

Heterocyclic imidazo-anthraquinone as an optical sensor: synthesis, characterization and evaluation of the chemosensory ability

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Abstract: A novel imidazo-anthraquinone derivative **3** was synthesized in moderate yield. The photophysical properties of the new compound were studied by UV-vis and fluorescence spectroscopy in ACN. The evaluation of the new compound as a colorimetric chemosensor was carried out by performing spectrophotometric titrations in ACN and ACN/H₂O in the presence of relevant organic and inorganic anions and transition metal cations. Imidazo-anthraquinone **3** exhibited great selectivity for the cyanide anion over other anions in ACN/H₂O (95:5) solution showing a distinct color change from yellow to pink.

Keywords: imidazo-anthraquinone, thiophene, colorimetric sensor, optical chemosensor, “naked-eye” detection, aqueous media.

1. Introduction

The research on selective chromo-fluorogenic sensors for anions, cations and neutral molecules is an exciting topic with recent developments, especially in the possibility of using colorimetric/fluorimetric probes to sense both anions and cations in aqueous solution. In particular, heterocyclic systems which have the ability to act as the recognition unit as well as the signalling unit are very interesting since variation of their absorption/fluorescence properties can happen during the recognition event. With careful design, for example by inclusion of additional heterocycles, the analyte recognition and overall photophysical properties can be improved, leading to higher sensitivity and selectivity.¹ Imidazole based chromophores have received increasing attention recently due to their distinctive optical properties and excellent thermal stabilities making them versatile systems for several applications such as optical chemosensors and two-photon absorbing molecules,² among other applications in materials and medicinal chemistry. For the recognition of certain anions, anthraquinone derivatives have been reported as suitable systems for colorimetric sensing since they are an example of electron acceptor groups that can be electronically connected with recognition units.³

Based on the above facts, herein we report the synthesis of one imidazo-anthraquinone and the characterization of its photophysical and chemosensory properties. The evaluation of the compound as a colorimetric chemosensor was carried out by performing spectrophotometric titrations in ACN and ACN/H₂O in the presence of relevant organic and inorganic anions and transition metal cations.

2. Experimental

2.1. Synthesis of 2-(5'-hexylthiophen-2'-yl)-1*H*-anthra[1,2-*d*]imidazole-6,11-dione **3**

i) Preparation of the imine: 1,2-diaminoanthraquinone **1** (0.05 g, 0.21 mmol) and 5-hexylthiophene-2-carboxaldehyde **2** (0.027 g, 0.17 mmol) were dissolved separately in ethanol (4 mL/mmol). The ethanolic solution of aldehyde and formic acid (0.04 mL/mmol of aldehyde) was added to the solution of 1,2-diaminoanthraquinone and the reaction mixture was heated under reflux during 8 h.

ii) Cyclisation of the imine: After cooling, the ethanol was evaporated and the crude imine was dissolved in a small volume of acetic acid (1 mL/mmol of imine). To this solution, lead tetraacetate was added (0.100 g, 0.18 mmol) and the mixture was stirred overnight at room temperature. The mixture was poured into water (10 mL) and extracted with chloroform (2x20 mL). The organic layer was dried with magnesium sulphate and evaporated under reduce pressure to give compound **3**, as a solid which was recrystallised from diethyl ether and chloroform.

Compound **3** was obtained as a light yellow solid (44 mg, 43 %). M.p. 144.1-145.0 °C. UV-vis (acetonitrile): λ_{max} nm (log ϵ) 426 (3.94). ^1H NMR (400 MHz, DMSO- d_6): δ = 0.93 (t, J = 7.2 Hz, 3H, CH₃), 1.31 – 1.44 (m, 6H, c-CH₂, d-CH₂, e-CH₂), 1.71 – 1.79 (m, 2H, b-CH₂), 2.91 (t, J = 7.2 Hz, 2H, a-CH₂), 6.92 (d, J = 4.4 Hz, 1H, H-4'), 7.76 – 7.83 (m, 3H, H-3', H-8 and H-9), 8.08 (d, J = 8.4 Hz, 1H, H-5), 8.20 (d, J = 8.4 Hz, 1H, H-4), 8.24 (dd, J = 7.2 and 2.2 Hz, 1H, H-10), 8.31 (dd, J = 7.6 and 2.4 Hz, 1H, H-7) ppm. ^{13}C NMR (100.6 MHz, DMSO- d_6): δ = 14.04 (CH₃), 22.53 (e-CH₂), 28.68 (d-CH₂), 29.67 (a-CH₂), 30.41 (b-CH₂), 31.49 (c-CH₂), 117.73 (C-11a), 122.56 (C-4), 124.55 (C-5), 126.07 (C-4'), 126.48 (C-10), 127.60 (C-7), 127.71 (C-2'), 128.56 (C-10a), 129.52 (C-3'), 132.54 (C-5a), 133.05 (C-6a), 133.79 (C-8), 133.91 (C-3a), 134.51 (C-9), 147.84 (C-11b), 151.71 (C-2), 153.00 (C-5'), 182.28 (C-11), 185.00 (C-6) ppm. MS (ESI) m/z (%): 415 ([M]⁺, 100). HRMS: (ESI) m/z (%) for C₂₅H₂₃O₂N₂S; calcd 415.14748; found 415.14695.

