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An Ampyrone based azo dye as pH-responsive and chemoreversible colorimetric fluorescent probe for Al³⁺ in semi-aqueous medium: Implication towards logic gate analysis

Gaurav Bartwal^a, Komal Aggarwal^a and Jitender M. Khurana*

A novel ampyrone based azo dye, 4-((6-hydroxybenzo[d][1,3]dioxol-5-yl)diazenyl)-1,5-dimethyl-2-phenyl-1H-pyrazol-3(2H)-one (1), has been synthesized by coupling sesamol and 4-amino antipyrine (ampyrone) and was characterized spectroscopically. The interaction of azo dye (1) with different metal ions has been studied using UV-vis and fluorescence spectra. Chemosensor 1 exhibits high selectivity and sensitivity towards Al^{3+} over other metal ions by fluorescence enhancement in methanol: water (1:1, v/v, at pH = 7.2), which could also be detected directly by the naked eye under visible light. The fluorescence of 1-Al³⁺ complex was found to be reversible in presence of EDTA. pH-dependent absorption behavior of chemosensor 1 was also investigated. It was observed that, chemosensor 1 could also be used as selective 'naked-eye' colorimetric sensor for H⁺, and displayed a very strong red shift in the absorption band from 492 nm to 540 nm with a notable color change from yellow to violet-blue. Moreover, the chemosensor 1 showed keto-enol tautomerization in the presence of acidic media and both forms have been confirmed by ¹H and ¹³C NMR spectra. Practical applicability of sensor 1 has been further explored by use of sensing strip analysis which allows rapid detection of Al³⁺ and H+ ions. NMR and DFT optimized geometries of 1 suggest that the compound is present in the azo form (enol form) in the ground state. In addition, one INHIBIT logic gate was constructed based on multi-responsive properties of 1 induced by Al³⁺ and EDTA²⁻ which contained two input signals (In1: AI³⁺, In2: EDTA) and an output signal (O1: Fluorescence intensity at 613 nm. The chemosensor 1 exhibited a high association constant with a detection limit of $3.55 \times 10-7$ M for A^{3+} in MeOH-water solution

Introduction

Aluminium is the most abundant metallic element found naturally on the planet comprising just over 8% of the earth's crust. It is also third most abundant of all elements after oxygen and silicon, and exits in nature in its ionic form Al³⁺. Aluminum and its alloys have diversified applications in our lifestyles, such as packaging materials, food additives, cooking utensils, building constructions etc.^{1,2} The content of dissolved aluminium in water and soil increased due to acid rain, results in the inhibition of plant growth³ and thus, most foods contain at least trace amount of aluminium. Food products containing aluminium based food additives have a higher amount of aluminium than natural level.

^aDepartment of Chemistry, University of Delhi, Delhi-110007, India *Corresponding author. Tel.: +91 11 2766772; fax: +91 11 27667624 E-mail addresses: <u>imkhurana1@yahoo.co.in</u> According to WHO, the average admissible value of Al³⁺ ions that human can intake is about 7 mg/kg of the body weight.^{4,5} Over accumulation of aluminium in our body may not only lead to the failure of nervous system but can also cause a wide range of diseases like Al-related bone disease (ARBD), idiopathic Parkinson's disease, impairment of memory and Alzheimer's disease, microcytic hypochromic anemia, amyotrophic lateral sclerosis, dementia etc.⁶⁻⁹ Therefore, the detection of Al³⁺ is essential to control its impact on the human health as well as on the environment.

In recent years, bipyridine, rhodamine, diazafluorene and naphthol functionalized fluorescent Schiff bases have been designed for Al³⁺ detection but lack of spectroscopic characterization, poor binding ability and strong hydration ability¹⁰⁻¹³ makes these sensors less compelling. Moreover, azo dye based probes have not been extensively explored in the literature for the selective sensing of aluminium ion. The detection of Al³⁺ is commonly interfered by

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other trivalent metal ions like In³⁺, Fe³⁺, Cr^{3+,} and Ga³⁺ in the binding process due to similarity in electronic configuration.¹⁴⁻¹⁶ Therefore, advancement in the synthesis of sensitive, selective and reversible Al³⁺ probes with improved properties is still in high demand.

