Hg and Pb ions in acetonitrile solution. To examine the solvent effects, we performed fluorescence measurements in different solvents and acetonitrile was found to show the highest fluorescence intensity over the different solvents with different polarities (Fig. 3a). After finding the best solvent medium, we successively found the complexation ratio by the mole fraction experiments. For this aim, the overall amount of molar concentrations was maintained by a sequence of solutions combining different amounts of the metal. This plot shows us the mole ratio of the ligand and metal is 1 : 2, respectively (Fig. 3b).

The indication of the response of our probe towards Hg and Pb cations was followed by the determination of the binding affinity competition of these two cations. For this aim, we performed analytic titration experiments of 10 μM solution of compound **I** in acetonitrile with the increasing concentration of the cations on both UV–Vis and fluorescence spectrophotometers (Figs. 4a–4d). According to the UV–Vis titration experiments, Hg ions show quick and strong binding affinity by decreasing the absorbance intensity of the ligand under the concentration of 33.3 μM while Pb ions do not give any response (Figs. 4a, 4c). Additionally, in the fluorescence titration experiments of the ligand under the same condition, Hg ions give a full fluorescence-quenching response at the concentration of 23.31 μM (Figs. 4b and 5). But, Pb ions give a small (approximately 20%) response towards our probe at the concentration of 33.3 μM which is a higher concentration than Hg ions full-quenching case. To better understand the full-quenching ability of Pb ions, the probe was treated with the increasing concentration of Pb ions and the fluorescence intensity of the probe was quenched at the concentration of 1000 μM of Pb ions (Fig. 5d). These two results show that our probe is more selective and gives more than 40 times strong affinity towards Hg ions over the Pb ions.

The limit of detection (LOD) and limit of quantification (LOQ) value of the probe was calculated using the standard deviation of the intercept and slope of the linear regression line of probe [10] (see the SI). According to the calculation, LOD and LOQ of the probes were found as 169 and 513 nM, respectively.

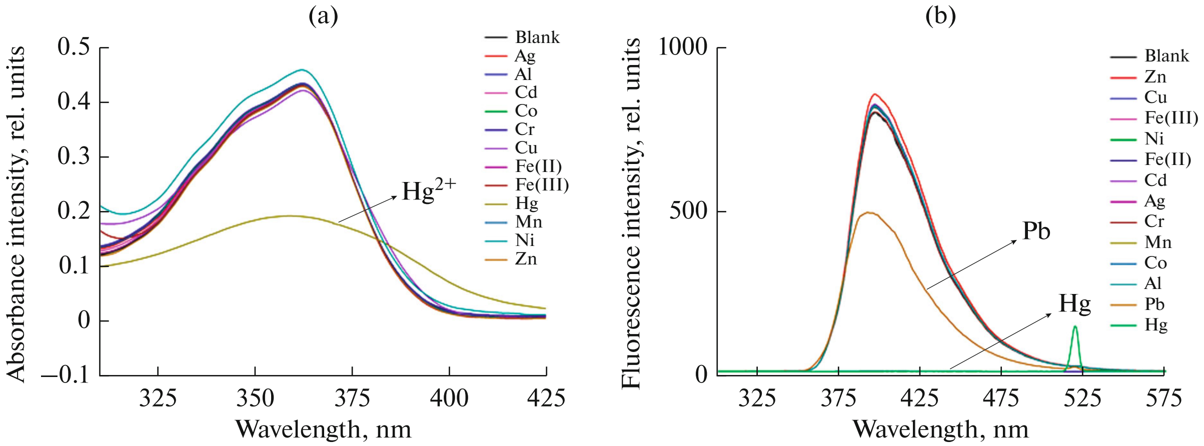


Fig. 2. UV–Vis absorbance (a) and fluorescence (b) spectrums of 10 μM solution of compound **I** with 33.3 μM solutions of different ions.

