Journal of Molecular Structure 977 (2010) 26–38

Contents lists available at ScienceDirect

Journal of Molecular Structure

journal homepage: www.elsevier.com/locate/molstruc

Synthesis of zinc phthalocyanine derivatives with improved photophysicochemical properties in aqueous media

Ali Erdoğmuş [a,b], Tebello Nyokong [a,*]

[a] Department of Chemistry, Rhodes University, Grahamstown 6140, South Africa
[b] Department of Chemistry, Yildiz Technical University, 34210 Esenler, Istanbul, Turkey

A R T I C L E I N F O

Article history:
Received 7 March 2010
Received in revised form 30 April 2010
Accepted 30 April 2010
Available online 11 May 2010

Keywords:
Zinc phthalocyanines
Water soluble
Triplet quantum yield
Fluorescence quantum yield
Singlet oxygen
Photodynamic therapy

A B S T R A C T

The synthesis, photophysical and photochemical properties of new peripherally (β) tetra-substituted thioquinoline Zn(II) (**2**) and quaternized thioquinoline Zn(II) phthalocyanines (**3**) and quaternized fluoro functional thiopyridine Zn(II) (**5**) are described for the first time. These complexes (**2**, **3** and **5**) have been synthesized and characterized by elemental analysis, IR, ^{1}H NMR spectroscopy and electronic spectroscopy. Complexes **2**, **4** and **6** have good solubility in organic solvents such as $CHCl_3$, DCM, DMSO, DMF, THF and toluene and are not aggregated in all solvents (except for **2** in DMSO) within a wide concentration range. Complexes **3** and **5** showed very good solubility in water as well as DMSO and DMF. General trends are described for singlet oxygen, photodegradation, fluorescence quantum yields, triplet quantum yields and triplet life times of these complexes in DMSO (**2**, **4** and **6**) and water (**3** and **5**). Complex **3** gave a very large triplet quantum yield in aqueous media ($\Phi_T = 0.8$ in water plus Triton X-100) and a reasonable triplet lifetime of 110 μs. Photophysical and photochemical properties of the phthalocyanines complexes **2**–**6** are very useful for PDT.

1. Introduction

Metallophthalocyanines (MPcs) have been known to have very interesting properties coupled with excellent stability to heat, light and strong chemical environments. Their optical and electronic properties have been exploited in various applications including as pigments, in infrared security devices, information storage and computer disk writing and in photodynamic therapy of cancer (PDT) [1–4]. For PDT applications, it is important that MPcs exhibit high absorption coefficients ($\varepsilon > 10^5\ M^{-1}\ cm^{-1}$) in the visible region of the spectrum, mainly in the phototherapeutic window (600–800 nm) and a long lifetime of triplet excited state in order to produce singlet molecular oxygen, $O_2(^1\Delta g)$ efficiently.

Applications of phthalocyanines are restricted due to their insolubility in common solvents and water [5]. The solubility of phthalocyanines can be improved by introducing different kinds of bulky substituents, such as crown ethers, alkyl, alkoxy and alkylthio; electron-withdrawing substituents (—F, —Cl, —Br, —NO_2, etc.) and donor atoms such as N and O at the periphery of the phthalocyanines [6–10]. For PDT applications, the drug is injected into the patient‘s blood stream, and since the blood itself is a hydrophilic system, water solubility becomes crucial for a potential photosensitizer for PDT [11]. The advantages of MPcs bearing cationic substituents over those with neutral and anionic substituents are numerous [12–15] and include the following: (i) they have been shown to be more efficient as PDT agents [14] improve cell uptake [15] and (ii) are selectively localized in the cell mitochondria, which induces apoptosis [16].