Azo dyes have attracted considerable importance in the recent years because of their utilities and applications in the field of indicators, colorimetric probes, dyeing of textile fibers, food additives, pigments and paint industries.¹⁷ An enormous variety of colors with a reasonably simple and rapid synthesis has made azo dye an illustrious mode for developing fluorescent enhancement probes. Incorporation of a bioactive heterocyclic moiety, such as antipyrine, into the backbone of azo dye, would further enhance their applications as colorant and chromophoric strength.¹⁸⁻²²

Recently ampyrone based azo dyes have been synthesized as fluorescent chemosensors for the detection of various metal ions.²³⁻ ²⁶ But no ampyrone azo dye based colorimetric probes are available in the literature for the detection of Al^{3+} . In continuation of our ongoing research on developing novel low cost and efficient fluorescent chemosensors²⁷⁻²⁹, we designed and synthesized a novel azo dye from the coupling of sesamol and ampyrone to investigate its fluorescence properties and role as a metal ion and pH sensor.

Results and Discussion

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Synthesis and characterization of chemosensor (1)

Herein, we report the synthesis of a novel PET (photoinduced electron transfer) based azo dye of ampyrone i.e. 4-((6hydroxybenzo[d][1,3]dioxol-5-yl)diazenyl)-1,5-dimethyl-2-phenyl-1Hpyrazol-3(2H)-one (1) by diazotization of 4-amino-1,5-dimethyl-2phenyl-1H-pyrazol-3(2H)-one followed by the addition of alkaline solution of sesamol at 0-5°C shown in Scheme 1. The novel product 1 has been characterized by ¹H NMR, ¹³C NMR, FTIR, and HRMS. The chemosensor 1 exhibited fluorescence enhancement upon binding with Al³⁺ which was found to be reversible with EDTA and also showed a visible color change from yellow to pink. Moreover, chemosensor 1 showed keto-enol tautomerism in the presence of an acid which was confirmed by ¹H and ¹³C NMR spectra.



Scheme 1: Synthesis of Compound 1

The design of synthesized compound 1 consists of antipyrine fluorophore unit attached to a sesamol ring (receptor) through a azo spacer. Sesamol ring can act as a receptor by transferring lone pair of electrons on oxygen to the antipyrine ring by PET mechanism shown in Fig. 1.



Fig. 1: Design of Azo dye with 'receptor-spacer-fluorophore' PET design.

Effect of metal ions on photophysical properties of 1

The photophysical properties like UV-vis and fluorescence of chemosensor **1** (1 x 10^{-5} M, MeOH : H₂O (1:1, v/v) have been studied by the addition of different metal ions such as Pb²⁺, Cu²⁺, Zn²⁺, Mn²⁺, Cd^{2+} , Hg^{2+} , Sr^{2+} , Co^{2+} , Sn^{2+} , Fe^{3+} , Al^{3+} , Cr^{3+} , La^{3+} , In^{3+} and Th^{4+} , Ni^{2+} , Mg^{2+} , Ca^{2+} , Ba^{2+} , Na^+ in MeOH : H_2O (1:1, v/v) buffered with HEPES solution at pH 7.2.

Absorption spectra

The UV-vis absorption spectrum of chemosensor 1 showed two weak absorption bands in short wavelength region centered at 238 nm, 334 nm and a broad band in the long wavelength range from 394 to 490 nm. Addition of one equiv. of different cations Pb²⁺, Cu²⁺, Zn²⁺, Mn²⁺, Cd²⁺, Hg²⁺, Sr²⁺, Co²⁺, Sn²⁺, Fe³⁺, Cr³⁺, La³⁺, In³⁺ and Th⁴⁺, Ni²⁺, Mg²⁺, Ca²⁺, Ba²⁺, Na⁺ exhibited no effect in the absorption spectrum of **1**. However, the addition of one equiv. of AI^{3+} into 1 x 10^{-5} M, 1:1 MeOH:H₂O solution of **1** resulted in a significant shift in the absorption spectra shown in Fig. 2(a). In the presence of Al³⁺ ions, band at 334 nm showed a bathochromic shift of 18 nm and appeared at 352 nm. The broad band appearing in the range of 394 to 490 nm disappeared completely and a new band appeared in a long wavelength region at 505 nm. The absorption spectrum of 1 has been further investigated in presence of increasing amount of Al³⁺. The broad band at 394 to 490 nm showed diminishment while band at 505 nm showed an enhancement in intensity with the isosbestic point at 460 nm (Fig. 2(b)). These absorption spectral changes

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resulted in a visible color change from yellow to pink in the presence of Al^{3+} ions as detected by the naked eye (Fig. 3). Therefore, **1** can be used as a potential colorimetric chemosensor for the detection of Al^{3+} ions.