2.2. Spectrophotometric titrations of compound **3**

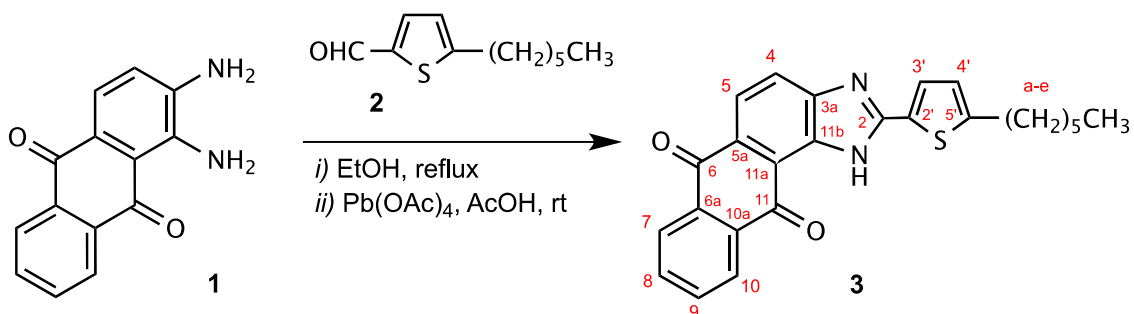
UV-visible absorption spectra (250–650 nm) were obtained using a Shimadzu UV/2501PC spectrophotometer. Fluorescence spectra were collected using a FluoroMax-4 spectrofluorometer. The relative fluorescence quantum yields were determined by using 10⁻⁶ M solution of quinine sulphate in sulfuric acid as standard (Φ_F = 0.54).⁴ Solvents used in the spectroscopic studies were of spectroscopic grade. Solutions of compound **3** (ca. 1.0 × 10⁻⁵ M) and of the ions under study (ca. 1.0 × 10⁻² and 1.0 × 10⁻³ M) were prepared in UV-grade ACN or ACN/H₂O (95:5). Titrations of compound **3** in the presence of relevant organic and inorganic anions (AcO⁻, F⁻, Cl⁻, Br⁻, CN⁻, NO₃⁻, BzO⁻, H₂PO₄⁻, HSO₄⁻), and transition metal cations (Cu²⁺, Cd²⁺, Pd²⁺, Ni²⁺, Hg²⁺, Zn²⁺, Fe²⁺, Fe³⁺ and Cr³⁺) was performed by the sequential addition of the ion

stock solution to the imidazo-anthraquinone solution, in a 10-mm path length quartz cuvette and absorption emission spectra were measured by excitation at the wavelength of maximum absorption with a 2-nm slit.

3. Results and discussion

3.1. Synthesis and characterization

The reaction between 1,2-diaminoanthraquinone **1** and 5-hexylthiophene-2-carboxaldehyde **2**, by heating at reflux in ethanol with formic acid as catalyst, resulted in the corresponding imine which was cyclised *in situ* using lead tetraacetate in acetic acid to imidazo-anthraquinone **3**, in moderate yield (43 %) after purification (Scheme 1). The new compound was completely characterized by the usual spectroscopic techniques (Scheme 1, Table 1).



Scheme 1. Synthesis of imidazo-anthraquinone **3**.

The absorption and emission spectra of compound **3** were measured in ACN solution and showed an intense lowest energy charge-transfer absorption band in the UV-visible region at 426 nm. As for the emission, it exhibited a moderate fluorescence quantum yield ($\Phi_F = 0.24$) with the wavelength of maximum emission at 583 nm and a 157 nm Stokes' shift (Table 1).