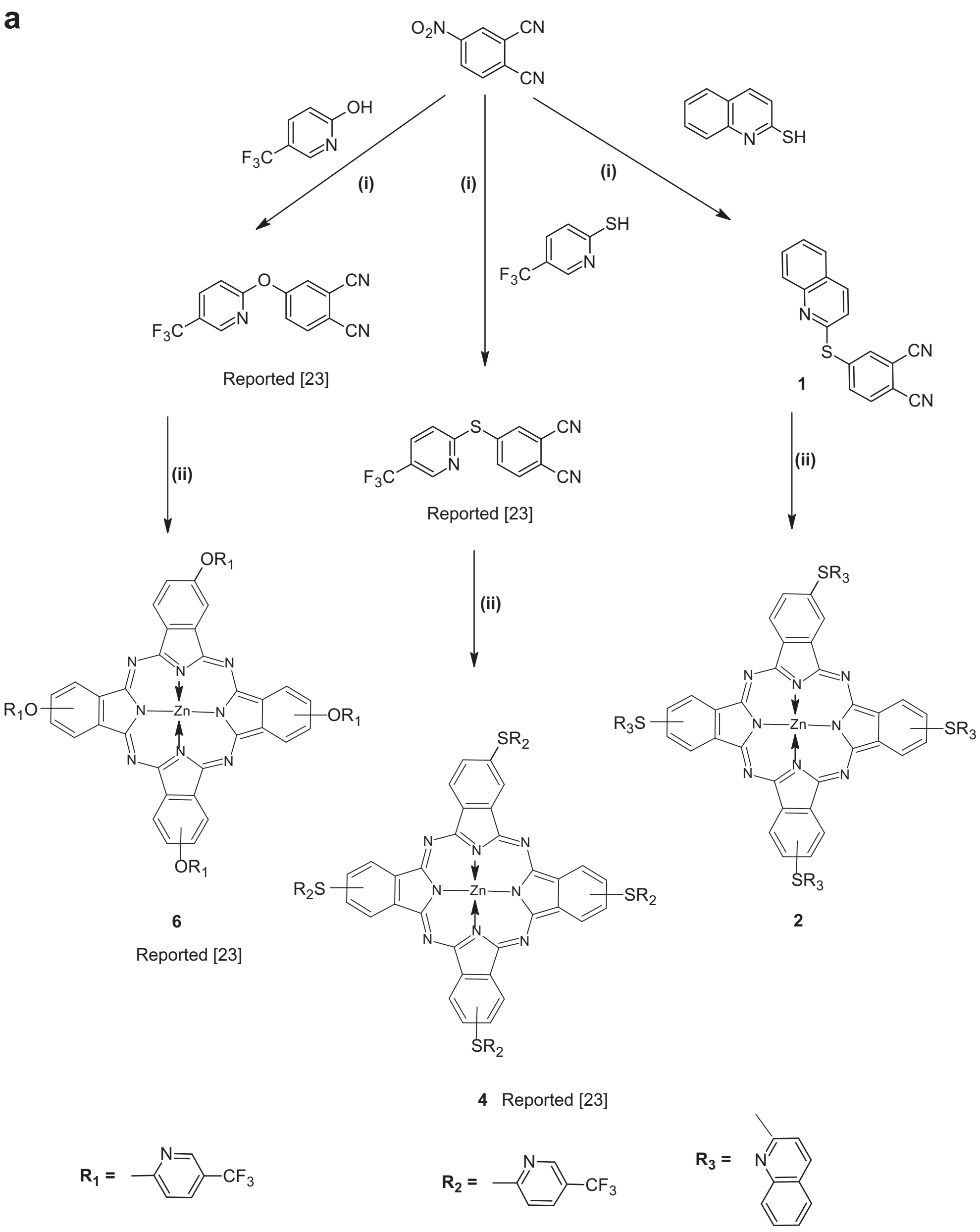
MPcs which are substituted with aryl thio groups have been reported [17,18]. MPcs substituted with thiopyridine groups and their quaternized derivatives have also been reported [19,20]. The use of thioquinoline followed by quaternization is reported here for the first time. Although phthalocyanines bearing electron-donating substituents have frequently been studied, those bearing electron-withdrawing ones have not been extensively studied, especially those containing fluorine atoms [21,22]. Therefore we report the synthesis, characterization and photophysical and photochemical properties of new organo-soluble and water soluble Zn phthalocyanines bearing fluoro-functionalised pyridine and thiopyridine substituents. The effect of the extension of the ring substituents (compared to thiopyridine) on the photophysical properties will be discussed.

This work investigates the photosensitizing tendencies of some Zn^{2+} tetra substituted phthalocyanines (Scheme 1a) and their quaternized derivatives (Scheme 1b). The effect of the substituent and solvent on the photophysical and photochemical properties of the new complexes will be discussed. The solvents employed are: dimethylsulfoxide (DMSO) and water (for **3** and **5**). The combination of fluorine substituents and quaternization results in

---

* Corresponding author. Tel.: +27 46 603 8260; fax: +27 46 622 5109.
E-mail address: t.nyokong@ru.ac.za (T. Nyokong).

0022-2860/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.molstruc.2010.04.048



Scheme 1. (a) Synthetic route of phthalonitrile. (**1**), and its zinc phthalocyanine. (i) Anhydrous $Zn(Ac)_2$, 1-pentanol, 12 h, argon atm. References in brackets. (b) Synthetic route of quaternized zinc phthalocyanines (**3** and **5**), (i) DMS, dry DMF, 10 h, argon atm.

molecules which are water soluble and with enhanced intersystem crossing, hence large triplet quantum yield in aqueous media.

