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A water-soluble bithiophene with increased photoluminescence efficiency and metal recognition ability†

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A new water-soluble tri-*tert*-butyl-bithiophenesulfonamide (**$\alpha 2$ -tbS**) was synthesized and a comprehensive spectroscopic and photophysical study was undertaken in organic solvents and water at different pH values. In contrast to the behaviour found for the parent (and un-substituted) α, α' -bithiophene (**$\alpha 2$**), in which radiationless decay processes are the main excited-state deactivation channels, the *tert*-butylsulfonamide derivative presents a significant fluorescence quantum yield (ϕ_F) (ca. one order of magnitude higher than that of **$\alpha 2$**). The high ϕ_F allowed further exploring **$\alpha 2$ -tbS** as a selective fluorimetric sensor for metal ions. A strong selectivity towards Cu(II) is observed at neutral pH values, whereas at pH = 9.5 a strong quenching upon the addition of Hg(II) is observed. An additional high sensitivity of 0.64 ± 0.02 ppm towards Cu(II) was observed, well below 1.25 ppm ($\sim 20 \mu\text{M}$), the maximum value allowed in drinking water by the EPA.

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Introduction

Fluorescent materials with high selectivity and sensitivity to metal ions and anions and other elements that may have an environmental impact play an essential role not only in fundamental biology, pathophysiology, in clinical diagnosis and therapy^{1–3} but also in materials science with the development of stimuli-responsive molecules for the fabrication of smart materials.^{4–6} Thiophene-based oligomers and polymers have attracted remarkable attention as organic materials showing semiconducting, fluorescent, nonlinear optical and liquid crystalline properties. All these features can be fine-tuned through minor structural modifications. As a consequence, thiophene oligomers and polymers are among the most investigated compounds for applications in organic electronics, optoelectronics, and thin film devices such as field effect transistors, light emitting diodes, and photovoltaic devices.^{7,8}

Among all these applications of thiophene oligomers and polymers, a further application as fluorescent sensors is explored. Actually, it is well-known that heavy metal ions such as Hg²⁺,⁹ Cd²⁺,¹⁰ Pb²⁺,¹¹ and Cu²⁺ (ref. 12) can easily bind with proteins, enzymes, and nucleic acids, which may cause changes in the biological functions of these substances.

Furthermore, there is growing evidence that copper and copper-binding proteins are common denominators in the mechanisms of neurodegenerative diseases such as Alzheimer's and Parkinson's.^{13,14} According to the National Primary Drinking Water Regulations of USA, the acceptable amount of copper ions in drinking water is 1.25 mg L^{-1} ($\sim 20 \mu\text{M}$),¹⁵ beyond which they can cause cellular damage and Alzheimer's and Wilson's diseases. Therefore, low-cost on-site detector chips that can offer quantitative real-time detection of copper ions with identifiable signals (based on fluorescence) are clearly relevant. A low-cost methodology to rapidly detect these cations with sufficient sensitivity, but most importantly, in aqueous media is therefore mandatory.

However, the remarkable opto-electronic properties of conjugated thiophenes such as their high quantum yield are only possible with an oligomerization degree higher than six, which introduces some drawbacks:¹⁶ (i) their relatively low solubility in a wide range of solvents¹⁷ and (ii) the high mobility of the thiophene–thiophene bond, which allows twisted conformations that can limit conjugation through the oligothiophene chain.

Indeed, some efforts have been made in order to synthesize soluble bithiophene or terthiophene derivatives in polar or aqueous solvents without losing their photophysical properties for sensing applications. For example, by the introduction of side acyclic polyamine chains, a water-soluble bithiophene able to form stable copper complexes was developed by García-España *et al.*¹⁸ Functionalization of bithiophene units with propylenic and/or ethylenic chains containing protonated

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amines promotes a decrease in the π - π stacking of the aromatic moieties by introducing electrostatic repulsive interactions between the positive charges present in the chains.

Although the synthesis of water-soluble bithiophene was accomplished, again some drawbacks can appear since a remarkable pH dependence is present in these derivatives: (i) the solubility of the compounds change depending on the pH value; (ii) some coordination with metal ions present in the media is also possible and, finally, (iii) the photophysical properties change depending on the protonation state of the amine groups. Other functional groups can be used for solubilizing polythiophenes, *e.g.* by attaching flexible pendant groups onto the conjugated backbone.¹⁹ However, almost all of them are charged groups that, once more, show pH dependence. Moreover, a work on a novel oligothiophene-phenylamine-based Schiff base as a dual fluorescent chemosensor for the detection of Hg^{2+} and Cu^{2+} ions has been reported recently; yet, the solubility of this sensor in water is very low.²⁰

Finally, the importance of solubilizing this fluorescent unit in water is based on its application as a synthetic precursor for biologically active compounds active against the acute phase of African trypanosomiasis^{21,22} or interact with multi-stranded DNA structures.^{23,24}

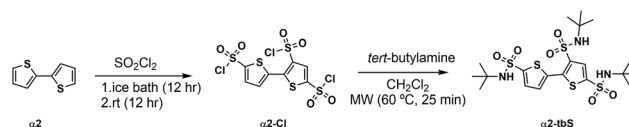
A new strategy, developed in this work, consists of the incorporation of sulfonamide groups into the bithiophene backbone. The SO_2 group is a strong electron acceptor that converts the amine into a very weak acid. Furthermore, the sulfonamide group is not a simple solubilizing agent and also the $-\text{SO}_2\text{NH}-$ group can play a role in the future application of the ligand since sulfonamide occurs in numerous biologically active compounds, which include antimicrobial drugs, saluretics, carbonic anhydrase inhibitors, antithyroid agents, and a number of others.²⁵

For this reason, here we present the synthesis of a new water soluble bithiophene derivative, and most interestingly, showing an improvement in the fluorescence emission in comparison with its parent compound. The acid-base behaviour is also evaluated over a wide pH range and the coordination of different transition metals is studied. All these improvements pave the way for a new line of research consisting of the development of a new family of stable compounds with high solubility in water and good fluorescence response for various applications including metal sensing.

