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Supramolecular assemblies of phenyl-pyridyl-triazolopyridine and β-cyclodextrin as sensor of divalent cations in aqueous solution

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ABSTRACT

The chemosensor 3-phenyl-7-(pyrid-2-yl)-[1,2,3]triazolo[1,5-*a*]pyridine (PhPTP) used in combination with two different cyclodextrins, enable its solubilization and stabilization in aqueous solution. The behavior of the inclusion complex, and its binding ability in both cyclodextrins were investigated by means of absorption and fluorescence spectroscopy. The best results were obtained for PhPTP-DMβCD assembly, and its orientation in the DMβCD nano cavity was obtained by 2D-NMR. This inclusion geometry was confirmed by docking studies. The binary complex was proved as chemosensor upon the presence of different divalent cations in aqueous solutions. The PhPTP-DMβCD system, displays a high sensitivity for Fe^{2+} by fluorescence quenching in neutral aqueous solution even in the presence of other metals showing high selectivity towards Fe^{2+}.

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1. Introduction

The design and synthesis of selective and sensitive chemosensors for the detection of transition metal ions has become an interesting field in supramolecular chemistry, particularly those in detecting biological active metal ions (Li et al., 2012; Rudrakanta, Wu, & Lin, 2012; Chen, Xing, & Pang, 2011; Kavitha & Stalin, 2014; Tang et al., 2014; Kacmaz et al., 2014). Mainly, the selective chemosensors for transition metal ions in aqueous environments are relatively rare because these metal ions are comparatively easy to chelate and detect in organic solvents, but they are rather difficult to recognize directly in aqueous environments (Valeur & Leray, 2000). The development of chemosensors with increased selectivity and sensitivity play a significant role in various fundamental biological processes (Wei et al., 2013).

Iron is the most abundant transition metal in these processes, plays an important role in cellular metabolism, enzyme catalysis, and as oxygen carrier in hemoglobin. Also, it is required by all living organisms due to its potent redox chemistry and possibility to engage in catalytic activity. However, if unregulated in humans, Fe^{2+} can lead to uncontrolled oxidative chemistry causing tissue damage and fibrosis to various organs (Lee et al., 2012), elevated iron levels are associated with neurodegeneration such as Parkinson's disease (Beard, 2003). Thus, it is so imperative to develop analytic and detective methods for sensitive sensing of iron in aqueous media, due to their potential applications in biological systems (Wei et al., 2013).

The fusion of a triazole (electron–donating group) and a pyridine moiety (electron acceptor group) form triazolo-pyridine (TP) that with conjugated aromatic substituent on the 3 or 7 position (Fig. 1) has been associated with useful fluorescent properties. Metal ion coordination to the donor groups changes the efficiency of the intramolecular charge transfer changing the fluorescence spectra. Most of the metal recognitions using triazolopyridine system were carried out in non-aqueous media or water-organic mixtures (Chadlaoui et al., 2006; Ballesteros-Garrido et al., 2009). However, one disadvantage of these compounds is their low aqueous solubility to be used as chemosensor under physiological condition.

Cyclodextrins (CDs) are cyclic oligosaccharides with a cage-like structure formed by α-1,4-linked D-glucopyranose units. CDs have the shape of a truncated cone with internal cavities ranging from 5 to 8 Å. The C—H bonds on the ring point inward producing a hydrophobic cavity. The nonbonding electron pairs of the glycosidic oxygen bridges are directed toward the inside of the cavity,

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producing a high electron density and lending it some Lewis base character. The primary and the secondary hydroxyl groups are located on the narrow and wide rims, respectively, of the truncated cone (Saenger et al., 1998). As a result of this spatial arrangement of the functional groups in the cyclodextrin molecules, the cavity shows a relatively hydrophobic character while the external surfaces are hydrophilic (Valente & Söderman, 2014), an important reason to be popular building blocks for supramolecular structures. The most extraordinary characteristic of cyclodextrins resides in their ability to form inclusion complexes with a variety of compounds, i.e. caging foreign molecules (guest) in its cavity (host). Generally, hydrophobic molecules or some hydrophobic residues have the highest affinity with the CD's cavity in aqueous solution. It has been established that the ability of β-cyclodextrin to enhance the stability and solubility of drugs is mediated through the formation of inclusion complexes (Connors, 1997). The fit of the entire or at least a part of the guest molecule in the cyclodextrine-host cavity determines the stability of the inclusion complex and the selectivity of the complexation process. Therefore, stability constant values of drug-cyclodextrin complexes are useful indexes of the binding strength and of great importance for the understanding and evaluation of the inclusion complex formation. Nevertheless, natural CDs have limited water solubility, thus to deal with this limitation, alkyl moieties such as hydroxyalkyl or methyl on free hydroxyl groups of CD has been introduced in order to enhance their solubility. In addition, the complexation ability of cyclodextrin derivatives compared to their natural counterparts is significantly modified (Folch-Cano et al., 2011; Jullian, 2009; Jullian et al., 2008a,b).