Fig. 2: UV-vis spectra of **1** (1 x 10^{-5} M) in MeOH : H₂O (1:1) containing HEPES (0.01 mM, pH=7.2) (**a**) upon addition of 1 equiv. of Pb²⁺, Cu²⁺, Cd²⁺, Zn²⁺, Mn²⁺, Co²⁺, Hg²⁺, Sr²⁺, Sn²⁺, Fe³⁺, Cr³⁺, La³⁺, Th⁴⁺, In³⁺, Al³⁺, Ni²⁺, Mg²⁺, Ca²⁺, Ba²⁺ and Na⁺ metal ions; (**b**) in the presence of varying amount of Al³⁺ (0 - 1 equiv.); Inset: line graph of absorbance intensities of **1** depending on the concentrations of Al³⁺.



Fig. 3: Visual color changes observed in MeOH : H_2O (1:1) solution of 1 (1 x10⁻⁵ M) after addition of 1 equiv. of various metal ions.

Fluorescence spectra

The emission spectrum of chemosensor **1** (1 x 10⁻⁵ M), displayed a very weak band at 587 nm ($\lambda_{ex} = 450$ nm). This weak emission band attributed to the existence of hydrazone form in solution phase which diminishes the population of azo form in the excited state and eventually undergoes photoisomerization.^{30,31} Another possibility for weak fluorescence could be the presence of PET (photoinduced electron transfer). The fluorescence spectrum of **1** was investigated in the presence of one equiv. of various cations Pb²⁺, Cu²⁺, Zn²⁺, Mn²⁺, Cd²⁺, Hg²⁺, Sr²⁺, Co²⁺, Sn²⁺, Fe³⁺, Cr³⁺, La³⁺, In³⁺, Th⁴⁺, Ni²⁺, Mg²⁺, Ca²⁺, Ba²⁺ and Na⁺ No such effect was observed in the emission spectra of **1** as shown in Fig. 4(a). However, a prominent enhancement in the fluorescence intensity of 16 nm from 587 nm to 613 nm. This enhancement in fluorescence intensity could be due to inhibition of PET upon binding with Al³⁺ ions [34].



Fig. 4: Emission spectra of **1** (1 x 10^{-5} M)) in MeOH : H₂O (1:1) containing HEPES (0.01 mM, pH=7.2) buffer solution (a) upon addition of 1 equiv. of Pb²⁺, Cu²⁺, Cd²⁺, Zn²⁺, Mn²⁺, Co²⁺, Hg²⁺, Sr²⁺, Sn²⁺, Fe³⁺, Cr³⁺, La³⁺, Th⁴⁺, In³⁺, Al³⁺, Ni²⁺, Mg²⁺, Ca²⁺, Ba²⁺ and Na⁺ metal ions; (b) in the presence of varying amount of Al³⁺ (0 – 1 equiv.) (λ_{ex} = 450 nm); Inset: line graph of fluorescence intensities of **1** depending on the concentrations of Al³⁺.

The fluorescence response of chemosensor **1** for various concentrations of Al^{3+} ions (0 – 1 equiv.) was also scanned. The fluorescence intensity of **1** was gradually increased upon addition of an incremental amount of Al^{3+} ions and remained steady after the addition of 1 equiv. of Al^{3+} ions, indicating the formation of 1:1 binding mode between **1** and Al^{3+} ions (Fig. 4(b)). Line graph of fluorescence intensities of **1** with varying Al^{3+} concentrations also showed no change in intensity after the addition of 1 equiv. of Al^{3+} ions.