Results and discussion

Synthesis

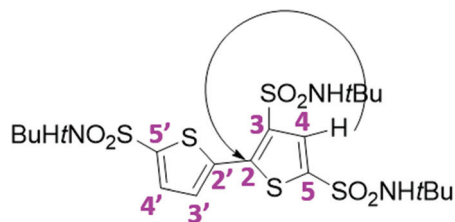
Scheme 1 depicts the procedure for the synthesis of the 3,5,5'-(*tert*-butyl)sulfonamidebithiophene derivative, $\alpha 2$ -tbS. Very briefly, chlorosulfonation of bithiophene through electrophilic aromatic substitution with neat chlorosulfonic acid at 0 °C for 24 h gives the trisulfonyl chloride derivative as a dark brown solid in almost quantitative yield. Posterior reaction under microwave irradiation with a primary amine allows the syn-



Scheme 1 Schematic synthetic route for the synthesis of the trisulfonamide derivative.

thesis of the trisulfonamide derivative tri-*tert*-butylsulfonamide ($\alpha 2$ -tbS).

The chlorosulfonation of aromatic systems has been successfully used for the synthesis of water-soluble derivatives, sulfonamides and sulfonic acids, of several aromatic compounds.^{26,27} Molecular orbital calculations of bithiophenes indicated that the order of reactivity with electrophiles is C-5 > C-3 > C-4²⁸ and experimentally, by controlling the stoichiometry of the reaction, it was possible to obtain 5,5'-disubstituted- or 3,3',5,5'-tetrasubstituted bithiophenes selectively.²⁹ Therefore, by performing the reaction under neat conditions with an excess of chlorosulfonic acid, the expected product is the tetrasubstituted derivative. The NMR spectra of the product of chlorosulfonation reaction performed in an ice bath for 12 hours and then 12 hours more at room temperature gave a distinct pattern of trisubstituted derivatives with three signals (two doublets and one singlet) with an integration ratio of 1 : 1 : 1. The substitution of hydrogen by sulfonyl groups with electron withdrawing character will decrease the rate of the electrophilic aromatic substitution, increasing the deactivation of the bithiophene with the increase of the degree of substitution, which could be responsible for the formation of the trisubstituted derivative as the major product and the absence of the tetrasubstituted bithiophene even under the neat conditions used. The full characterization of the trisulfonamide derivative, obtained by reaction with *tert*-butylamine under microwave irradiation with 70% yield, allows confirming the position of the substituents in the bithiophene ring. Together with the signal at higher magnetic field assigned to the *tert*-butyl and NH hydrogen, the ¹H-NMR spectrum shows three signals in the aromatic region, two doublets at 7.50 ppm and 7.65 ppm and a singlet at 7.95 ppm with a relative integration ratio of 1 : 1 : 1 (Fig. S4†). The ¹³C spectrum shows ten signals, at 30.0 and 47.1 ppm corresponding to the aliphatic groups; at 129.2, 130.1, and 131.3 ppm corresponding to the C of the aromatic structure bearing one H atom; at 136.5 and 137.0 ppm corresponding to the carbons in the bridge of the two thiophene units; and finally at 141.2, 145.7, and 149.5 ppm corresponding to the C of the aromatic structure bearing the *tert*-butyl group (Fig. S5†). The bidimensional HMBC spectrum shows a correlation between the hydrogen of the disubstituted thiophene ring (the singlet in the ¹H NMR) and only one of the quaternary carbons of the 2-2' linker, which should be the nearest, indicating that the other carbon of the linker is at least at four bond distance which is only possible with substitutions at positions 3 and 5 of the thiophene ring (Scheme 2 and



Scheme 2 Nomenclature used in the attribution of the NMR signals of $\alpha 2$ -tbS.

Fig. S6†). Therefore, the singlet in the ^1H NMR is attributed to the H at position 4.

Absorption and fluorescence

The absorption and fluorescence emission spectra of the tri-(*tert*-butylsulfonamide)bithiophene, $\alpha 2$ -tbS, and the unsubstituted bithiophene, $\alpha 2$, in dioxane are shown in Fig. 1 and the data of the other solvents of different viscosities and dielectric constants are summarized in Table 1. In general, the absorption and emission spectra of $\alpha 2$ -tbS display the characteristic spectroscopic features of the parent oligothiophene (with a

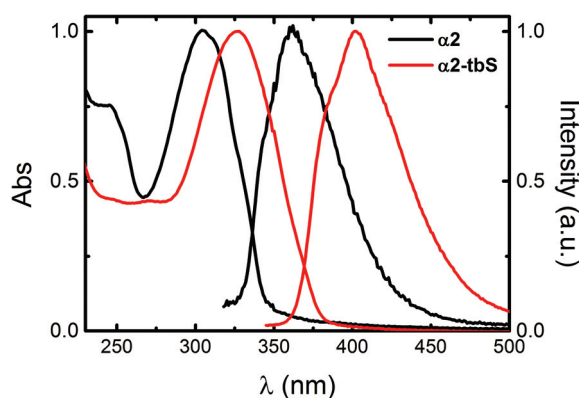


Fig. 1 Normalized absorption and fluorescence emission spectra of $\alpha 2$ -tbS (red) and $\alpha 2$ (black) in dioxane at $T = 293$ K.