The aim of this work is to develop a method for the determination of Fe^{2+} in aqueous medium utilizing PhPTP-CD complex as a chemosensor. The inclusion complex of PhPTP with two cyclodextrin is studied, native β-cyclodextrin and 2,6-dimethyl-β-cyclodextrin (Fig. 1), utilizing absorption and fluorescence spectroscopy. The association constants, estimated from fluorescence studies at different temperatures were analyzed and used in order to get information on the plausible thermodynamic mechanism involved in the association process. The best results are for PhPTP-DMβCD assembly ruling out the use of native cyclodextrin, which was studied by 2D-NMR, to obtain the orientation of PhPTP in the DMβCD nano cavity. This inclusion geometry was rationalized with docking studies. Finally, this binary complex was proved as chemosensor upon the presence of different divalent cations in aqueous solutions. This new chemosensor displays a highly selectively and sensitivity of fluorescent signal toward Fe^{2+}.

2. Material and methods

Fluorescence spectra were recorded with a LS 55 Perkin–Elmer spectrofluorometer equipped with a xenon lamp source. All the samples have an absorbance less than 0.1 to avoid inner filter effect. Absorption spectral measurements were carried out with an Agilent 8453. NMR spectra were recorded on a Bruker Avance DRX-300 operating at 300.13 MHz for 1*H*. Rotating-frame overhausser effect spectroscopy (ROESY) spectra were acquired in the phase sensitive mode with the same spectrometer and Bruker standard parameters.

The 3-phenyl-7-(pyrid-2-yl)-[1,2,3]triazolo[1,5-*a*]pyridine (PhPTP) was synthesized according to method described earlier (Bentabed-Ababsa et al., 2009). βCD (β-cyclodextrin), DMβCD (Heptakis-2,6-*O*-dimethyl-β-cyclodextrin) and metal perchlorate salts (Zn^{2+}, Pb^{2+}, Ni^{2+}, Mg^{2+}, Cu^{2+}, Co^{2+}, Cd^{2+}, Mn^{2+}, Ca^{2+} and Fe^{2+}) were purchased from Sigma-Aldrich, Inc., St. Louis, MO. All solvents employed in the spectrophotometric analyses were of spectroscopic reagent grade. Deionised water from Milli-*Q* system apparatus (Millipore Corp., Billerica, MA) was used throughout the experiments.

Inclusion complexes were obtained as described earlier (Jullian et al., 2014). For the determination of association constants the concentration of PhPTP was 1×10^{-5} M and increased buffered solution of DMβCD was added. The resulting mixture was equilibrated in a Precision thermostatic shaking water bath for 24 h after which the equilibrium was reached.

The stoichiometry of the inclusion complex was determined by the method developed by Job (1928). Equimolar solutions of PhPTP and CD were mixed to a standard volume, varying the molar ratio but keeping the total concentration of the species constant. After stirring for 24 h, the absorbance at 340 nm was measured for all solutions and $\Delta A = A - A_o$, the difference in absorbance in the presence and in the absence of CD, was plotted against R; $R = [\text{PhPTP}]/([\text{PhPTP}] + [\text{CD}])$.

The effect of various metal ions was investigated by analyzing the inclusion complex containing 1×10^{-5} M of PhPTP and 1×10^{-4} M of DMβCD in phosphate buffer pH 7.4 and adding 1×10^{-4} M interfering metal ions. Before fluorimetric detection, the mixed solution was allowed to stand for 5 min to complete formation of stable solution.