Selectivity and Reversibility of chemosensor 1

The selectivity of chemosensor **1** for AI^{3+} ions was examined by determining the changes in fluorescence intensity of **1**- AI^{3+} complex in presence of various interfering metal ions (Fig. 5). The fluorescence intensity of **1** in presence of 1 equiv. of AI^{3+} ions followed by the addition of 10 equiv. of other metal ions like Pb²⁺, Cu²⁺, Zn²⁺, Mn²⁺, Cd²⁺, Hg²⁺, Sr²⁺, Co²⁺, Sn²⁺, Fe³⁺, Cr³⁺, La³⁺, In³⁺ and Th⁴⁺ was remain unaffected. This clearly indicates that the chemosensor **1** is highly selective for AI^{3+} ions in presence of other competitive metal ions.



Fig. 5: Selectivity of **1** for Al³⁺ on the addition of 10 equiv. of various metal ions.

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Reversibility plays a significant role in the development of a novel chemosensor for practical applicability. Therefore, we also examined the interfering effect of various anions on the emission spectrum of $1-AI^{3+}$ complex. It can be inferred from Fig. 6 that the addition of 5 equiv. of various anions like F⁻, Cl⁻, Br⁻, I⁻, NO₂⁻, SCN⁻, ClO₃⁻, PO₄²⁻, CrO₄²⁻ and SO₃²⁻ to $1+AI^{3+}$ complex has no major effect on the fluorescence intensity but addition of 5 equiv. of EDTA resulted in fluorescence quenching and color change from pink to yellow.



Fig. 6: (a) Effect of various anions on the fluorescence behaviour of (1 + Al³⁺) complex in MeOH : H₂O (1:1) containing HEPES (0.01 mM, pH=7.2) buffer solution (λ_{ex} = 450 nm). (b) Reversible switching of the emission of **1** (1 x 10⁻⁵M) at 613 nm upon alternate addition of Al³⁺ and EDTA. Inset: Images of color change during fluorescence reversibility.

Further addition of AI^{3+} ions to the solution of $1 + AI^{3+} + EDTA$, resulted in the enhancement of fluorescence intensity again along with the color change from yellow to pink, thus confirming the reversible behavior of chemosensor **1** for AI^{3+} ions. Complexation of 1 with AI^{3+} ions and then decomplexation with EDTA is shown in Scheme 2. Therefore, chemosensor **1** could be used as a reversible fluorescent as well as a colorimetric sensor for the detection of AI^{3+} ions. This on-off switching phenomenon could be repeated several times by alternate AI^{3+} and EDTA additions.



Scheme 2: Proposed sequential sensing process of Al³⁺ and EDTA

Determination of Binding Constant and Detection limit

The binding stoichiometry of **1** and Al^{3+} was calculated from Job's plot analysis on the basis of fluorescence (Fig. 7). The Job's plot measurement revealed 1:1 complexation stoichiometry between **1** and Al^{3+} . A graph was plotted by varying the mole fraction of Al^{3+} ions while keeping the resultant concentration of **1** and Al^{3+} constant (1.0 x 10⁻⁵ M). The plot displayed a maximum when the mole fraction of Al^{3+} was nearly half.



Fig. 7: Job's plot for stoichiometric determination of 1 and Al³⁺.

The stoichiometry of **1** and AI^{3^+} was further confirmed by HRMS (ESI, m/z) data analysis. The mass spectrum of **1**- AI^{3^+} complex showed a peak at 478.1198 which corresponds to [(**M** + Al + Cl + 2CH₃OH) + H]⁺ (calcd. m/z: 478.1194, found: 478.1198, Fig. S1). This clearly confirms the formation of 1:1 complex between chemosensor **1** and AI^{3^+} ion. The association constant (K_a) of **1** and AI^{3^+} was obtained from Benesi-Hildebrand plot³² (Fig. 8). The fluorescence titration plot of F_o/(F- F_o) against $1/[M^{n^+}]$ (M^{-1}) based on 1:1 binding mode shows good correlation and the association constant was found to be 5.42 x 10^5 by the ratio of intercept/slope (linearly dependent coefficient R² = 0.9827) which is within the range 10^4 – 10^7 M⁻¹ of other reported sensors for $AI^{3^+, 33}$ This demonstrates the formation of strong complex between **1** and AI^{3^+} .