Table 1 Spectral data (including absorption, λ_{abs} ; excitation λ_{ex} ; and emission, λ_{em} wavelength maxima; Stokes shifts) of $\alpha 2$ and $\alpha 2$ -tbS at $T = 293$ K

Compound	Solvent	η (cP)	ϵ ($\times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$)	$\lambda_{\text{max}}^{\text{Abs}}$ (nm)	$\lambda_{\text{max}}^{\text{Fluo}}$ (nm)	Δ_{SS} (cm^{-1})
$\alpha 2$	Dx	1.439	2.2	306	361	4979
	DMF	0.924	36.7	305	363	5239
	MeOH	0.593	32.7	302	358	5180
$\alpha 2$ -tbS	Dx	1.439	2.2	326	403	5861
	DMF	0.924	36.7	332	402	5245
	MeOH	0.593	32.7	323	401	6022
	2MeTHF	0.575	7.6	328	402	5612
	H ₂ O pH 0.4	1.009	80.2	313	403	7135
	H ₂ O pH 6.6			316	403	6972
	H ₂ O pH 13.8			323	402	5612

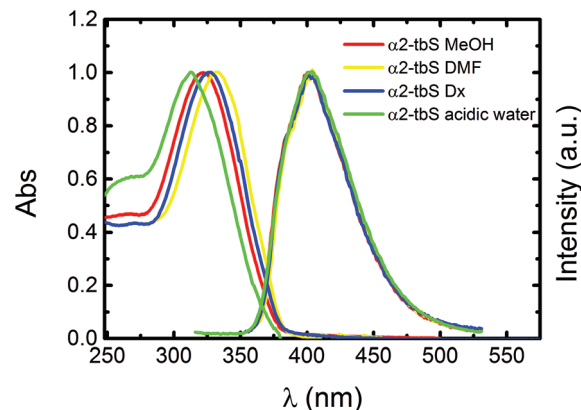


Fig. 2 Normalized absorption and fluorescence emission spectra in dioxane (blue), methanol (red), dimethylformamide (yellow), and water at acidic pH = 0.4 (green) solutions at $T = 293$ K.

broad absorption band—lacking vibronic structure—and a more structured fluorescence emission, see Fig. 1).

The characteristics of the absorption and emission spectra of $\alpha 2$ are the result of the existence of different conformations in the ground state (the spectra mirror the ensemble of conformers with different dihedral angles between the two thiophene rings) and of a more planar and rigid quinoidal-type *trans*-conformation in the excited state.³⁰ Although a similar spectral behaviour is found for $\alpha 2$ -tbS, some interesting different features are worthy of note. Indeed, $\alpha 2$ -tbS exhibits large spectral solvent dependent red-shifts of the absorption (20–27 nm) and emission wavelength maxima (39–43 nm) when compared to $\alpha 2$ (see Table 1), thus pointing to an increase in the π -electronic delocalization in the former. The identical characteristic absorption and emission spectra, together with the similar Stokes shift values (Δ_{SS}) of $\alpha 2$ (Table 1), point to the identical structural changes in the ground and excited states for $\alpha 2$ -tbS and $\alpha 2$.

Fig. 2 shows the absorbance and emission spectra in both aprotic and protic organic solvents of different polarities (representative solvents are shown in Fig. 2; for more solvents, see Fig. S8†), together with the absorbance in water at different pH values (Fig. S9).† A red-shift with the increase in the polarity of the media was observed in the absorption spectra whereas no observable change in the fluorescence was found. These results point out once again for a quinoidal-like structure in the excited state of $\alpha 2$ -tbS and absence of intramolecular charge transfer transitions.

Dependence on pH

As mentioned in the introduction section, despite the high number of applications of oligothiophenes as fluorescent sensors, their use in biological media is often hampered by their low solubility in aqueous or polar solvents. However, with the present *tert*-butylsulfonamide derivatization in the bithiophene moiety, a significant improvement in the solubility in water was obtained, which allowed the study of the spectroscopic and photophysical properties of $\alpha 2$ -tbS in a wide pH

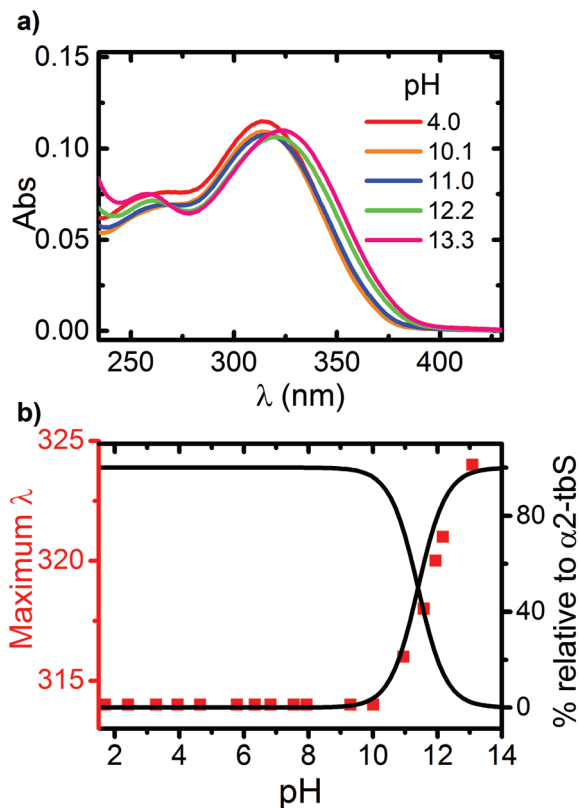
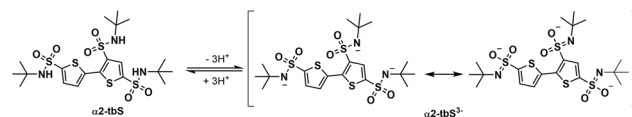