Autodock Vina (Trott & Olson, 2010) program was used to carry out docking studies. This software handle docking as a stochastic global optimization of the scoring function, precalculating grid maps and the interactions between every atom type pair at every

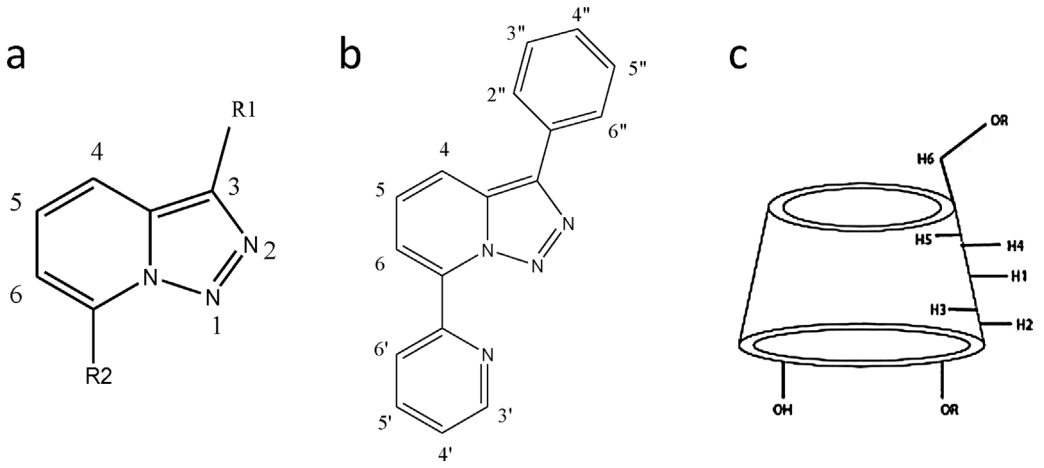

Fig. 1. Structures of 3- and/or 7-substituted-[1,2,3]triazolo[1,5-*a*]pyridine (a), 3-phenyl-7-(pyrid-2-yl)-[1,2,3]triazolo[1,5-*a*]pyridine (PhPTP) (b), β-cyclodextrin, with R = H; 2,6-*O*-di-methyl-β-cyclodextrin, with $R = CH_3$ (c).

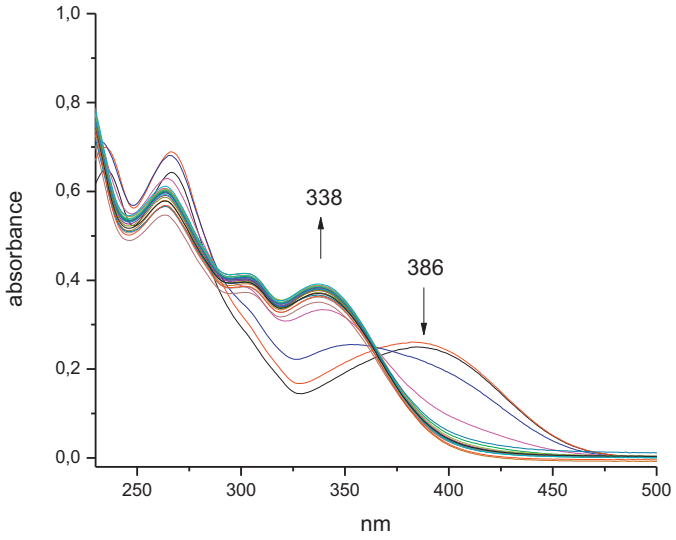

Fig. 2. Absorption spectra of PhPTP as a function of pH.

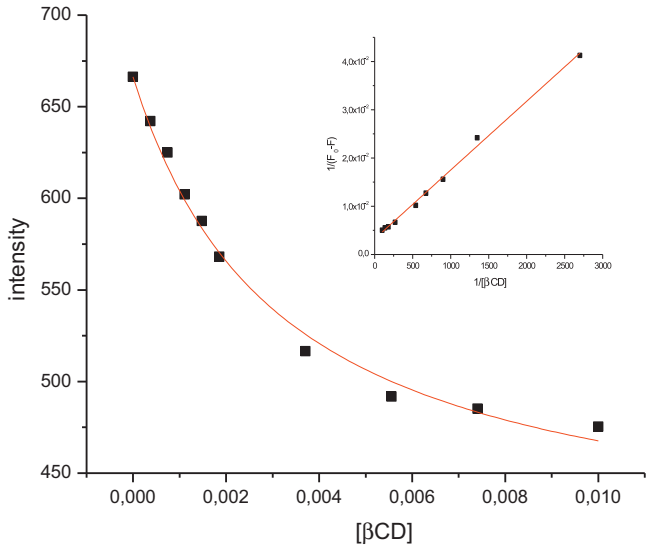

Fig. 3. Non linear curve fitting of PhPTP upon addition of increasing concentration of β-CD. *Inset*: Linear curve fitting according to Benesi–Hildebrand equation.

distance. In order to carry out docking studies it was necessary a prior 2,6-methoxy-βCD modelling. Therefore, it was extracted the βCD from the crystalized structure of Cyclodextrin Glycosyltransferase (PDB code: 3CGT). Then, the methyl groups where added using XLeap implemented in AMBER program .The new structure was then energy minimized. Finally, the PhPTP ligand was modelled and optimized using Gaussian98 at B3LYP/6-31G(d,p) level of theory.