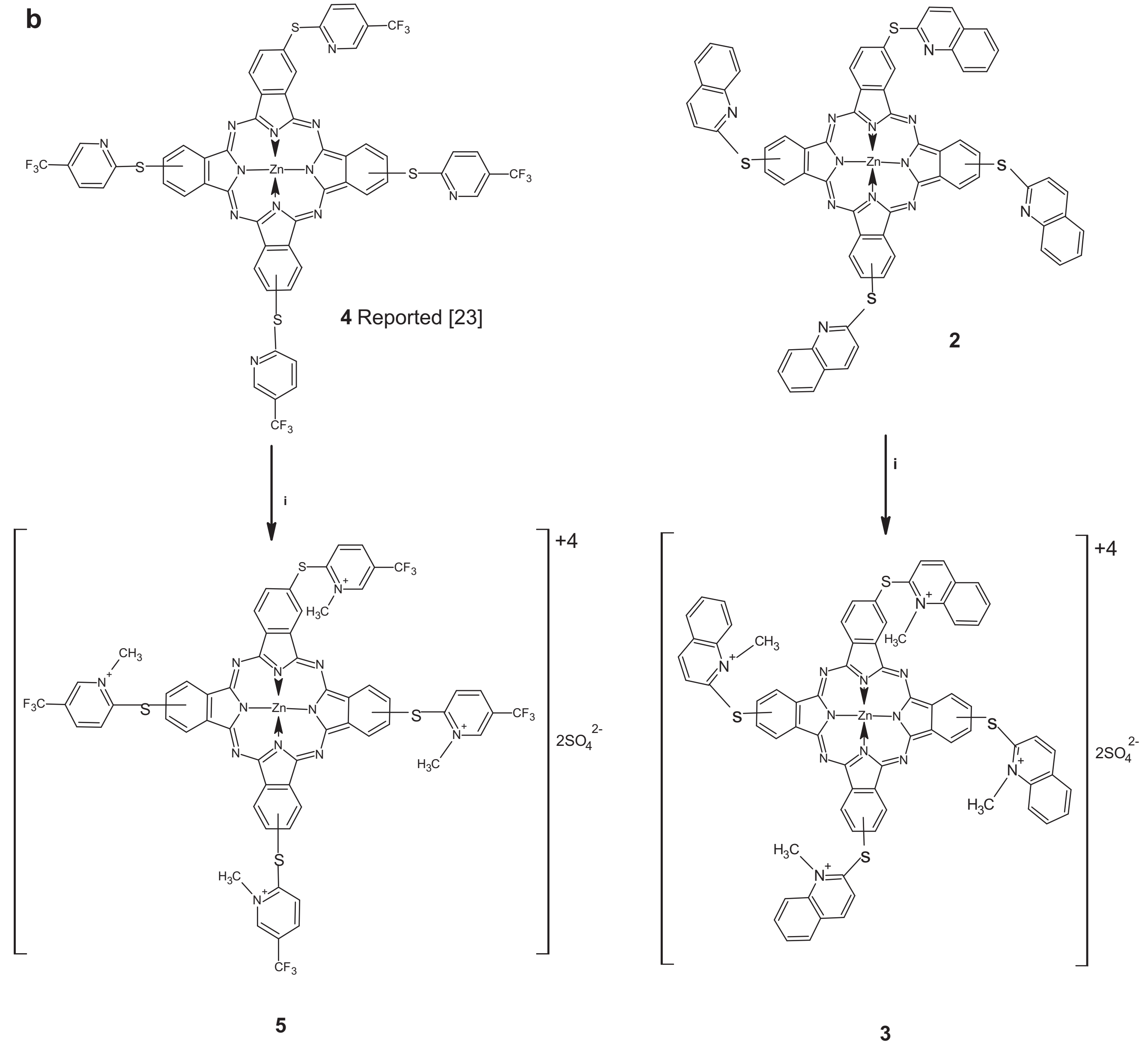
2. Experimental

2.1. Materials

Dimethyl sulfoxide (DMSO), *N,N′*-dimethylformamide (DMF), chloroform, tetrahydrofuran (THF), methanol (MeOH), dichloromethane (DCM), 1-pentanol, *n*-hexane, acetone and toluene were purchased from SAARCHEM; zinc phthalocyanine (ZnPc) 1,2-diphenyl*iso*benzofuran (DPBF), 9,10-antracenediyl-bis(methylene) dimalonoic acid (ADMA), 4-nitrophthalonitrile, 2-quinolinethiol, 5-(trifluoromethyl)-2-thiopyridine, 2-hydroxy-5-(trifluoromethyl) pyridine, 1,8-diazabicyclo[5.4.0] undec-7-ene (DBU), potassium carbonate, dimethylsulphate (DMS), zinc acetate ($Zn(OAc)_2$), zinc phthalocyanine, tetrasulphonated zinc phthalocyanine and zinc acetate were purchased from Aldrich. The synthesis and characterization of 4-(*tetra*-5-(trifluoromethyl)-2-thiopyridinephthalocyaninato) zinc(II) (**4**) and 4-(*tetra*-5-(trifluoromethyl) pyridinephthalocyaninato) zinc(II) (**6**) have been reported before [23].

2.2. Equipment

FT-IR spectra (KBr pellets) were recorded on a Perkin–Elmer spectrum 2000 FT-IR spectrometer. UV/Vis spectra were recorded on a Cary 500 UV/Vis/NIR spectrophotometer. ^1H NMR spectra were obtained in DMSO-d_6, $CDCl_3$, D_2O using a Bruker EMX 400 NMR spectrometer. Elemental analyses were done on Vario Elementar EL III. Fluorescence spectra were recorded on the Varian Eclipse spectrofluorimeter. Triplet absorption and decay kinetics were recorded on a laser flash photolysis system, the excitation pulses were produced by a Nd: YAG laser (Quanta-Ray, 1.5 J/90 ns) pumping a dye laser (Lambda Physic FL 3002, Pyridin 1 in



Scheme 1 (*continued*)

methanol). The analyzing beam source was from a Thermo Oriel xenon arc lamp, and a photomultiplier tube was used as detector. Signals were recorded with a two-channel digital real-time oscilloscope (Tektronix TDS 360); the kinetic curves were averaged over 256 laser pulses. Photo-irradiations were done using a General electric Quartz line lamp (300 W). A 600 nm glass cut off filter (Schott) and a water filter were used to filter off ultraviolet and infrared radiations respectively. An interference filter (Intor, 670 nm with a band width of 20 nm) was additionally placed in the light path before the sample. Light intensities were measured with a POWER MAX 5100 (Molelectron detector incorporated) power meter.