Fig. 8: Benesi-Hildebrand plot for calculation of binding constant between 1 and AI^{3+} .

Thereafter, the detection limit was calculated from the fluorescence titration data by plotting a graph between normalized fluorescence intensity, $(I - I_{min})/(I_{max}-I_{min})$ and log $[AI^{3+}]$ at 602 nm (Fig. 9) by the

reported methods $.^{34\cdot36}$ A linear curve ranging from 2.82 x 10^{-7} M to 2.5 x 10^{-6} M with the straight relationship was obtained. The intercept at the ordinate axis corresponds to the detection limit of 3.55 x 10^{-7} M which is much lower than the tolerance limit of Al³⁺ in drinking water (1.85 x 10^{-3} M). Therefore, chemosensor **1** is sensitive enough to monitor the quality of drinking water.



Fig. 9: Plot of (I - I_{min})/(I_{max} - I_{min}) vs log [Al³⁺] for the calculation of minimum detection limit for **1**.

Effect of acid and base on chemosensor 1

Effect of pH on the UV-vis absorption spectra of **1** was investigated in MeOH: H_2O (1:1, v/v). pH of the solution was adjusted by adding an appropriate amount of NaOH and HCI. The titration of chemosensor **1** at different pH suggested the existence of tautomerisation between two species (I and II) as shown in Scheme 3. The compound **1** exhibits three absorption bands at 236 nm, 334 nm and 492 nm at pH 7 as shown in Fig. 10. When pH of the solution was increased from 7 to 11, a new broad band appeared at 401 nm which showed hyperchromic shift (enhancement in intensity) and the band at 492 nm showed a hypochromic shift.



Fig. 10: Change in absorption spectra of compound $\mathbf{1}$ (1 x 10⁻⁵ M) in MeOH in presence of acid and base.

Lowering the pH from 7 to 2 resulted in the diminishment of broad band at 401 nm while the band at 492 nm showed an enhancement

in intensity with the appearance of an isosbestic point at 452 nm, which clearly indicates that there are two species in equilibrium. This could be due to the existence of tautomeric form (II) i.e. the keto form of dye **1**. At pH 1, the band at 401 nm disappeared completely and the band at 492 nm showed a strong bathochromic shift of 48 nm and appeared at 540 nm. These spectral changes were also detected by the naked eye as the color of the solution changes from yellow to violet-blue with the change of pH from basic to acidic range (Fig. 11).

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Scheme 3: Two tautomeric structures of compound 1.



Fig. 11: Visual color changes observed in MeOH: $\rm H_2O$ (1:1) solution of 1 (1 $\times 10^{-5}$ M) at different pH.

Sensing with paper strips

The practical utility of chemosensor **1** was explored by paper test strips. Whatman filter papers were dipped in 1×10^{-3} M MeOH: H₂O (1:1, v/v) solution of **1** for 15 minutes and then dried in air. The test strips loaded with probe were then dipped in the Al³⁺ ion solution (1 $\times 10^{-3}$ M in MeOH : H₂O, 1:1, v/v).



Fig. 12: Color changes detected for **1** immobilized on Whatman filter paper, dipped in (a) 1×10^{-3} M MeOH: H₂O (1:1, v/v) solution of **1** (b) 1×10^{-3} M Al³⁺ ion solution in MeOH : H₂O (1:1, v/v) (c) in 0.01 N of aq. HCl (pH = 1) (d) Al³⁺ ion solution followed by EDTA.

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(1mM) in MeOH : H_2O (1:1, v/v). The yellow colored strip was converted to pink when dipped in Al^{3+} ion solution (Fig. 12a). The original yellow color of **1** could be regenerated by dipping pink strip in 1mM EDTA solution (Fig. 12c). Yellow colored strip changed to violet-blue when exposed to 0.01N aq. HCl solution (pH = 1) which allows selective sensing of highly acidic solution as well (Fig. 12b). Development of such strips is so handy for instant on-site sensing analysis which can also negate the dependency on instrumental techniques.