3. Results and discussion

The detection of metal ions by floroionophores is usually influenced by the pH of the media. So become acquainted of the influence of operative pH values upon the sensitive of fluorescent chemosensor is extremely important. Fig. 2 shows the pH-dependent absorption spectra of PhPTP. It can be noticed that at low pH values the lowest energy band is centered at 385 nm. Its intensity decreases with an increase of pH. At the same time, a new band appears, at lower wavelength, 337 nm. Also, there is an isobestic point at 365 nm, indicating the presence of protonated and neutral species. The absorption intensity change reaches a maximum at pH values above 4. From the absorbance versus pH plot, (Figs. S1–S3), it is possible to obtain the p*K*a value for PhPTP, PhPTP-βCD and for PhPTP-DMβCD of 2.7, 2.7 and 2.5, respectively. These values can be understand in terms of monocation formation, in βCD medium is the same than PhPTP in the aqueous media or the protonated moiety of PhPTP is not included in the cyclodextrin cavity. Nevertheless, a small difference is observed in the case for DMβCD medium, where a higher hydrogen ion concentration is needed. This could be due to the ligand is included into the nano cavity of DMβCD and the H^+ ions are more difficult to protonate PhPTP making the complex PhPTP-DMβCD more acidic than PhPTP without cyclodextrin (Srinivasan, Stalin, & Sivakumar 2012). In a previous work we studied the effect of the pH on other derivative of triazolopyridine, where the pyridine is in position 3 of triazolopiridine ring (Jullian et al., 2014). There, p*K*a values of 3.7 and 2.9 were obtained for PTP without DMβCD medium and forming the inclusion complex PTP-DMβCD. The difference between the p*K*a values of PTP (without and with DMβCD) is higher than in PhPTP (without and with DMβCD), notwithstanding the protonated group is the same, a pyridine. This may be due to the protonated part of PTP is embedded entirely into the cyclodextrin cavity, unlike PhPTP, so we can assume that the protonated part of the ligand is exposed to the solvent.

The maximum of fluorescence of PhPTP is at 505 nm at pH 2 (exciting wavelength 365 nm). An ipsochromic displacement is observed until 490 nm with increasing pH, the fluorescence intensity rises notably up to pH 6 where it remains constant. For PhPTP-βCD and PhPTP-DMβCD complexes the behavior is the same, except that the emission maxima at low pH is centered at 494 and 497 nm, respectively, and the emission at pH > 6 is practically at ~490 nm.

When increasing concentrations of CD are added to the reaction medium containing PhPTP in phosphate buffer pH 7.4, the recorded absorption spectra show very slight changes, however, the effect of CD on the fluorescence spectra is more pronounced. At pH 7.4 the emission maxima is at 489 nm and practically no displacement of the maxima is observed with increasing CD concentration. The fluorescence intensity decreased with the variation of CD concentration from 0 to 12 mM, until a minimum was reached indicating that the triazolopyridine is entrapped in the cyclodextrin cavity forming an inclusion complex, Fig. 3. The obtained stoichiometry of the complex formation was 1:1 determined analyzing the changes in the intensity of emission maxima with the CD concentration according to the Benesi–Hildebrand plot; inset Fig. 3, which gave a straight line, also corroborated by the continuous variation method for both cyclodextrins, data not shown.

Nonlinear least-squares regression analysis (NLR) was used to determine the association constant of PhPTP with native and derivatized cyclodextrin accordingly to the following equation (Connors, 1987):

$$F = F_0 + \frac{(F_\infty - F_0)K\left[CD\right]}{1 + K\left[CD\right]} \quad (1)$$

where F_∞ correspond to the fluorescence intensity when total PhPTP has been complexed in CD, F_0 is the fluorescence of PhPTP in the absence of CD, and F is the observed fluorescence at each CD concentration tested. The NLR program estimates K_a by fitting the data through iteration and this representation showed a good correlation with the experimental comportment observed when CD concentration is increased.

The association constants, K_a, of PhPTP-CDs at different temperatures were determined and the results are summarized in Table 1, which shows that the association constant of PhPTP-DMβCD is

Table 1
Association constant (K_a) of PhPTP-βCD and PhPTP-DMβCD complexes at different temperatures and thermodynamic parameters.