Fig. 3 (a) Absorption spectra of $\alpha 2$ -tbS recorded at $T = 298$ K in water as function of pH; (b) absorption maximum wavelength (■) and mole fraction distribution curves (% relative to $\alpha 2$ -tbS) as functions of pH for the different protonated forms (solid lines).

range. Fig. 3 shows the absorption spectra as a function of the pH together with the corresponding titration curve (for the complete titration curve, please see Fig. S9†). The acid–base equilibrium in the ground state involves the presence of a neutral ($\alpha 2$ -tbS) and a tri-deprotonated species ($\alpha 2$ -tbS $^{3-}$) (see Scheme 3) with absorption maxima at 313 nm and 323 nm, respectively. From the spectrophotometric titration (Fig. 3b), a $p\beta_{13}$ —defined as the cumulative constant of the tri-deprotonation of $\alpha 2$ -tbS (see supplementary data for equilibria equations, Scheme S1)†—value of around 11.4 was obtained when the wavelength absorption maximum was plotted *versus* the pH. Indeed, secondary sulfonamides (without electron-withdrawing groups on nitrogen) are considered relatively acidic ($pK_a \sim 10$) because the charge formed in the conjugate base can be stabilized by resonance.³¹

From the fluorescence emission titration (Fig. 4a), the characteristic emission of the neutral form of $\alpha 2$ -tbS is observed with a strong decrease in the fluorescence intensity with the pH. At very basic pH values (see inset), a blue shift in the emission band is also observed. The gradual decrease in the fluorescence emission with the pH increase (see Fig. 4a and Table 2) is a consequence of the competitive quenching (electron transfer) promoted by the unprotonated sulfonamide groups. Furthermore, the emissive spectral changes can be quantitatively obtained from the fluorescent quantum yield



Scheme 3 Acid–base equilibria for $\alpha 2$ -tbS together with the proposed resonant structures for the tri-deprotonated form.

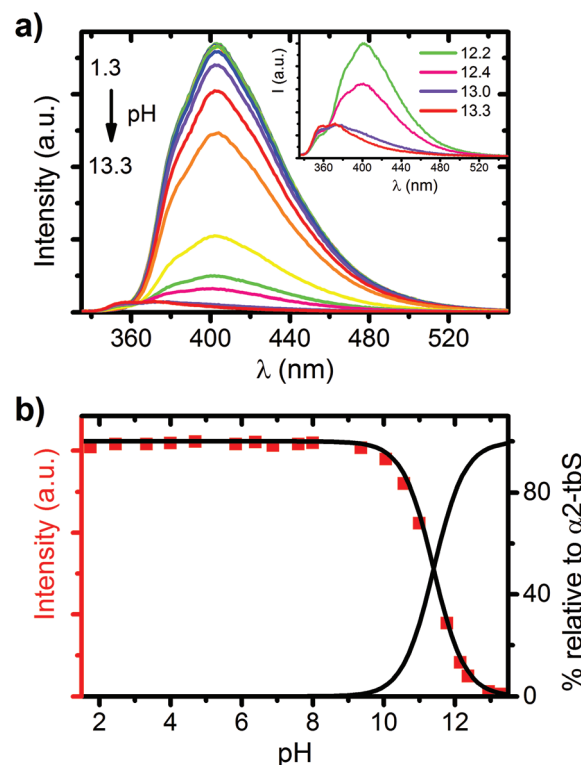


Fig. 4 (a) Steady-state fluorescence emission spectra of $\alpha 2$ -tbS ($\lambda_{exc} = 282$ nm) recorded at $T = 298$ K in water as a function of pH. Inset: emission of fluorescence from pH 12.15 to 13.29; and (b) emission of fluorescence at 402 nm (■) and mole fraction distribution curves for the different protonated forms (solid lines).

Table 2 Photophysical data including fluorescence quantum yields (ϕ_F), fluorescence lifetimes (τ_F), and rate constants (k_F and k_{NR}) of $\alpha 2$ -tbS obtained in water at different pH values and at $T = 293$ K with $\lambda_{exc} = 339$ nm and $\lambda_{em} = 402$ nm (decays). The chi-squared (χ^2) values resulting from the analysis of the fluorescence decays are also given as criteria to judge the quality of the fit

pH	ϕ_F	τ_F (ns)	χ^2	k_F^a (ns $^{-1}$)	k_{NR}^b (ns $^{-1}$)
1.0	ND	0.45	1.07	—	—
1.6	0.1	0.41	1.02	0.24	2.20
3.6	ND	0.41	0.96	—	—
7.1	0.1	0.41	1.04	0.24	2.20
9.0	0.08	0.43	1.03	0.19	2.14
10.8	0.08	0.45	1.13	0.18	2.04
11.1	ND	0.45	0.98	—	—
12.6	0.01	0.46	1.35	0.02	2.15

^a $k_F = \frac{\phi_F}{\tau_F}$. ^b $k_{NR} = \frac{1 - \phi_F}{\tau_F}$. ND = not determined.