Spectroscopic studies

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NMR spectra in presence of aluminium

The binding ratio of **1** and Al³⁺ has already been calculated by Job's plot. The binding sites of chemosensor **1** and Al³⁺ were identified by recording ¹H NMR spectra of **1** in presence and absence of Al³⁺ in DMSO-d₆. Significant changes were observed in the peak positions in presence of Al³⁺ ions (Fig S2). One phenolic –OH proton at 11.55 ppm in ¹H NMR spectrum of **1** disappeared upon binding with Al³⁺ ions which clearly indicates the coordination between aluminum and oxygen atom as shown in Fig 13 (a and b). The aromatic protons of sesamol ring at $H_a = 7.0$ ppm and $H_b = 6.52$ ppm shifted downfield and upfield and appeared at 7.12 ppm and 6.26 ppm, respectively. One methyl group of antipyrine ring showed a strong downfield shift from 2.36 ppm to 2.68 ppm, clearly indicating the involvement of carbonyl group of antipyrine with Al³⁺. These appreciable changes in ¹H-NMR spectrum of **1** primarily confirm that the coordinative cites of **1** for Al³⁺ were hydroxyl group from sesamol, one nitrogen atom of the azo moiety and carbonyl oxygen of antipyrine ring.

NMR spectra in presence of acid and base

The ¹H and ¹³C NMR spectra of chemosensor **1** in DMSO-d₆ were also recorded in presence of acid. ¹H NMR spectra of **1** in presence of acid (10 μ L HCl) showed the clear disappearance of phenolic –OH group suggesting the formation of keto form (II) in acidic media. This was confirmed by the appearance of a new peak at 207.28 ppm in ¹³C NMR corresponding to the carbonyl carbon of sesamol ring as shown in Fig. 14(b) (Fig S3). Furthermore, both aromatic protons of sesamol ring H_a = 7.0 ppm and H_b = 6.42 ppm shifted downward to 7.38 ppm and 6.78 ppm, respectively in ¹H NMR (Fig. 13(c)). These changes in 1 H and 13 C NMR spectra of **1** confirm that compound **1** exists in hydrazone form in acidic medium.

Change in ¹H NMR of **1** with the addition of base (10 μ L NaOH) was also observed. There was a change in chemical shift of proton H_b in ¹H NMR (shifted upfield from 6.425 ppm to 5.87 ppm) only due to the abstraction of hydroxyl proton as shown in Fig. 13(d). No other significant changes were observed.



Fig. 13: ¹H NMR spectra in DMSO-d₆ of (a) neat 1; (b) 1 in presence of 5 eq. Al^{3+} ; (c) 1 in presence of acid; (d) 1 in presence of base.



Fig. 14: ${}^{13}C$ NMR spectra in DMSO-d₆ of (a) neat 1; (b) 1 in presence of acid.

FT-IR spectral behavior

Binding of chemosensor **1** with AI^{3+} has been further confirmed by IR spectra. The v(O-H) broad band at 3448 cm⁻¹ in free azo dye disappeared when complexed with AI^{3+} . The v(C=O) band at 1604

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cm⁻¹ for **1** shifted to 1637 cm⁻¹ after complex formation. The -N=Nstretching band at 1490 cm⁻¹ also disappeared after binding with Al^{3+} . These notable changes in IR spectra clearly indicate the participation of –O-H, C=O and -N=N- groups in the binding of **1** with Al^{3+} (Fig. 15).

(a)





Application as Logic gate circuit

Logic gates have emerged as crucial building blocks in the formation of combinational circuits. In this current work, we report a simple two input based INHIBIT logic gate. It was observed that yellow solution of **1** turns pink upon complexion with Al³⁺. The original yellow color reappeared when EDTA²⁻ was added to the **1**-Al³⁺ solution. However, the addition of EDTA²⁻ alone did not produce any color change.

This enchanting "off–on" colorimetric behavior of ligand **1** allow us to mimic the INHIBIT logic gate. An INHIBIT gate is nearly similar to an AND gate with one input inverted by a NOT function. The presence and absence of chemical inputs ($In1 = AI^{3+}$ and $In2 = EDTA^{2-}$) were assigned with Boolean values '1' (ON-state) and '0' (OFFstate), respectively. The output emission signals were monitored at 613 nm. The enhanced fluorescence of **1** was assigned as 1 (ONstate) and the low fluorescence as 0 (OFF-state). When neither input was on (In1 = In2 = 0), fluorescence intensity of **1** at 613 nm was nearly zero (Output = 0) indicating 'OFF' state. On complexion with Al^{3+} (In1 = 1, In2 = 0), fluorescent intensity enhanced significantly indicating 'ON' state of the system.