In the ¹H NMR spectrum, the NH signal was visible as a broad singlet at 11.04 ppm confirming the formation of the imidazole ring through an intramolecular cyclization of the intermediate imine.

Table 1. Yields, UV-visible absorption and fluorescence data for imidazo-anthraquinone **3** in ACN solution.

	η (%)	Absorption		Fluorescence		
		λ_{\max} (nm)	$\log \varepsilon$	λ_{em} (nm)	Φ_F	Stokes' shift (nm)
3	43	426	3.94	583	0.24	157

3.2 Spectrophotometric titrations of imidazo-anthraquinone **3** with anions and metallic ions

Evaluation of new anthraquinone **3** (10^{-5} M) as colorimetric chemosensor was carried out in ACN and ACN/H₂O (95:5) solutions, in the presence of several ions (AcO⁻, F⁻, Cl⁻, Br⁻, CN⁻, NO₃⁻, BzO⁻, H₂PO₄⁻, HSO₄⁻, Cu²⁺, Cd²⁺, Pd²⁺, Ni²⁺, Hg²⁺, Zn²⁺, Fe²⁺, Fe³⁺ and Cr³⁺) with biological, environmental and analytical relevance.

Preliminary tests were carried out by addition of up to 50 equiv of each ion to the solution of anthraquinone **3** in ACN and in aqueous mixture ACN/H₂O (95:5). It was found that compound **3** displayed a marked colour change, from yellow to pink (upon interaction with CN⁻, F⁻) and from yellow to light yellow (upon interaction with Fe²⁺, Hg²⁺ and Ni²⁺) in ACN solution and it was possible to obtain selectivity for the cyanide in aqueous mixture.

Considering these preliminary results, spectrophotometric titrations of compound **3** in ACN with these selected ions were undertaken. Titrations with CN⁻ and F⁻ revealed a trend in the UV-Vis spectra, the intensity of the longest wavelength absorption band at 427 nm decreased progressively upon addition of the anion, with the simultaneous growth of a new red-shifted absorption band located at 498 nm (Figure 1). It can be seen that a very small amount of cyanide and fluoride ions (less than 1 equiv) caused large changes in the absorption spectrum, thus showing the high sensitivity of the new sensor to these anions.

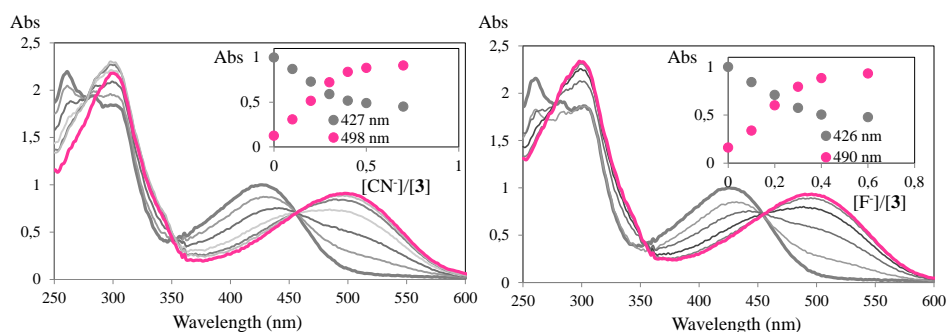


Figure 1. Spectrophotometric titrations of imidazo-anthraquinone **3** with addition of increasing amounts of CN^- and F^- in ACN. The inset represents the normalized absorption ($[\mathbf{3}] = 1 \times 10^{-5} \text{ M}$, $T = 298 \text{ K}$).

In the titration with Fe^{2+} , Hg^{2+} and Ni^{2+} , compound **3** revealed a trend in the UV-Vis spectra, with the intensity of the longest wavelength absorption band at 427 nm decreasing progressively upon addition of the cations, with the simultaneous growth of a new blue-shifted absorption band located at 397 nm (Figure 2). In the titration with Fe^{2+} 11 equiv were used, 4 equiv were needed for titration with Hg^{2+} , and 5 equiv for the titration with Ni^{2+} . Thus, although not selective, compound **3** in ACN was more sensitive to the presence of anions, considering that only 0.7 equiv of CN^- and 0.6 equiv of F^- were required for the visible colour change.