2.3. Synthesis

2.3.1. 4-[2-Thioquinoine]-phthalonitrile (*1*)

4-Nitrophthalonitrile (1.10 g, 6.30 mmol) was dissolved in DMF (15 ml) under argon and 2-quinolinethiol (1.00 g, 6.30 mmol) was added. After stirring for 30 min at room temperature, finely ground anhydrous potassium carbonate (2.17 g, 15.80 mmol) was added in portions during 2 h with efficient stirring. The reaction mixture was stirred under argon atmosphere at room temperature for a total of 24 h. Then the mixture was poured into 200 ml iced water, and the precipitate was filtered off, washed with water and methanol and then dried. The crude product was recrystallized from methanol–ethanol mixture. Finally the pure product was dried in vacuum. Yield: 1.25 g (69%). IR spectrum (cm^{-1}): 3072, 3052 (Ar—CH), 2229 (C≡N), 1579 (C=C), 1560 (C=N), 1474, 1421, 1385, 1288, 1096, 1037, 966, 778, 664 (C—S—C). ^1H NMR ($CDCl_3$): $\delta = 8.14$ (d, $J = 8.63$ Hz, 2H, Ar—H), 7.95 (2H, s, Ar—H), 7.86–7.82 (3H, m, Ar—H), 7.59 (1H, s, Ar—H), 7.38 (d, $J = 8.54$ Hz, 1H, Ar—H). Calcd for $C_{17}H_9N_3S$: C, 71.06; H, 3.16; N, 14.62; S, 11.16%. Found: C, 71.10; H, 3.12; N, 14.59; S, 11.20%.

2.3.2. (*4*)-Tetra[2-thioquinoline]phthalocyaninato zinc(II) (*2*)

Compound **1** (0.50 g, 1.74 mmol), anhydrous zinc acetate ($(Zn(OAc)_2$, 0.38 g, 1.74 mmol) and 3 ml of dry 1-pentanol were placed in a standard Schlenk tube in the presence of 1,8-diazabicyclo

[5.4.0] undec-7-ene (DBU) (0.39 ml, 0.25 mmol) under an argon atmosphere and held at reflux temperature for 12 h. After cooling to room temperature, the reaction mixture was precipitated by adding it drop-wise into *n*-hexane. The crude product was precipitated, collected by filtration and washed with hot hexane, ethanol and methanol. The crude green product was further purified by chromatography over a silica gel column using THF and a mixture of THF and CH_2Cl_2 (1:25 by volume), as eluents respectively. Yield 0.27 g (51%). UV–Vis (DMSO): λ_{max} nm (log ε) 356 (4.90), 619 (4.68), 645 (5.07), 688 (5.11), (Toluene): λ_{max} nm (log ε) 365 (4.89), 617 (4.70), 689 (5.44), (DMF): λ_{max} nm (log ε) 368 (4.88), 616 (4.63), 684 (5.37). IR spectrum (cm^{-1}): 3057 (Ar—CH), 1588, (C=C), 1554 (C=N), 1491, 1419, 1386, 1218, 1097, 942, 816, 745, 686 (C—S—C). ^1H NMR ($CDCl_3$): δ = 9.47–8.42 (10H, m, Ar—H), 8.46–8.00 (12H, m, Pc—H), 7.79 (4H, s, Ar—H), 7.64–7.52 (7H, m, Ar—H), 7.45–7.38 (3H, m, Ar—H). Calcd for $C_{68}H_{36}N_{12}$ S_4Zn: C, 67.23; H, 2.99; N, 13.84; S, 10.56%. Found: C, 66.36; H, 3.22; N, 13.34; S, 9.79%.

2.3.3. Quaternized (**4**)-tetra[2-thioquinoline]phthalocyaninato zinc(II) (**3**)

This complex was prepared according to the method previously reported by Smith et al. [24]. Compound **2** (50 mg, 0.041 mmol) was heated to 120 °C in freshly distilled 2 ml DMF and excess dimethylsulphate (0.1 ml) was added drop-wise using a micro syringe. The mixture was stirred at 120 °C for 10 h. After this time, the mixture was cooled to room temperature and the product was precipitated with hot acetone and collected by filtration. The green solid product was washed successively with acetone, ethanol, ethyl acetate, DCM, THF, chloroform, *n*-hexane and diethylether. The resulting hygroscopic product was dried over phosphorous pentoxide. Yield: 50 mg (85%). UV–Vis (DMSO): λ_{max} nm (log ε) 364 (4.99), 621 (4.60), 689 (5.24), (DMF): λ_{max} nm (log ε) 360 (4.93), 635 (4.45), 692 (5.13), (Water + Triton X-100): λ_{max} nm (log ε) 360 (4.94), 645 (4.74), 687 (5.12). IR spectrum (cm^{-1}): 3060 (Ar—CH), 2960 (C—H), 1637, 1572 (C=C), 1559 (C=N), 1503, 1486, 1456, 1231 (S=O), 1141 (S=O), 743, 682 (C—S—C), 617 (S—O). ^1H NMR (D_2O): δ = 9.21–7.48 ppm (36H, m, Pc—H and Ar—H), 3.78 (12H, s, CH_3). Calcd for $C_{72}H_{48}N_{12}O_8S_6Zn$ (+$6H_2O$): C, 54.90; H, 3.84; N, 10.67%. Found: C, 55.86; H, 3.76; N, 10.79.