Both inputs Al³⁺ and EDTA²⁻, when present, failed to induce any appreciable change in emission intensity at 613 nm i.e. 'OFF' state of the system. Thus, In 2 inhibits the gate from responding to In1. All these combinations lead to the construction of INHIBIT logic gate shown in Fig. 16. Monomolecular circuit and truth table for this proposed logic gate are shown in Fig. 16.



Fig. 16: (a) Fluorescence spectra of 1 (1 x 10⁻⁵ M) in the presence of different chemical inputs at λ_{ex} = 450 nm in MeOH : H₂O (1:1, v/v) containing HEPES (0.01 mM, pH=7.2) buffer solution (b) Truth table for sequential logic circuit. (c) Sequential logic circuit representing the INHIBIT gate.

HOMO-LUMO analysis

The optimized structure of **1** and its tautomeric form (II) calculated by quantum chemical calculations at DFT using B3LYP/6311G basis set is shown in Fig. 17. HOMO-LUMO analysis of **1** (I, enol form) revealed that the HOMO is mainly localized over antipyrine linked with sesamol ring through azo linkage and LUMO is localized over sesamol ring and azo linkage. Therefore, the charge transfer occurs from the azo group to the sesamol ring with energy gap (ΔE) of -0.12274 eV.

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Fig. 17: Optimised structures and HOMO-LUMO diagrams of both tautomeric forms (I & II) of chemosensor **1.**

However the HOMO-LUMO analysis of Keto form (II) indicates the charge transfer occurs between antipyrine and sesamol rings with the energy gap of -0.10107 eV (Fig. 17). Therefore, there is a less charge transfer from HOMO to LUMO in case of enol form (azo form) which implies more electron density is available for metal binding. In case of keto form (hydrazone form) because of the low energy gap ($\Delta E = -0.10107 \text{ eV}$), there is more charge transfer which means less electron density is available for metal binding. Therefore, chemosensor **1** exists in its tautomeric form **I** (enol form) for metal binding.

Experimental

Reagents

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4-Amino-1,5-dimethyl-2-phenyl-1*H*-pyrazol-3(2*H*)-one (ampyrone) and sesamol were purchased from Alfa-Aesar, HPLC water and methanol from S.D. Fine. All the metal salts were in chloride form while all the anions tested were the corresponding sodium salt. All other reagents and solvents used in the synthesis and analysis were of analytical reagent grade. All spectroscopic measurements were performed in HEPES buffer solution (pH = 7.2).

Physical measurements

Melting point was recorded on a Tropical Lab equip apparatus (Buchi M-560) and is uncorrected. IR (KBr) spectrum was recorded on Perkin-Elmer FTIR spectrophotometer and the values are expressed as v_{max} cm⁻¹. The NMR (¹H and ¹³C) spectra were recorded on Jeol JNM ECX-400P at 400 MHz and 100 MHz, respectively using TMS as an internal standard. The mass spectrum was recorded on Agilent 6520 Q-TOF (ESI-HRMS) mass spectrometer having ESI source in positive mode. Ultraviolet-visible (UV–vis) absorption spectra were recorded on Analytikjena specord 250 Spectrophotometer. The fluorescence spectra were measured at Cary Eclipse Fluorescence Spectrophotometer. All spectroscopic measurements were done at room temperature. The hybrid density function B3LYP (Becke–Lee–Young–Parr composite of exchange-correction functional) method³⁷ and the standard 6-311G basis set were used for structure optimization. All the theoretical calculations are performed with GAUSSIAN 09W software package.³⁸