(ϕ_F). With the addition of sulfonamide groups in the structure of bithiophene, a 10-fold increase in the value of the fluorescence quantum yield of $\alpha 2$ (reported to be 0.01 in ethanol³²) was achieved with values of $\phi_F \sim 0.1$ in the pH range from 2.1 to 9.0; lower values of $\phi_F \sim 0.01$ at pH = 12.5 show that the deprotonation of the sulfonamide groups allows them to quench the excited fluorophore by electron transfer.³³

From the fluorescence emission titration, the excited state dissociation constant for the equilibrium between the neutral and deprotonated species was found to be $p\beta_{13}^* \sim 11.4$ (see Fig. 4b), in good agreement with the value previously reported for sulfonamide derivatives and the one obtained from the spectroscopic titration.³⁴

Time-resolved fluorescence

Time-resolved fluorescence measurements in water at different pH values and in organic solvents were obtained for $\alpha 2$ -tbS at $T = 293$ K.

Table 2 summarizes the lifetime values, fluorescence quantum yield and rate radiative and radiationless rate constants of $\alpha 2$ -tbS at different pH values with the objective to rationalize the influence of the deprotonation of sulfonamide on the photophysics of the compound. The analysis of the data revealed that the fluorescence decays are always single exponential even when the deprotonation of the sulfonamide is reached where a double exponential could be anticipated due to the simultaneous presence of protonated and unprotonated species in the ground state (see Fig. S10[†]). This behavior indicates that despite the (ground state) deprotonation, the resulting excited state is a species that is independent of the solvent. This is further complemented by the consistency of the lifetime values with pH (Table 2) indicating the same excited state emissive species. However, the deprotonation of the sulfonamide is indeed affecting the fluorescence quantum yield since there is a decrease from 0.1 to 0.01 after the $p\beta_3$ is reached. This effect is further mirrored in the radiative rate constant, which decreases by one order of magnitude upon the increase in pH from 10.1 to 12.56, whereas the radiationless rate constant remains approximately identical in value (~ 2 ns⁻¹).

The photophysical data were also obtained for $\alpha 2$ -tbS in solvents of different viscosity and polarity (Fig. S11[†]). The data is summarized in Table 3. Again, and similarly to what was found with $\alpha 2$, the ϕ_F and τ_F values are insensitive to the media.

For $\alpha 2$ in dioxane, the radiative and radiationless rate constants are found to be 0.37 and 21 ns⁻¹.³² Comparison with the data in Table 3 for $\alpha 2$ -tbS clearly shows a high decrease in the radiationless decay, pointing out for a much more efficient radiative channel with this derivative while keeping essentially the same spectroscopic characteristics. This paves the way for sensor applications of these compounds as demonstrated in the next section.

Metal sensing ability

The high solubility of the ligand $\alpha 2$ -tbS in water allowed further evaluating the feasibility of $\alpha 2$ -tbS as a fluorescent

Table 3 Fluorescence quantum yields (ϕ_F), radiative (k_F), and radiationless (k_{NR}) rate constants and fluorescence lifetimes (τ_F) of $\alpha 2$ -tbS in different organic solvents and at $T = 293$ K obtained with $\lambda_{exc} = 339$ nm and $\lambda_{em} = 402$ nm. The chi-squared (χ^2) values resulting from the analysis of the fluorescence decays are also given as criteria to judge the quality of the fit

Solvent	ϕ_F	τ_F (ns)	χ^2	k_F^a (ns ⁻¹)	k_{NR}^b (ns ⁻¹)
Dioxane	0.16	0.51	0.85	0.32	1.65
DMF	0.15	0.53	0.95	0.28	1.62
MeOH	0.12	0.39	1.06	0.30	2.30

$$^a k_F = \frac{\phi_F}{\tau_F}, \quad ^b k_{NR} = \frac{1 - \phi_F}{\tau_F}$$

sensor toward metal ions. Therefore, spectrofluorimetric titrations of $\alpha 2$ -tbS with Cu²⁺, Co²⁺, Hg⁺, Hg²⁺, Cd²⁺, Pb²⁺, Mn²⁺, and Zn²⁺ were performed. As shown before, the fluorescence of $\alpha 2$ -tbS is not pH sensitive until the deprotonation of the sulfonamide group occurs (Fig. 4); therefore, a wide range of pH values was used in the spectrofluorimetric titrations with the metal ions. The corresponding emission intensity at 402 nm for the whole pH range studied is included in ESI (see Fig. S12[†]). During the titrations with different metals, no significant changes in absorbance were observed. However, remarkable changes in the emission of fluorescence were observed with Cu²⁺ and Hg²⁺. In case of mercury and manganese, the hydrolysis equilibria could compete with binding reactions at basic pH values. Nevertheless, no recognition has been found for any species of these two metal ions.