	K_a (M^{-1}) 303 K	K_a (M^{-1}) 308 K	K_a (M^{-1}) 313 K	ΔH (kJ/mol)	ΔS (kJ/kmol)	ΔG (kJ/mol)
PhPTP-βCD	228 ± 25	286 ± 31	291 ± 28	18.703	0.108	−13.481
PhPTP-DMβCD	1016 ± 24	1420 ± 36	1865 ± 27	46.371	0.213	−17.103

higher than PhPTP-βCD complex and both increase with increasing temperature, as expected for an endothermic process for both cyclodextrin used. It is observed that the modified cyclodextrin in general bind the guest more strongly than their unmodified parents (Zhang, Shuang, Dong, & Pan 2003; Jullian et al., 2008a,b, 2010a; Jullian, Alfaro, Zapata-Torres, & Olea-Azar 2010; Jullian, Brossard, Gonzalez, Alfaro, & Olea-Azar 2011). The increased binding capacity of the modified CDs was explained as a result of the extension of the cavity by the hydroxypropyl, methyl and so on groups, which could hold the guest in place more effectively. Thus, the highest stability constant value exhibited by DMβCD could be ascribed to the presence of methyl groups that expand the hydrophobic region of the CD cavity and thus increase its affinity towards the ligand PhPTP.

Thermodynamic parameters were calculated based on the temperature dependence of the binding constant for PhPTP-CDs binding. The enthalpy changes (ΔH) and entropy changes (ΔS) of the binding reaction are important to confirm the force of interactions between PhPTP with cyclodextrins. It has been generally accepted that the main driving forces for complexation are hydrogen bonding, van der Waals force interactions, hydrophobic interaction, and the release of 'high-energy water' molecules from the cavities of CDs towards the bulk. Large negative enthalpy and entropy changes, either negative or slightly positive, are usually attributed to strong van der Waals interaction and formation of hydrogen bonds between host and guest. Therefore, the inclusion reaction is primarily an enthalpy driven process. A positive entropy change together with a slightly positive enthalpy change is an entropic driven process and essentially involves hydrophobic interaction (Liu & Guo, 2002).

If the enthalpy change (ΔH) does not vary significantly over the temperature range studied, then its value as well as that of entropy change (ΔS) can be determined from the van't Hoff equation:

$$\ln K = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \quad (2)$$

where K is the associative binding constants corresponding to various temperatures, and R is the gas constant (8.314 J/mol K). The enthalpy change (ΔH) can be calculated from the slope of the van't Hoff relationship and the free energy change (ΔG) can be estimated from the following relationship:

$$\Delta G = \Delta H - T\Delta S \quad (3)$$

The plot of $\ln K$ versus $1/T$ for both formed complexes is linear, Fig. 4, and the thermodynamic parameters are listed in Table 1. By careful inspection, the following conclusions can be obtained: The negative value for free energy (ΔG) means that the binding process is a spontaneous process and thermodynamically favored. ΔH and ΔS are positive in the experimental range, which indicates that the inclusion for both CDs is entropically driven. Apparently, when triazolpyridine is free in solution, it seems to have a strong interaction with its solvent shell. Upon binding, this solvent shell is broken up, leading to the partly unfavorable enthalpic change. Furthermore, the inclusion complexation involves desolvation of host and guest, which takes place when PhPTP penetrate inside the CD cavity.

Since DMβCD is most effective in PhPTP complexation, where their association constants are 5 times higher than for PhPTP-βCD, we choose the PhPTP-DMβCD complex to continue our

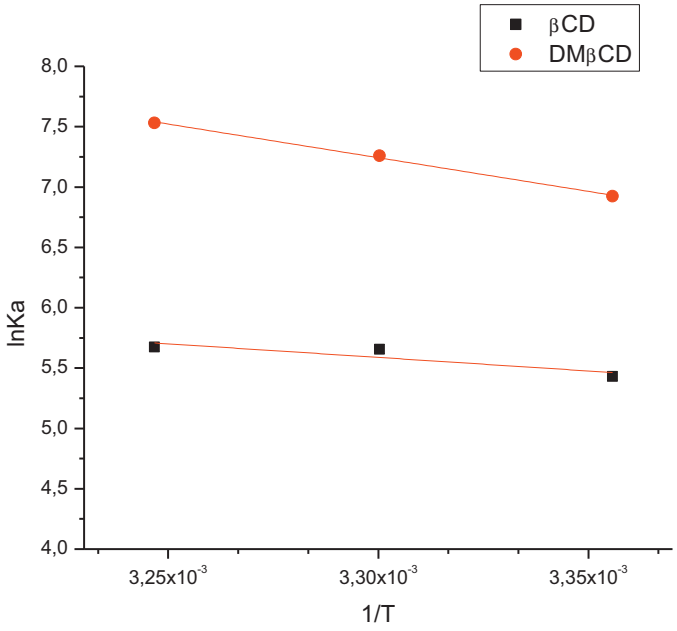

Fig. 4. Van't Hoff plot ($\ln K$ versus $1/T$) for PhPTP-βCD (■) and for PhPTP-DMβCD (●) association.