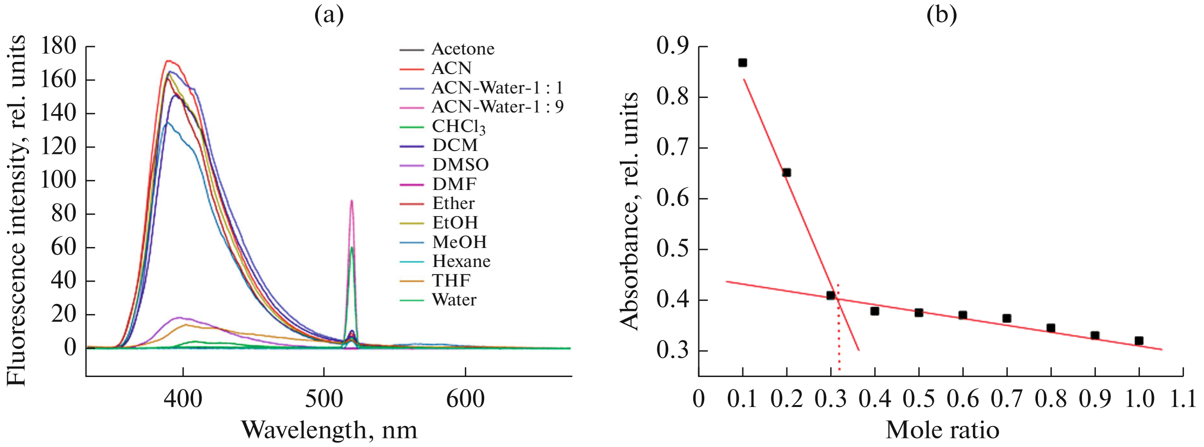


Fig. 3. Fluorescence spectrum of 10 μM solution of compound **I** in different solvents (a); mole ratio graph of the compound **I** with different Hg ion concentrations (b).

These values are considered to be a good position when compared within the literature (see SI) [11].

To better understand photophysical properties, energy changes, and to demonstrate the thermodynamic feasibility of binding of the Hg ion and compound **I**, we also performed gas-phase DFT and the time dependent-DFT (TD-DFT) theoretical calculations in Gaussian 09 program with the Becke three-parameter hybrid exchange function with the Lee—Yang—Parr gradient-corrected correlation functional (B3LYP functional) with LanL2DZ and 6—31G (d, p) as the basis set [12—16]. According to the optimization results, Hg ions are coordinated by three nitrogen atoms of the indole ring, imine and amine functionality. It is located in the position of 2.45, 2.51 and 2.56 Å distance of these three nitrogen atoms, respectively. The optimized structure of the complex is configurated in the *trans*-conformation. This arrangement arises from the steric interaction of the atoms on the aromatic rings (Fig. 6). According to TD-DFT computation results, the main excitation peak of the ligand is caused by the singlet transition of HOMO-1 (S_{-1}) to LUMO (S_1) at 384 nm (3.23 eV) with the oscillator strength of f = 0.7332, which is close to our experimental results, 356 nm. Although, in the ligand-Hg complex case, the contribution of the excitation peak is originated from two main transitions which are HOMO (S_0) to LOMO+1 (S_2) at 422 nm (2.93 eV) with the oscillator strength of f = 0.4841 and HOMO-1 (S_{-1}) to LUMO (S_1) at 388 nm (3.19 eV) with the oscillator strength of f = 0.5429 of the complex. This is supported by the experimental results. Two different absorption peaks are seen at 356 and 390 nm caused by these two different singlet transitions of the probe. Additionally, according to the TD-DFT calculation, binding of Hg cation to the ligand decrease the HOMO energy which increases the HOMO–LUMO gap by 0.01069 a.u.