2.3.4. Quaternized (**4**)-(tetra-5-(trifluoromethyl)-2-thiopyridinephthalocyaninato) zinc(II) (**5**)

This complex was prepared according to the method previously reported by Smith et al. [24]. Compound **3** (60 mg, 0.047 mmol) was heated to 120 °C in freshly distilled 2 ml DMF and excess dimethylsulfate (0.1 ml) was added drop-wise using a micro syringe. The mixture was stirred at 120 °C for 12 h. After this time, the mixture was cooled to room temperature and the product was precipitated with acetone and collected by filtration. The green solid product was washed successively with ethyl acetate, DCM, THF, chloroform, *n*-hexane and diethylether. The resulting hygroscopic product was dried over phosphorous pentoxide. Yield: 47 mg (65%). UV–Vis (DMSO): λ_{max} nm (log ε) 355 (4.64), 641 (4.01), 690 (4.98). IR spectrum (cm^{-1}): 3051 (Ar—CH), 2944 (C—H), 1636, 1598 (C=C), 1503, 1486, 1334 (C—F), 1259 (S=O), 1174 (S=O), 743, 682 (C—S—C), 614 (S—O). ^1H NMR(D_2O): δ = 8.33–8.01 ppm (24H, m, Pc—H and pyridyl—H), 3.79 (12H, s, CH_3). Calcd for $C_{60}H_{36}F_{12}N_{12}O_8S_6Zn$ ($7H_2O$): C, 43.28; H, 3.03; N, 10.10%. Found: C, 43.24; H, 3.03; N, 9.85%.

2.4. Photophysical studies

2.4.1. Fluorescence quantum yields

Fluorescence quantum yields (Φ_F) were determined by the comparative method) [25,26], (Eq. (1)):

$$\Phi_F = \Phi_F(\mathrm{Std})\frac{F \cdot A_{\mathrm{Std}} \cdot n^2}{F_{\mathrm{Std}} \cdot A \cdot n^2_{\mathrm{Std}}} \tag{1}$$

where F and F_{Std} are the areas under the fluorescence curves of **2**, **3** or **5**, and the standard respectively. A and A_{Std} are the respective absorbances of the sample and standard at the excitation wavelengths (which was ~0.05 in all solvents used), and n and n_{Std} are the refractive indices of solvents used for the sample and standard, respectively. ZnPc in DMSO (Φ_F = 0.20) [27], was employed as the standard.

2.4.2. Triplet quantum yields and lifetimes

The solutions for triplet quantum yields and lifetimes were introduced into a 1.0 mm pathlength UV/Vis spectrophotometric cell, deaerated using nitrogen and irradiated at the Q band maxima. Triplet state quantum yields (Φ_T) of **2**, **3** or **5**, were determined by the triplet absorption method [28], using zinc phthalocyanine (ZnPc) as a standard, Eq. (2):

$$\Phi_T = \Phi_T^{\mathrm{Std}} \cdot \frac{\Delta A_T \cdot \varepsilon_T^{\mathrm{Std}}}{\Delta A_T^{\mathrm{Std}} \cdot \varepsilon_T} \tag{2}$$

where ΔA_T and ΔA_T^{Std} are the changes in the triplet state absorbances of **2**, **3** or **5**, and the standard, respectively. ε_T and ε_T^{Std} are the triplet state molar extinction coefficients for **2**, **3** or **5**, and the standard, respectively. Φ_T^{Std} is the triplet quantum yield for the standard, ZnPc (Φ_T = 0.65 in DMSO [29] and $ZnPcS_4$ (in H_2O; Φ_T = 0.56 [30]). ε_T and ε_T^{Std} were determined from the molar extinction coefficients of the respective ground singlet state (ε_S and ε_S^{Std}) and the changes in absorbances of the ground singlet states (ΔA_S and ΔA_S^{Std}), according to Eq. (3):

$$\varepsilon_T = \varepsilon_S \cdot \frac{\Delta A_T}{\Delta A_S} \tag{3}$$

Quantum yields of internal conversion (Φ_{IC}) were obtained from Eq. (4), which assumes that only three processes (fluorescence, intersystem crossing and internal conversion), jointly deactivate the excited singlet state of the **2**, **3** or **5**.

$$\Phi_{IC} = 1 - (\Phi_F + \Phi_T) \tag{4}$$

2.5. Photochemical studies

2.5.1. Singlet oxygen quantum yields

Quantum yields of singlet oxygen photogeneration were determined in air (no oxygen bubbled) using the relative method with ZnPc (in DMSO and DMF) and $ZnPcS_4$ (in water) as reference and DPBF (in DMSO and DMF) and ADMA (in water) as chemical quenchers for singlet oxygen, using Eq. (5):

$$\Phi_\Delta = \Phi_\Delta^{\mathrm{Std}} \frac{R_{\mathrm{DPBF}} I_{\mathrm{abs}}^{\mathrm{Std}}}{R_{\mathrm{DPBF}}^{\mathrm{Std}} I_{\mathrm{abs}}} \tag{5}$$

where Φ_Δ^{Std} is the singlet oxygen quantum yield for the standard, ZnPc (Φ_Δ = 0.67 in DMSO [31]) and $ZnPcS_4$ (Φ_Δ = 0.30 in aqueous solution in the presence of Triton X-100 [32]). R_{DPBF} and R_{DPBF}^{Std} are the DPBF and ADMA photobleaching rates in the presence of **2**, **3** or **5**, and the standard respectively. I_{abs} and I_{abs}^{Std} are the rates of light absorption by **2**, **3** or **5**, and the standard respectively. To avoid chain reactions induced by DPBF in the presence of singlet oxygen [33], the concentrations of DPBF and ADMA were lowered to $\sim 3 \times 10^{-5}$ mol l^{-1}. Solutions of sensitizer (absorbance = 0.2 at the irradiation wavelength) containing DPBF or ADMA were prepared in the dark and irradiated in the Q-band region using the setup described above. DPBF degradation was monitored at 417 nm. ADMA degradation was monitored at 381 nm. The light intensity for singlet oxygen studies was 2×10^{15} photons s^{-1} cm^{-2}. The error in the determination of Φ_Δ was ~10% (determined from several Φ_Δ values).