investigation. Additional information about the inclusion mode of PhPTP in the cyclodextrin cavity can be derived from the evidence of spatial proximities between protons of the CD and the ligand.

NMR is a powerful technique used to determine the inclusion of a guest molecule into the hydrophobic CD cavity in solution. It is well known that the chemical shifts of the hydrogen atoms located in the interior of the CD cavity (H-3 and H-5) become shielded and usually show significant upfield shifts in the presence of a guest molecule. Besides, the aromatic protons of ligands are influenced due to its inclusion in the cyclodextrin's nanocavity. Regrettably, the solubility of PhPTP in D_2O is very low to make an analysis of its protons chemical shifts variation as a consequence of the cyclodextrin presence. However, further information regarding PhPTP inclusion mode in the cyclodextrin cavity can be derived from the evidence of spatial proximities between its protons and cyclodextrin ones. In this context, two-dimensional (2D) NMR is a powerful tool for investigating inter and intra-molecular interactions so as to determine PhPTP orientation respect to the cyclodextrin. Thus, inclusion geometry of cyclodextrin complex was studied by acquiring ROESY spectra and analyzed qualitatively. In ROESY experiments, NOE can be detected between protons from two species at distance smaller than 5 Å, so protons at this distance or less could correlate and the ROESY experiment will present cross peak. HSQC spectrum was acquired in order to unambiguously determine DMβCD chemical shifts of H-3, H-5 and H-6.

Partial contour plot of ROESY spectrum of PhPTP-DMβCD is shown in Fig. 5. In the F1 dimension ^{1}H NMR spectrum of DMβCD appears, showing the inner cyclodextrins proton, unambiguously identified by the HSQC experiment. In the F2 dimension, we can see the aromatic zone, corresponding to the PhPTP hydrogens. Due to the interactions between PhPTP and DMβCD, cross peaks appears between H4, H5, H2″/6″ and H3″/5″ protons of PhPTP with H3 and H5 DMβCD protons. Altogether with the observed cross peaks

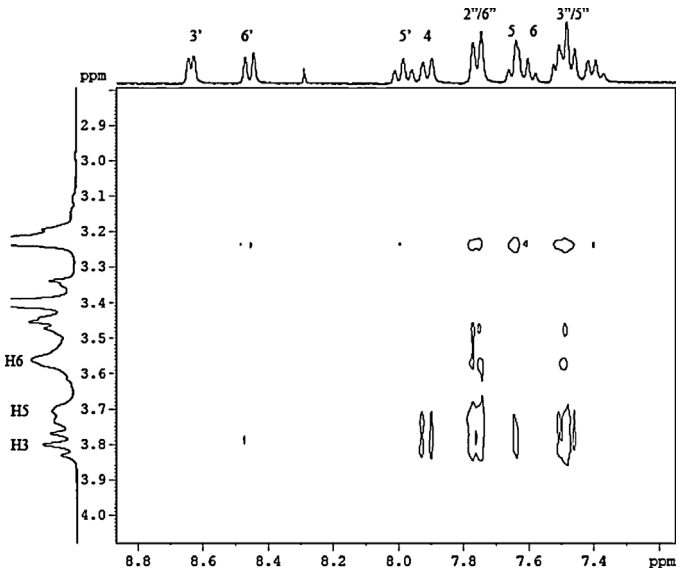

Fig. 5. Partial contour plot of the ROESY spectrum of the PhPTP-DMβCD complex in D_2O.