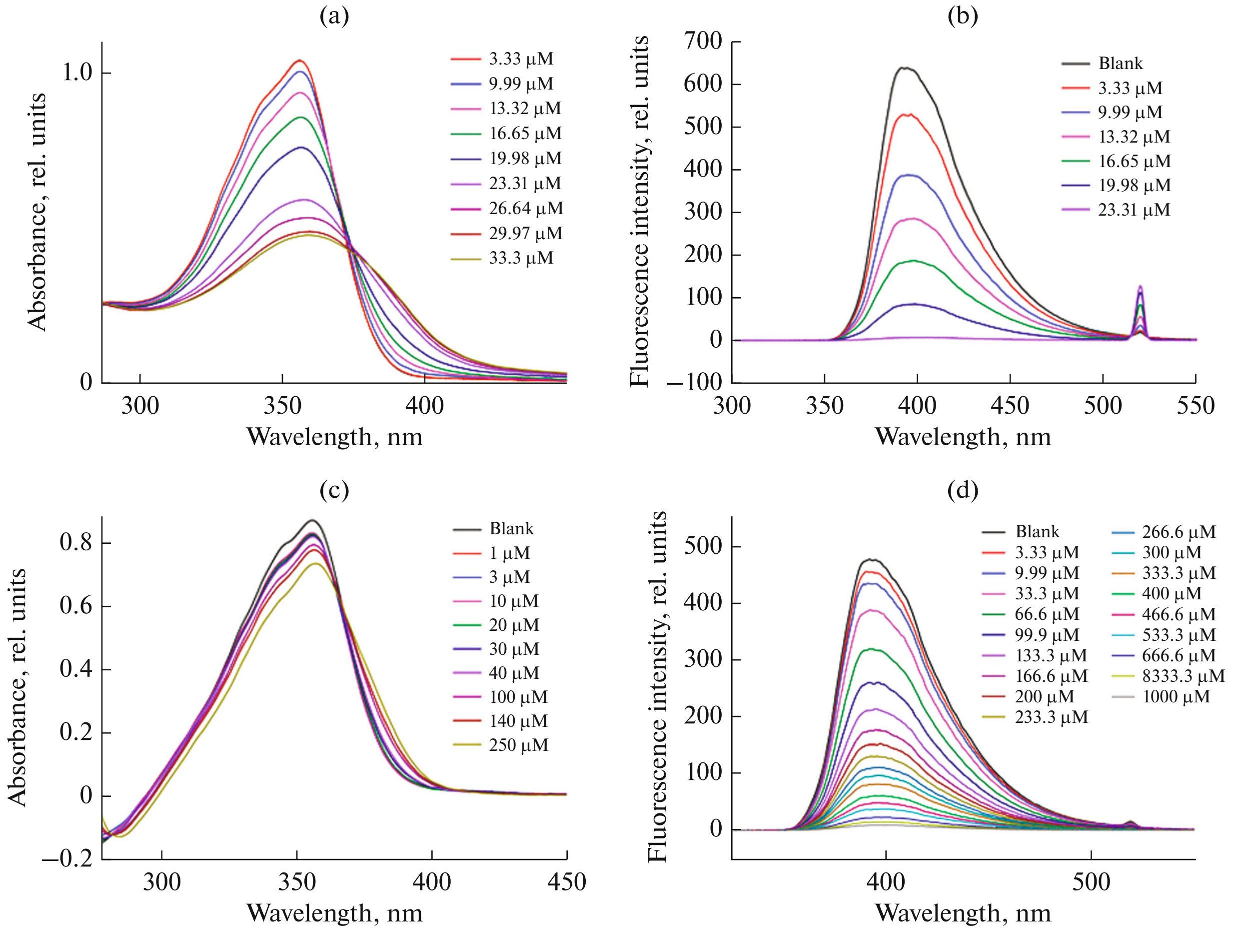