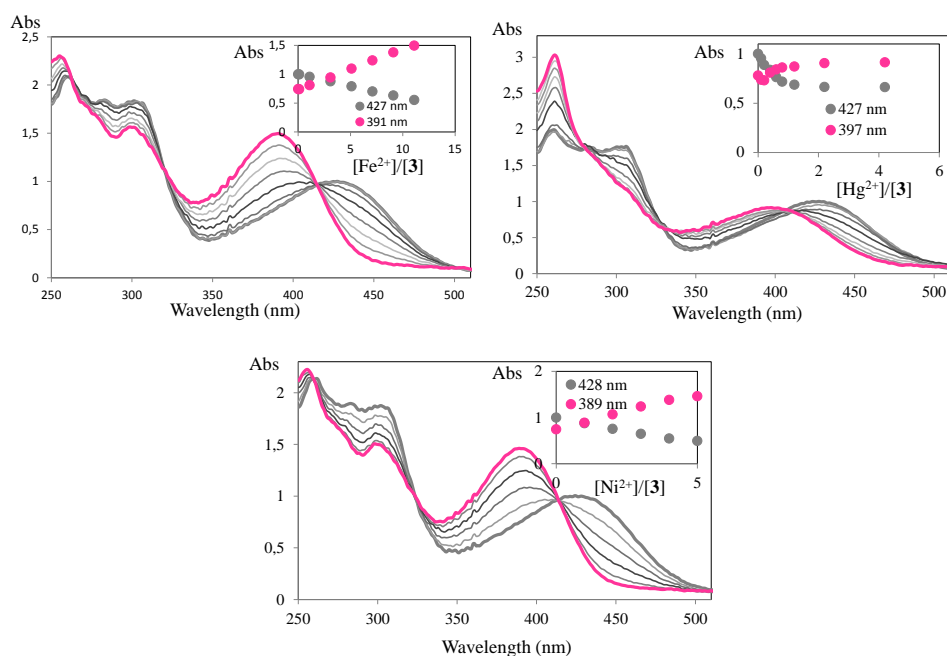


Figure 2. Spectrophotometric titration of **3** with addition of increasing amounts of Fe^{2+} , Hg^{2+} and Ni^{2+} in ACN. The inset represents the normalized absorption at 427 nm ($[\mathbf{3}] = 1 \times 10^{-5} \text{ M}$, $T = 298 \text{ K}$).

In an attempt to increase sensitivity and selectivity, spectrophotometric titrations of compound **3** in ACN/H₂O (95:5) were carried out, which confirmed the preliminary sensing results, with compound **3** being selective for the cyanide ion although it required a larger amount of ion to achieve a similar colour change (100 equiv), when compared to the titration in ACN. In Figure 3 it can be seen that there was a gradual decrease in absorption intensity upon addition of the cyanide ion, accompanied by a red-shift with the formation of a new band at 428 nm.

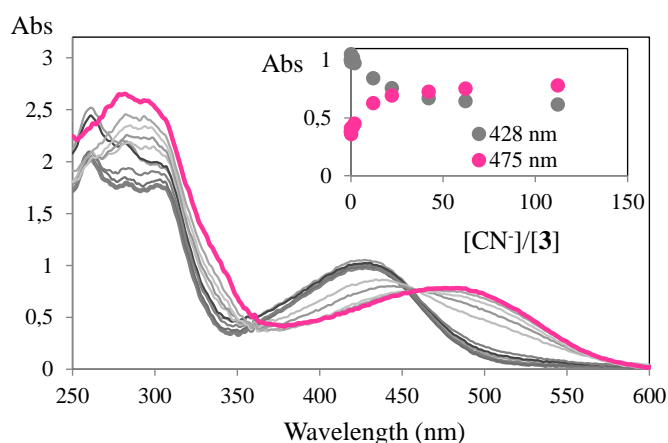


Figure 3. Spectrophotometric titration of compound **3** with addition of increasing amounts of CN⁻ in ACN/H₂O (95:5). The inset represents the normalized emission ([**3**] = 1x10⁻⁵ M, T = 298 K).

4. Conclusions

The synthesis of a new imidazo-anthraquinone **3** was achieved in moderate yield by a simple experimental procedure. The sensory ability was evaluated for several ions by spectrophotometric titrations in ACN and ACN/H₂O (95:5). Compound **3** was selective for the cyanide ion in ACN/H₂O (95:5), which is a very promising result as a colorimetric chemosensor for application in aqueous media.

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