Fig. 5 shows the changes in the emission intensity observed resulting from the interaction of $\alpha 2$ -tbS with the metal ions at pH = 7.0. From these results, the high selectivity of the system $\alpha 2$ -tbS for sensing Cu²⁺ cations in aqueous solution in a pH window around 7 should be highlighted. A strong CHEQ (chelation enhancement quenching) effect can be observed with

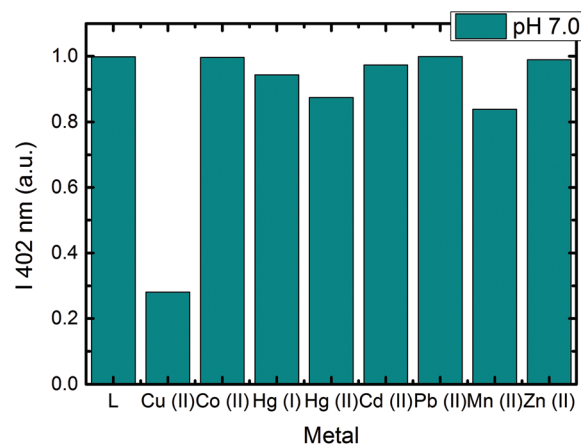


Fig. 5 Bar diagram representation of the normalized response fluorescence intensity of $\alpha 2$ -tbS upon the addition of divalent metal at pH 7.0. The y-axes have been constructed so that the fluorescence of the free ligand is normalized to 1. Titrations performed in water (pH = 7, [$\alpha 2$ -tbS] = 1.3×10^{-5} M) at $T = 298.1$ K with $\lambda_{exc} = 317$ nm.

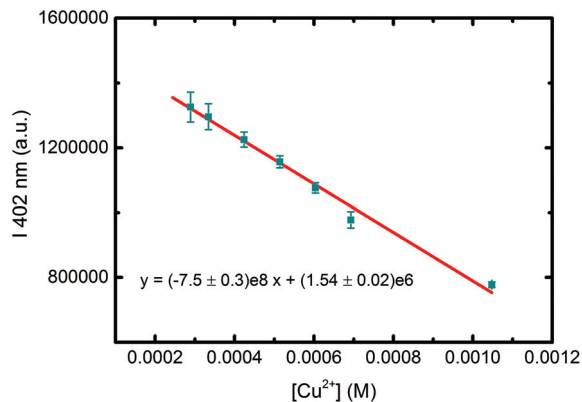


Fig. 6 Plot of the fluorescence intensity at 402 nm for $\alpha 2$ -tbS vs. $[Cu^{2+}]$ obtained at pH = 7.5. $[\alpha 2$ -tbS] = 1.3×10^{-5} M, λ_{exc} = 317 nm.

the copper complex formation that is allowed due to the deprotonation of the amide unit at this pH.^{35,36} This quenching of the fluorescence is commonly observed in nitrogenated ligands containing aromatic fluorophores and is attributed to an energy transfer quenching of the π, π^* emissive state (of the ligands) through low-lying metal-centered states.³⁷

The behavior at other pH values was also evaluated in order to test $\alpha 2$ -tbS for metal recognition. The corresponding intensity variation at pH 7.6 and 9.5 are shown in Fig. S13.† At higher pH values Hg^{2+} —and in lower extent Mn^{2+} —can be selectively recognized by $\alpha 2$ -tbS. In both cases, the metal recognition is achieved by the formation of a complex through the deprotonation of the amide, causing a decrease in the emission of the fluorescence.^{38,39}

In addition to this high selectivity for Cu^{2+} , a remarkable additional feature of this sensing system is its sensitivity. The detection limit depends on the instrumentation (*i.e.* the signal-to-noise ratio, SNR, gives a quantitative indication of the sensitivity of the equipment) and on the sensitivity of the ligand towards Cu^{2+} , defined as the slope of $d(\text{luminescence})/d[\text{cation}]$ (Fig. 6). Using these two parameters, the limit of detection can then be calculated as $3 \cdot \text{SNR}/(\text{sensitivity of the ligand})$. The mean value of 0.64 ± 0.02 ppm, with a linear range from 0.64 ppm to 389 ppm, lies far below the value of 1.25 ppm, which is the maximum allowed value of Cu^{2+} amount in drinking water by the USA Environmental Protection Agency (EPA).¹⁵

Experimental

Materials and methods

The chemicals chlorosulfonic acid, sodium bicarbonate, and *tert*-butylamine were obtained from commercial sources and used as received. 2,2'-Bithiophene was purified by sublimation with a cold finger. Water was twice distilled and passed through a Millipore apparatus. All the solvents (spectroscopic or equivalent grade) were used without further purification. The pH values were measured with a 3510 Jenway pH meter

and adjustments of the hydrogen ion concentration of the solutions were made with diluted $HClO_4$ and NaOH solutions.

Perchlorate salts for Cu(II), Zn(II), and Co(II) solutions, sulphate salts for Mn(II), chloride salts for Hg(I) and Hg(II) and triflate salts for Cd(II) and Pb(II) were employed in the preparation of the solutions. The solutions of the ligand $\alpha 2$ -tbS were prepared by keeping the concentration equal to 1.3×10^{-5} M.

Microwave-assisted synthesis was performed using a CEM Discover S-Class single-mode microwave reactor, featuring continuous temperature, pressure, and microwave power monitoring. ¹H NMR and ¹³C NMR spectra were recorded using a Bruker-AMX with an operating frequency of 400 and 101 MHz, respectively. High-resolution mass spectrometry (HRMS) was performed using a Bruker microTOF-Focus mass spectrometer equipped with an electrospray ionization time-of-flight (ESI-ToF) source.