Sensing experiments

The stock solution of the sensor **1** was prepared in MeOH : H₂0 (1:1, v/v, HEPES 0.01 mM, pH = 7.2) at the concentration of 1.0 x 10^{-3} M and diluted to 1 x 10^{-5} M. The stock solutions of different metal salts (Pb²⁺, Cu²⁺, Zn²⁺, Mn²⁺, Cd²⁺, Hg²⁺, Sr²⁺, Co²⁺, Sn²⁺, Fe³⁺, Al³⁺, Cr³⁺, La³⁺, In³⁺, Th⁴⁺, Ni²⁺, Mg²⁺, Ca²⁺, Ba²⁺ and Na⁺) in HEPES (0.01 mM, pH = 7.2) of concentration 0.1 M were prepared and were diluted accordingly before experimentation. While examining the sensing behaviour of **1** with different metal ions, 3 mL stock solution was taken and metal salt solution was added accordingly.

Procedure for the synthesis of compound 1

A solution of 4-Amino-1,5-dimethyl-2-phenyl-1*H*-pyrazol-3(2*H*)-one (0.5 g, 0.0024 mol) in water (10 mL) and conc. HCl (5 mL) was cooled to 0-5°C in an ice bath. A solution of sodium nitrite (0.254g, 0.00368 mol) in water (10 mL) was added dropwise to the above solution. The mixture was stirred for 45 min and disappearance of starting material was observed by TLC using ethyl acetate: petroleum ether (50: 50) as eluent. The diazonium chloride was then coupled with an alkaline solution of sesamol (0.339 g, 0.00246 mol) in 10% NaOH solution (10 mL) by slow addition over 30 min at 10-15°C. The stirring was continued for 1 h at room temperature. A deep orange solid was obtained which was filtered at pump and washed several times with cold water (3 x 5 mL). The crude product was purified by recrystallization from hot ethanol to give pure product as dark red solid. The product was characterized by IR, ¹H NMR and ¹³C NMR and mass spectra.

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4-((6-Hydroxybenzo[d][1,3]dioxol-5-yl)diazenyl)-1,5-dimethyl-2phenyl-1*H*-pyrazol-3(2*H*)-one (1)

Dark red solid; Yield: 95 %; m.p.> 200 °C; IR (KBr, cm⁻¹): 3448, 1604, 1521, 1490, 1458, 1417, 1325, 1203, 1028, 862; ¹H NMR (DMSO-d₆, 400 MHz): δ = 11.55 (1H, brs, OH, D₂O exchangable), 7.42 (m, 2H), 7.32 (m, 1H), 7.23 (d, 2H), 7.0 (s, 1H), 6.42 (s, 1H), 5.88 (s, 2H), 3.20 (s, 3H), 2.36 (s, 3H); ¹³C NMR (DMSO-d₆, 100 MHz): δ = 169.7 (s), 157.4 (s), 152.5 (s), 151.0 (s), 136.8 (s), 133.8 (s), 129.3 (s, 2C), 127.8 (s), 125.9 (s, 2C), 122.8 (s), 101.9 (s), 100.0 (s), 93.4 (s), 34.8 (s, 3C), 9.74 (s, 3C); HRMS (ESI) calcd. for C₁₈H₁₆N₄O₄ [M + H]⁺ 353.1172, found: 353.1241. (Fig S4-S7)

Conclusion

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In summary, we have designed and synthesized a new PET-based "turn on" fluorescent as well as colorimetric chemosensor (1) for selective recognition of AI^{3+} ion. The addition of EDTA quenches the fluorescence of $1 + AI^{3+}$ complex indicating that 1 could be used as a reversible "off-on-off" fluorescent sensor. The binding stoichiometry suggests a 1:1 complexation with a large association constant for AI^{3+} ions. The detection limit was found to be sufficiently low to detect micromolar concentrations of AI^{3+} . Moreover, chemosensor 1 can also act as a "naked-eye" colorimetric sensor for the detection of H^+ ions when pH < 2 because of the intramolecular charge transfer. Based on these characteristics, one logic gate circuit was constructed. Therefore, the novel chemosensor can be used as a color-tunable pH sensor in highly acidic environment as well as an excellent fluorescent sensor for the detection of AI^{3+} ion.

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Graphical Abstract

An Ampyrone based azo dye as pH-responsive and chemo-reversible colorimetric fluorescent probe for Al³⁺ in semi-aqueous medium: Implication towards logic gate analysis

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