2.5.2. Photodegradation quantum yields

For determination of photodegradation quantum yields, the usual Eq. (6) was employed [34]:

$$\Phi_{Pd} = \frac{(C_0 - C_t)VN_A}{I_{abs}St} \quad (6)$$

where C_0 and C_t in mol dm^{-3} are the concentrations of **2**, **3** or **5**, before and after irradiation respectively; V is the reaction volume; S, the irradiated cell area (2.0 cm^2); t, the irradiation time; N_A, the Avogadro's number and I_{abs}, the overlap integral of the radiation source intensity and the absorption of **2**, **3** or **5**, (the action spectrum) in the region of the interference filter transmittance. The light intensity for photodegradation studies was 2.97×10^{16} photons s^{-1} cm^{-2}.

3. Results and discussion

3.1. Synthesis and characterization

The synthetic procedure for novel phthalocyanines **2**, **3** and **5** is as outlined in Scheme 1. Complex **2** was prepared by the template cyclotetramerization of 4-[2-thioquinoline]-phthalonitrile (**1**), and anhydrous Zn(OAc)$_2$ in 1-pentanol (reflux temperature and under Ar atmosphere) and in the presence of DBU as a strong base. The new zinc phthalocyanine (**2**) was purified by column chromatography and a high yield (51%) was obtained. Complex **2** was also characterized by elemental analysis together with spectral data (^{1}H NMR, FT-IR and UV–Vis). Quaternized zinc phthalocyanines (**3** and **5**) were synthesized by reactions of **2** or **4** with excess dimethylsulphate (DMS) as quaternization agent in DMF at 120 °C. The yield of the quaternized complex **3** was 85%, for **5**, the yield was 65%. The compounds are very soluble in water, after reaction with DMS.

Generally, phthalocyanines derivatives are insoluble in common organic solvents and water, however introduction of substituents on the ring can increase the solubility. Complexes **2, 4** and **6** showed high solubility in DMF, DMSO, THF, CHCl$_3$, DCM, toluene and acetone. Quaternized complexes **3** and **5** have good solubility in water as well as DMSO and DMF. Both complexes are insoluble in acetone and are slightly soluble in ethanol.

In this study, complex **2** was isolated as a mixture of isomers, as expected. The presence of isomers might be verified by the slight broadening encountered in the UV–Vis absorption bands and broadening in the ^{1}H NMR. No attempt was made to separate the isomers of **2**, **3** and **5**.

The characteristic vibrations corresponding to CN and thioethers groups (C—S—C) at 2229 cm^{-1} and 664 cm^{-1} were observed for **1** in the FT-IR spectra. Aromatic C—H peaks were observed at 3072 and 3052 cm^{-1} for the phthalonitrile (**1**). The ^{1}H NMR spectrum of compound **1** showed signals with δ ranging from 7.38 to 8.14, belonging to aromatic protons integrating for nine protons as expected.

After conversion into zinc phthalocyanine derivations, the characteristic CN stretch at 2229 cm^{-1} of the phthalonitrile **1** disappeared in the FT-IR spectrum, indicative of metallophthalocyanine formation. The characteristic vibrations corresponding to ether groups (C—S—C) were observed at 686 (for **2**), 682 cm^{-1}(for **3**), 682 cm^{-1} (for **5**) and aromatic C—H stretching at ca. 3050 cm^{-1} for the complexes **2**, **3** and **5**. Aliphatic C—H stretching at ca. 2960 cm^{-1} (for **3**), 2944 cm^{-1} (for **5**), S=O stretching at 1231 and 1141 cm^{-1} (for **3**), 1259 and 1174 cm^{-1} (for **5**) and S—O stretching at 617 cm^{-1} (for **3**), 614 cm^{-1} (for **5**) for complexes **3** and **5** are indicative of quaternization.

The compounds were found to be pure by ^{1}H NMR with both the substituents and ring protons observed in their respective regions. The ^{1}H NMR spectra of tetrasubstituted phthalocyanine (**2**) and quaternized derivative (**3**) were almost identical with starting compound **1** except for broadening and a small shift. ^{1}H NMR spectra of **2**, **3** and **5** showed complex patterns due to the mixed isomer character of these compounds. In the ^{1}H NMR spectra of **2** and **3** the aromatic and Pc protons appear between 7.38 and 9.47 ppm and 7.48 and 9.21, respectively. The methyl protons which integrated for 12 protons were observed at 3.78 ppm for **3** as a singlet. Quaternization of **4** [23] was done by reaction with excess dimethylsulfate (DMS) as quaternization agent in DMF at 120 °C. Other quaternizing agents such as methyl iodide did not work. However, quaternization of **6** failed. The NMR spectra of the quaternized phthalocyanine complex (**5**) showed unresolved patterns between 8.33 and 8.01 ppm integrating for a total of 24 protons. The methyl protons which integrated for 12 protons were observed 3.79 ppm for **5** as a singlet.

Elemental analysis results were also consistent with the proposed structures of **2**, **3** and **5** as shown in Section 2, with the percent carbon values differing by less than 2% from the calculated values. Quaternized phthalocyanines are very hygroscopic compounds, so elemental analysis include some water.