The absorption and fluorescence spectra were recorded with a Cary 5000 spectrophotometer and a Horiba-Fluoromax spectrofluorimeter, respectively. All the fluorescence spectra were corrected for the wavelength response of the system. The fluorescence quantum yields were measured using the absolute method with a Hamamatsu Quantaaurus QY absolute photoluminescence quantum yield spectrometer model C11347 (integration sphere). The absorption of the solutions was kept under 0.1 at the excitation wavelength to avoid the inner filter effect.⁴⁰ Fluorescence decay times were obtained using two (ps- and ns-time resolution) Time-Correlated Single Photon Counting (TCSPC) technique with nanosecond time resolution using equipment described elsewhere.^{41,42} The obtained fluorescence decays were deconvoluted employing the method of modulating functions implemented by George Striker.⁴³

Synthetic procedures

Synthesis [2,2'-bithiophene]-3,5,5'-trisulfonyltrichloride, $\alpha 2$ -Cl. 2,2'-Bithiophene ($\alpha 2$) (0.6 g, 3.61 mmol) was placed in a round bottom flask under nitrogen in an ice-bath. Keeping an inert atmosphere, chlorosulfonic acid (13 mL, 180 mmol) was added. The mixture was stirred at 0 °C for 12 hours and then overnight at room temperature. The solution was neutralized with saturated $NaHCO_3$ (aq) and the solid was then filtered and washed with water (2.01 g, 82% yield (90% purity by NMR)). ¹H NMR (DMSO, 400 MHz): δ (ppm), 7.04 (d, J = 3.7 Hz, 1H), 7.22 (s, 1H), 7.49 (d, J = 3.7 Hz, 1H). ¹³C NMR (DMSO, 101 MHz): δ (ppm), 126.4, 128.1, 129.3, 132.3, 134.3, 142.9, 146.4, 151.0.

Synthesis $N^3, N^5, N^{5'}$ -tri-*tert*-butyl-[2,2'-bithiophene]-3,5,5'-trisulfonamide, $\alpha 2$ -tbS. The chlorosulfonic intermediate $\alpha 2$ -Cl (0.52 g, 1.01 mmol) was dissolved in dichloromethane (2 mL). Then, *tert*-butylamine (331.7 μ L, 3.16 mmol) and triethylamine (440.6 μ L, 3.16 mmol) were added. The reaction was carried out under microwave conditions at 60 °C for 25 min. The solvent was removed under vacuum. To the reaction crude, 50 mL of water was added and the organic compounds were with CH_2Cl_2 (3 \times 40 mL). The combined organic phases were dried over Na_2SO_4 , filtered and evaporated to dryness. The residue was purified through SiO_2 column chromatography

using as eluent CH₂Cl₂:acetone (80:20) to obtain the desired compound **α2-tbS** in 70% yield. ¹H NMR (CDCl₃, 400 MHz): δ (ppm), 1.31–1.32 (m, 27H), 4.99 (s, 1H), 5.17 (s, 1H), 7.50 (d, *J* = 3.9 Hz, 1H), 7.65 (d, *J* = 3.9 Hz, 1H), 7.95 (s, 1H). ¹³C NMR (CDCl₃, 101 MHz): δ (ppm), 30.1, 129.6, 131.6, 133.9, 137.8, 138.1, 142.0, 142.1, 147. ESI-MS (*m/z*): calculated for C₂₀H₃₃N₃O₆S₅: 571.0973; found: [L + H]⁺ 572.1046

Conclusions

The study undertaken paves the way to the discovery of structural requirements for the synthesis of new water-soluble bithiophenes, with a strong increment in fluorescent efficiency and selectivity towards metal ions. The solubility of **α2-tbS** in water enabled its application as a selective sensor for copper and mercury in aqueous solutions, in a wide range of pH values. The low detection limit obtained for copper in pure water showed that sulfonamide bithiophene derivatives have a very promising application in the detection of Cu²⁺. Moreover, the increase in the fluorescence quantum yield (also valid for the fluorescence lifetime) on going from **α2** to **α2-tbS** is the key to the design and subsequent preparation of highly fluorescent oligothiophenes for potential use as functional materials.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- K. P. Carter, A. M. Young and A. E. Palmer, *Chem. Rev.*, 2014, **114**, 4564–4601.
- K. Nienhaus and G. Ulrich Nienhaus, *Chem. Soc. Rev.*, 2014, **43**, 1088–1106.
- B. Liu and G. C. Bazan, *Chem. Mater.*, 2004, **16**, 4467–4476.
- R. D. McCullough, *Handbook of Oligo- and Polythiophenes*, 1998, ch. 1, pp. 1–44, DOI: 10.1002/9783527611713.ch1.
- K. P. R. Nilsson and O. Inganäs, *Nat. Mater.*, 2003, **2**, 419–424.
- L. Chen, D. W. McBranch, H.-L. Wang, R. Helgeson, F. Wudl and D. G. Whitten, *Proc. Natl. Acad. Sci. U. S. A.*, 1999, **96**, 12287.
- R. D. McCullough, *The Chemistry of Conducting Polythiophenes: from Synthesis to Self-Assembly to Intelligent Materials*, Wiley, 2008.
- Handbook of Thiophene-Based Materials: Applications in Organic Electronics and Photonics*, Wiley, 2009.
- D. T. Quang and J. S. Kim, *Chem. Rev.*, 2010, **110**, 6280–6301.
- A. Rani, A. Kumar, A. Lal and M. Pant, *Int. J. Environ. Health Res.*, 2014, **24**, 378–399.
- G. Flora, D. Gupta and A. Tiwari, *Interdiscip. Toxicol.*, 2012, **5**, 47–58.
- J. J. A. Cotruvo, A. T. Aron, K. M. Ramos-Torres and C. J. Chang, *Chem. Soc. Rev.*, 2015, **44**, 4400–4414.
- I. F. Scheiber, J. F. B. Mercer and R. Dringen, *Prog. Neurobiol.*, 2014, **116**, 33–57.
- E. Tiffany-Castiglioni, S. Hong and Y. Qian, *Int. J. Dev. Neurosci.*, 2011, **29**, 811–818.
- U. S. EPA, *Fed. Regist.*, 1991, **56**, 5.
- J. S. Seixas de Melo, F. Elisei, C. Gartner, G. G. Aloisi and R. S. Becker, *J. Phys. Chem. A*, 2000, **104**, 6907–6911.
- Y. Miyata, T. Nishinaga and K. Komatsu, *J. Org. Chem.*, 2005, **70**, 1147–1153.
- P. Díaz, A. Doménech, E. García-España and C. Soriano, *Polyhedron*, 2002, **21**, 1523–1530.
- S. Das, D. P. Chatterjee, R. Ghosh and A. K. Nandi, *RSC Adv.*, 2015, **5**, 20160–20177.
- S. Zhang, Q. Niu, L. Lan and T. Li, *Sens. Actuators, B*, 2017, **240**, 793–800.
- M. A. Ismail, S. A. E. Bialy, R. Brun, T. Wenzler, R. Nanjunda, W. D. Wilson and D. W. Boykin, *Bioorg. Med. Chem.*, 2011, **19**, 978–984.
- D. G. J. Batista, M. G. O. Pacheco, A. Kumar, D. Branowska, M. A. Ismail, L. Hu, D. W. Boykin and M. N. C. Soeiro, *Parasitology*, 2009, **137**, 251–259.
- R. Nhili, P. Peixoto, S. Depauw, S. Flajollet, X. Dezitter, M. M. Munde, M. A. Ismail, A. Kumar, A. A. Farahat, C. E. Stephens, M. Duterque-Coquillaud, W. David Wilson, D. W. Boykin and M.-H. David-Cordonnier, *Nucleic Acids Res.*, 2012, **41**, 125–138.
- D. N. Kaluzhny, O. F. Borisova and A. K. Shchyolkina, *Biopolymers*, 2010, **93**, 8–20.
- C. A. Fink, J. M. McKenna and L. H. Werner, *Diuretic and uricosuric agents*, John Wiley & Sons, New York, 2003.
- R. C. Pereira, M. Pineiro, A. M. Galvão and J. S. Seixas de Melo, *Dyes Pigm.*, 2018, **158**, 259–266.