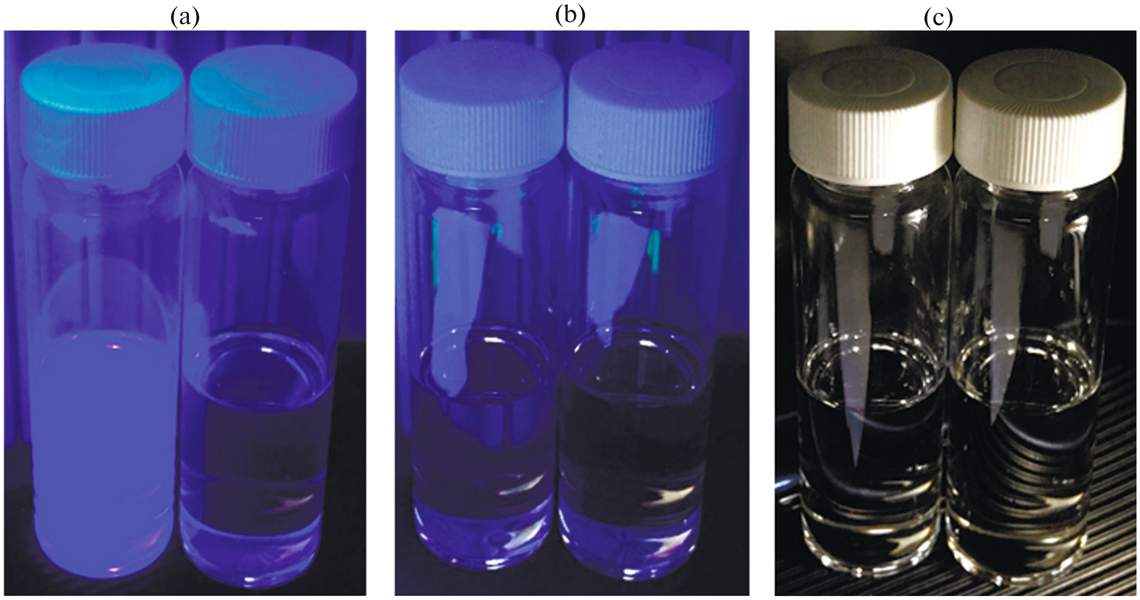