3.2. Ground state electronic absorption spectra

The UV–Vis spectra of complex **2** in different solvents (Fig. 1) showed characteristic absorptions ranging from 685 to 690 nm in the Q-band region (only results in DMSO and aqueous media are shown in Table 1). When aggregation occurs, a band in the region of 630–645 nm is observed in the electronic absorption spectrum of MPcs as a result of the intramolecular interactions between the Pc units [35–37]. Thus, the band at around 640 nm in DMSO for **2** can be attributed to aggregation. Normally, DMSO is known to prevent aggregation since it is strong coordinating solvent. However, it has been observed before that aggregation occurs in DMSO for some MPc derivatives [17]. The aggregates in this case were attributed to the rare J aggregates which are not usually observed in aqueous media [17]. For complex **2** in DMSO, evidence of aggregation was judged by the faster decrease of the high energy band (due to H aggregates), Fig. 2a. Also addition of Triton X-100 to solutions **2** in DMSO resulted in the decrease in the high energy band due to the aggregates and the increase in the low energy band

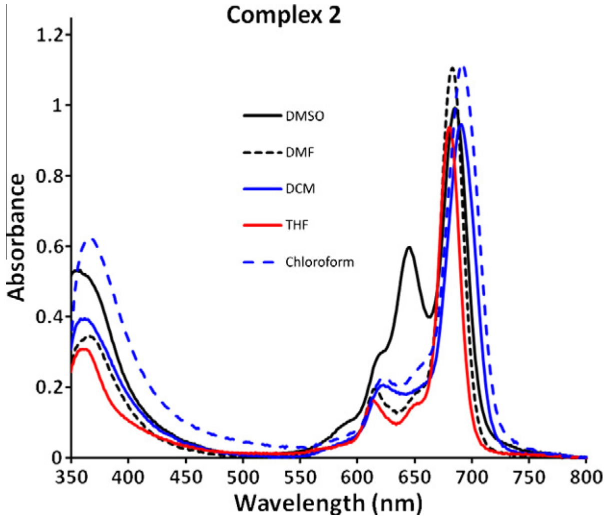


Fig. 1. UV–Vis absorption spectra of complex **2** in different solvents (concentration ~4×10^{-6} mol dm^{-3}).

Table 1
Spectral parameters of **2**–**6** in DMSO and aqueous media.

Complex	Solvent	Q band λ_{max}, (nm)	Log ε	Excitation λ_{Ex}, (nm)	Emission λ_{Em}, (nm)	Stokes shift Δ_{Stokes}, (nm)
2	DMSO	688	5.11	688	701	13
3	DMSO	689	5.24	688	704	15
3	Water (Triton X[a])	687	5.12	686	700	13
4	DMSO[b]	685[b]	5.21[b]	686	698	13
5	DMSO	690	4.98	689	704	14
5	Water (Triton X[a])	683	4.73	684	702	19
6	DMSO[b]	678[b]	5.28[b]	677	689	11

[a] Triton X = Triton X-100.
[b] Values from Ref. [23].