- 27 R. C. Pereira, A. D. R. Pontinha, M. Pineiro and J. S. Seixas de Melo, *Dyes Pigm.*, 2019, **166**, 203–210.
- 28 R. M. Kellogg, A. P. Schaap and H. Wynberg, *J. Org. Chem.*, 1969, **34**, 343–346.
- 29 I. Novak, S. C. Ng, H. H. Huang, C. Y. Mok, E. Khor and B. Kovač, *J. Phys. Org. Chem.*, 1991, **4**, 675–680.
- 30 A. Almenningen, O. Bastiansen and P. Svendsås, *Acta Chem. Scand.*, 1958, **12**, 3.
- 31 B. A. Caine, M. Bronzato and P. L. A. Popelier, *Chem. Sci.*, 2019, **10**, 6368–6381.
- 32 R. S. Becker, J. S. Seixas de Melo, A. L. Maçanita and F. Elisei, *J. Phys. Chem.*, 1996, **100**, 18683–18695.
- 33 F. Pina, J. C. Lima, C. Lodeiro, J. S. Seixas de Melo, P. Díaz, M. T. Albelda and E. García-España, *J. Phys. Chem. A*, 2002, **106**, 8207–8212.
- 34 T. Koike, E. Kimura, I. Nakamura, Y. Hashimoto and M. Shiro, *J. Am. Chem. Soc.*, 1992, **114**, 7338–7345.
- 35 H. Sigel and R. B. Martin, *Chem. Rev.*, 1982, **82**, 385–426.
- 36 H.-J. Liu, Y.-H. Hung, C.-C. Chou and C.-C. Su, *Chem. Commun.*, 2007, 495–497, DOI: 10.1039/B613583H.
- 37 R. Aucejo, J. Alarcón, E. García-España, J. M. Llinares, K. L. Marchin, C. Soriano, C. Lodeiro, M. A. Bernardo, F. Pina, J. Pina and J. Seixas de Melo, *Eur. J. Inorg. Chem.*, 2005, **2005**, 4301–4308.
- 38 S. Syed Shoaib Ahmad, A. Muhammad, N. Tayyaba, A. Muhammad Mehboob, S. Salma, T. Rukhsana and E. Syeda Abida, *Curr. Bioact. Compd.*, 2013, **9**, 211–220.
- 39 M. Pervaiz, A. Riaz, A. Munir, Z. Saeed, S. Hussain, A. Rashid, U. Younas and A. Adnan, *J. Mol. Struct.*, 2020, **1202**, 127284.
- 40 D. Magde, R. Wong and P. G. Seybold, *Photochem. Photobiol.*, 2002, **75**, 327–334.
- 41 A. L. Maçanita, F. P. Costa, S. M. B. Costa, E. C. Melo and H. Santos, *J. Phys. Chem.*, 1989, **93**, 336.
- 42 J. Pina, J. S. Seixas de Melo, H. D. Burrows, A. L. Maçanita, F. Galbrecht, T. Bunnagel and U. Scherf, *Macromolecules*, 2009, **42**, 1710–1719.
- 43 G. Striker, V. Subramaniam, C. A. M. Seidel and A. Volkmer, *J. Phys. Chem. B*, 1999, **103**, 8612.