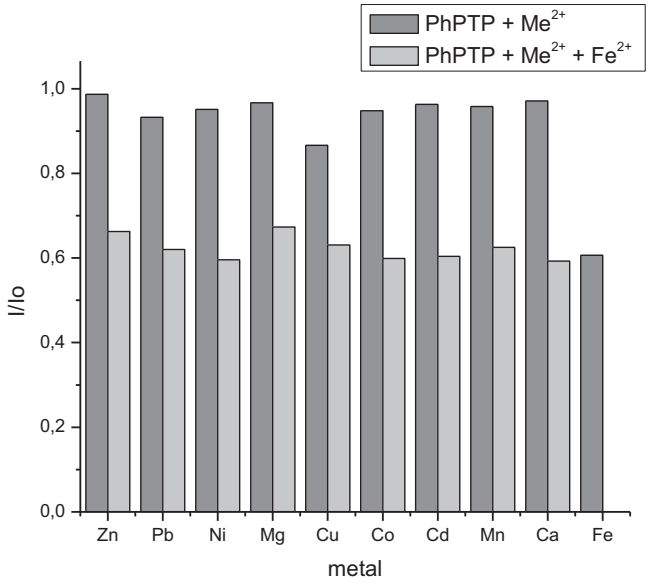

Fig. 7. Selectivity of the fluorescence quenching of PhPTP-DMβCD by Fe^{2+} in phosphate buffer pH 7.4. Black bars indicates the fluorimetric responses of PhPTP-DMβCD with 10 equivalents of Zn^{2+}, Pb^{2+}, Ni^{2+}, Mg^{2+},Cu^{2+}, Co^{2+}, Cd^{2+}, Mg^{2+}, Ca^{2+},Fe^{2+}. Grey bars represent the fluorescence response after addition to the same solutions 10 equivalent of Fe^{2+}.

between H2″/6″ and H3″/5″ of PhPTP with H6 of DMβCD, it can be noticed that triazolopyridine fragment is inserted in the cyclodextrin cavity, with the phenyl group oriented towards the primary hydroxyl group. On the other hand, the pyridine moiety protruded towards the secondary hydroxyl group remaining in the exterior of the cyclodextrin as evidenced by the lack of observed interactions with cyclodextrin, Fig. 6A.

In order to rationalize the NMR experimental results, we carried out molecular modeling studies of the complex. Our study revealed a preferred final orientation for the complex. This preferential pose occurs in spite of the different initial configurations arbitrarily imposed. The minimum energy complex obtained for DMβCD under study is shown in Fig. 6B. The results are in very good agreement with that obtained by the 2D ROESY spectra.

The effect of various metal ions on the fluorescence spectra of PhPTP-DMβCD chemosensor was examined in phosphate buffer at pH 7.4 with the addition of 10 equivalent of Zn^{2+}, Pb^{2+}, Ni^{2+}, Mg^{2+},Cu^{2+}, Co^{2+}, Cd^{2+}, Mg^{2+}, Ca^{2+} and Fe^{2+} ions to a 1×10^{-5} M solution of PhPTP-DMβCD. However the addition of these cations did not induce any obvious change in the fluorescence spectra with the exception for Fe^{2+}. This cation decreases the emission intensity by about one third upon addition to the complex, Fig. 7.

The binding stoichiometry of the ternary complex PhPTP-DMβCD-Fe was determined by Job plot experiments according to the fluorescence intensity at 490 nm plotted against molar fraction of PhPTP-DMβCD under a constant total concentration. The concentration of the complex approached a maximum intensity when the molar fraction was 0.5. These results indicate that chemosensor PhPTP-DMβCD forms a 1:1 PhPTP-DMβCD-Fe complex, Fig. S4.

As stated above, the selectivity is one of the most important properties of a sensor response. The selectivity toward Fe^{2+} alone was further assayed by competition experiments, adding 10 equivalent of Fe^{2+} ion over other competitive species, Zn^{2+}, Pb^{2+}, Ni^{2+}, Mg^{2+},Cu^{2+}, Co^{2+}, Cd^{2+}, Mg^{2+}, Ca^{2+}. The emission was quenched only in the presence of Fe^{2+}, Fig. 7. Thus, the competitive metal ions did not cause any significant changes in fluorescence intensity compared to Fe^{2+} solutions that contained no other metal ions. These results suggest that PhPTP-DMβCD can be used as a potential selective fluorescent chemosensor for Fe^{2+}.