Fig. 4. UV–Vis absorbance (a) and fluorescence (b) spectrums of 10 μM solution of compound **I** with the increasing concent ration of Hg ion; UV–Vis absorbance (c) and fluorescence spectrums of 10 μM solution of compound **I** with the increasing concentration of Pb ion (d).



Fluorecence (366 nm) UV light (254 nm) Day light

Fig. 5. PiPictures of compound **I** (left vial of each picture) and Hg complex of compound **I** (right vial of each picture) under 366 nm light (a), UV light (b) and daylight (c).

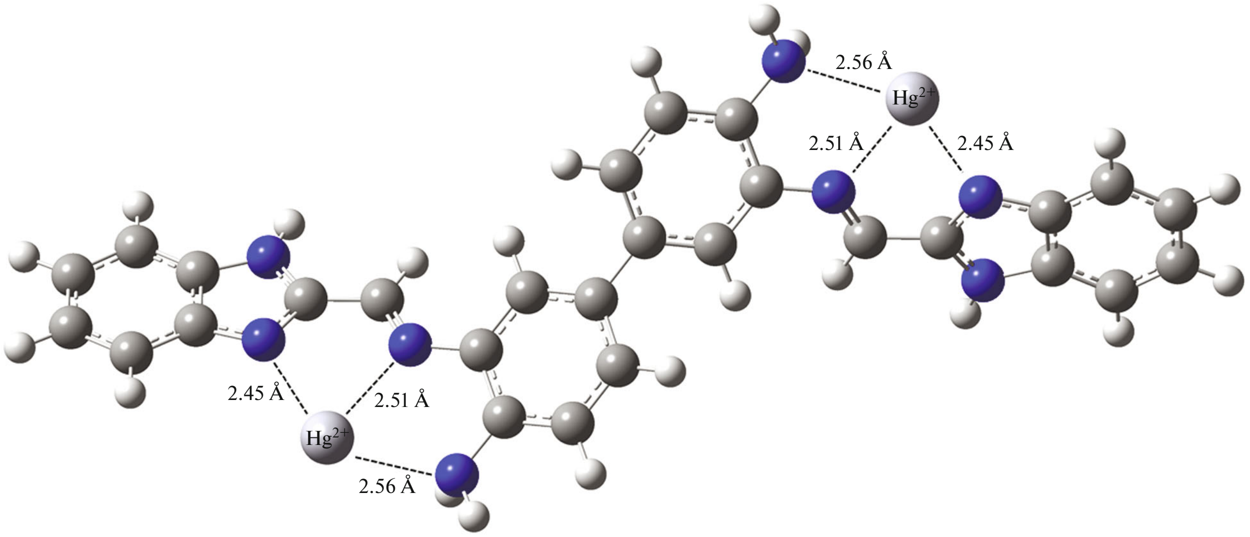


Fig. 6. Optimized structure of the Hg complex of compound **I**.

(70.11 kcal/mole). This can cause the blue shift of the fluorescence of the complex (see the SI) and results in the quenching of the fluorescence intensity [17].

In summary, we have designed and synthesized a new indole substituted biphenyldiamine derivative Schiff base **I**. The fluorometric sensor application was performed and its selective affinity towards Hg ions from 13 different competing cations was obtained. The limit of detection of the compound was found as 169 nM which has a good place compared within the previous studies.

FUNDING

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY MATERIALS

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REFERENCES

1. Chen, G., Guo, Z., Zeng, G., and Tang, L., *Analyst*, 2015, vol. 140, p. 5400.
2. Karakuş, E., Cakan-Akdogan, G., and Emrullahoʇlu, M., *Anal. Methods*, 2015, vol. 7, p. 8004.
3. Karakılıç, E., Durmuş, S., Sevmezler, S., et al., *Bioorganic Med. Chem.*, 2018, vol. 26, p. 76.
4. Ha Na Kim, Wen Xiu Ren, Jong Seung Kim, and Juyoung Yoon, *Chem. Soc. Rev.*,2012, vol. 41, p. 3210.
5. Pomal, N.C., Bhatt, K.D., and Modi, K.M., *J. Fluoresc.*, 2021, vol. 31, p. 635.
6. Gopal, K.V., *Neurotoxicol. Teratol.*, 2003, vol. 25, p. 69.
7. Wang, Y., Ding, H., Wang, S., et al., *RSC Adv.*, 2019, vol. 9, p. 11664.
8. Wang, Y., Ding, H., Zhu, Z., et al., *J. Photochem. Photobiol., A*, 2020, vol. 390, p. 112302.
9. Vasimalai, N., Sheeba, G., and John, S.A., *J. Hazard. Mater.*, 2012, vols. 213–214, p. 193.
10. Zor, E., Alpaydin, S., Arici, A., et al., *Sens. Actuators, B*, 2018, vol. 254, p. 1216.
11. Şahin, S., Caglayan, M.O., and Üstundağ, Z., *Talanta*, 2020, vol. 220, p. 121437.
12. Becke, A.D., *J. Chem. Phys.*, 1993, vol. 98, p. 5648.
13. Lee, C., Yang, W., and Parr, R.G., *Phys. Rev. B: Solid State*, 1988, vol. 37, p. 785.
14. Stephens, P.J., Devlin, F.J., Chabalowski, C.F., and Frisch, M.J., *J. Phys. Chem.*, 1994, vol. 98, p. 11623.
15. Vosko, S.H., Wilk, L., and Nusair, M., *Can. J. Phys.*, 1980, vol. 58, p. 1200.
16. Frisch, M., Trucks, G., Schlegel, H., et al., *Gaussian 09, Revision D.01*, 2009.
17. Afaneh, A.T. and Schreckenbach, G., *J. Phys. Chem., A*, 2015, vol. 119, p. 8106.