A quantitative analysis of the fluorescence data was made as a function of the Fe^{2+} ion concentration. The data were

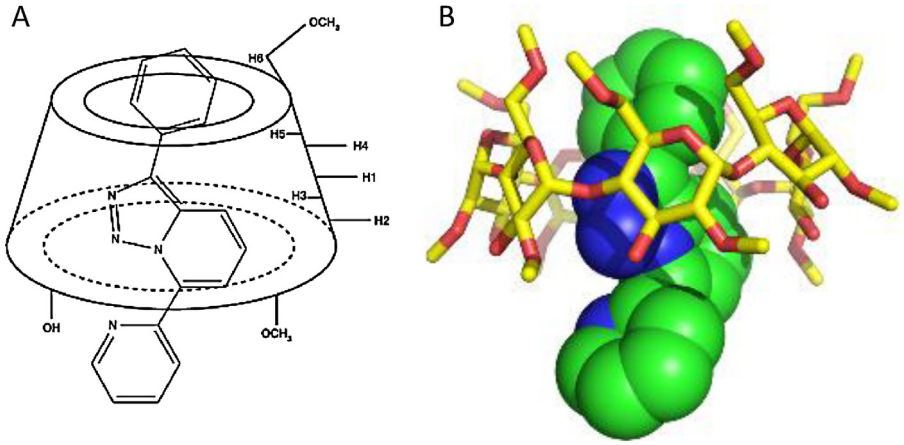

Fig. 6. (A) Possible PhPTP-DMβCD inclusion geometry based on the ROESY spectra, (B) molecular structure of the most stable PhPTP-DMβCD complex calculated by docking studies.

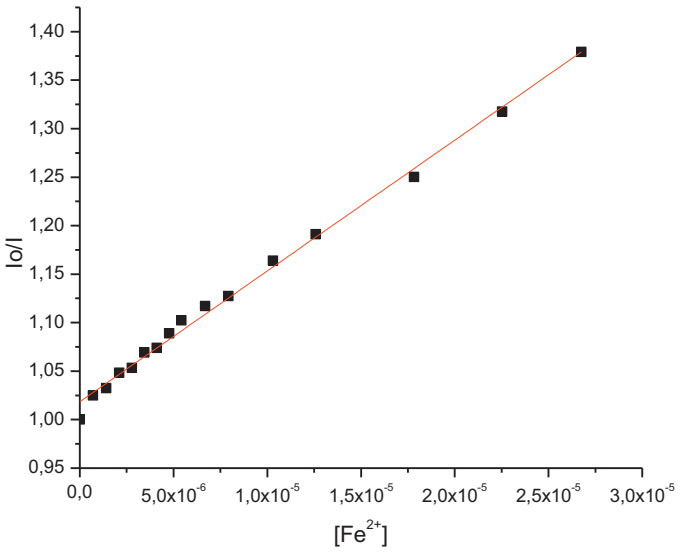

Fig. 8. Stern–Volmer graph of PhPTP-DMβCD [1×10^{-5}] upon addition of [Fe^{2+}].

plotted according to the Stern–Volmer equation. The Stern–Volmer quenching constant K_{SV} was estimated as $1.34 \times 10^4\ M^{-1}$ with a $R = 0.995$, Fig. 8.

The limit of detection (LOD) for the analysis of iron is determined from the plot of fluorescence intensity (i.e., $I - I_0$, where I_0 and I are the fluorescence intensities in the absence and presence of Fe^{2+}, respectively), as a function of the concentration of Fe^{2+} in the range from 0.5 to 6 μM. PhPTP-DMβCD showed a linear response of the emission intensity to the micromolar concentration of Fe^{2+} in aqueous solution, with a slope of -7.13163×10^6 and a correlation coefficient of 0.990 ($n = 9$). The LOD was calculated based on $3 \times Sb/m$, where Sb is the standard deviation of the intensity of a free sensor, m is the slope of a plot of the intensity at 488 nm vs. concentration. The detection limit is 7.2 μM (0.41 mg/L) indicating that this result is acceptable for recognition Fe(II) in aqueous solution.

4. Conclusion

A simple and water-soluble chemosensors system PhPTP-CDs for recognition of transition metal ions was designed. The inclusion complexes of PhPTP-βCD and PhPTP-DMβCD have a 1:1 molar ratio determined by Job plot. For both complexes the binding process is a spontaneous process and the inclusion are entropically driven. Due to DMβCD have its association constant 5 times higher than βCD, PhPTP-DMβCD was chosen as a possible divalent metal chemosensor. Inclusion geometry was determined by 2D-ROESY experiments, indicating that PhPTP is included in the hydrophobic cavity, with the phenyl group oriented towards the primary hydroxyl group and the pyridine is oriented towards the secondary hydroxyl group, totally exposed to the aqueous medium. This geometry was confirmed by molecular modeling studies. So, the PhPTP-DMβCD system, displays a high sensitivity for Fe^{2+} by fluorescence quenching in neutral aqueous solution even in the presence of other metals showing high selectivity towards Fe^{2+}.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.carbpol.2014.12.026.

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