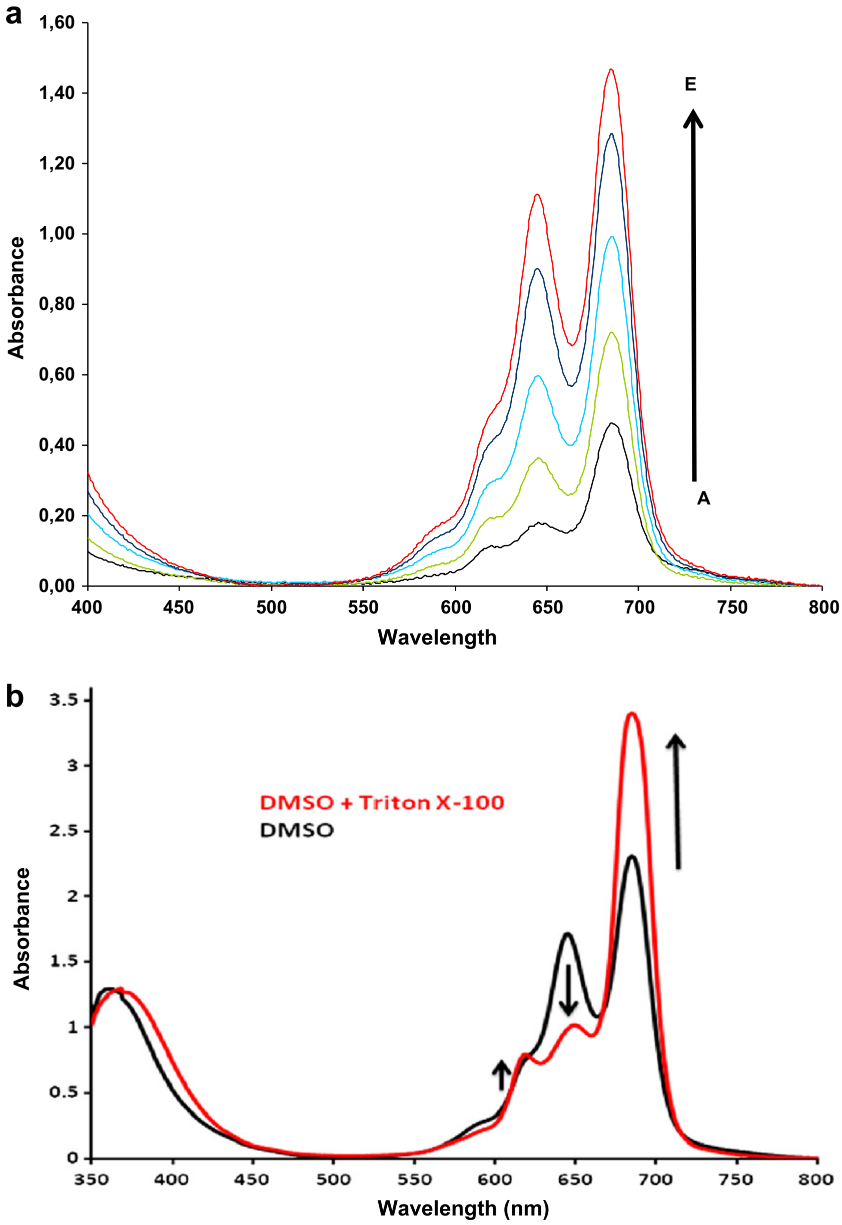


Fig. 2. Absorption spectra of **2** in ((a) DMSO at different concentrations: (A) 2×10^{-6}, (B) 4×10^{-6}, (C) 6×10^{-6}, (D) 8×10^{-6}, (E) 10×10^{-6} mol dm^{-3}, (b) in DMSO and DMSO containing Triton X-100 and (c) in toluene at different concentrations: (A) 2×10^{-6}, (B) 4×10^{-6}, (C) 6×10^{-6}, (D) 8×10^{-6}, (E) 10×10^{-6} mol dm^{-3}.

due to the monomer, Fig. 2b. Surfactants such as Triton X-100 breaks up the aggregates. For **2** in other solvents (other than DMSO), as concentration increased, the intensity of the Q band also increased and there were no new bands due to the aggregated species, Fig. 2c [38]. Lambert–Beer law was obeyed for these compounds in the concentrations ranging from 2.0×10^{-6} to 1.0×10^{-5} mol dm^{-3} as shown for **2** in toluene as an example, Fig. 2c.

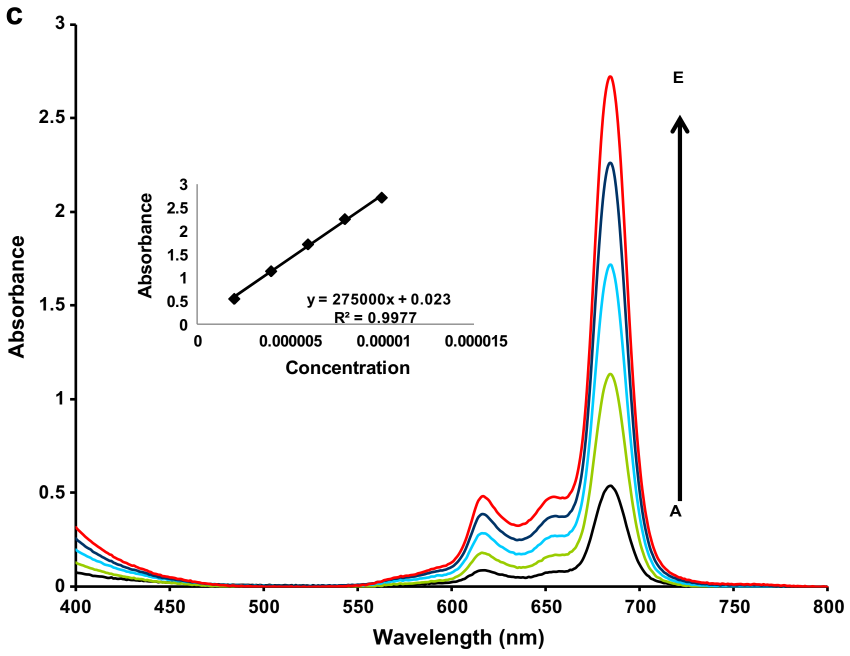


Fig. 2 (*continued*)

Aggregation behavior of Pc is depicted as a coplanar association of rings progressing from monomer to dimer and higher order complexes and it is dependent on concentration, nature of solvent and substituents, metal ions and temperature [37]. Aggregation is not desired in MPc complexes since aggregates are generally photoinactive. Aggregation is more enhanced for peripherally substituted MPc complexes when compared to non-peripherally substituted ones.

The UV–Vis spectrum of the quaternized metallophthalocyanines (**3** and **5**) show extensive aggregation in water with the presence of two main bands one at 680 nm (weak) and due to monomeric species and the other at 640 nm due to aggregated species. Surfactants are known to decrease aggregation. Addition of a drop of Triton X-100 to an aqueous solution of **3** and **5** brought about increase in intensity of the low energy side of the Q band (687 nm for **3**, Fig. 3a and 683 nm for **5**, Fig. 3b). However, some aggregation of **3** and **5** still remained in solution even after addition of Triton X-100, as shown in Fig. 3a and b. Complexes **3** and **5** exhibited lower aggregation properties in DMSO than in water plus Triton X-100 (Fig. 3c).

3.3. Fluorescence spectra, and quantum yields

The absorption and fluorescence emission and excitation spectra of **2** and **3** are similar in DMSO and water (plus Triton X-100) for **3**. Fig. 4 shows the absorption, fluorescence excitation and emission spectra of **2**, **3** and **5** in DMSO (and in water for **3**). Note that at the low concentrations employed for fluorescence, there is reduced aggregation in DMSO compared to Fig. 1. The excitation spectrum was not exactly similar to absorption spectrum due to aggregation in complex **2**. The excitation spectrum was a mirror image of the fluorescent spectra for **2**. For complexes **3** and **5** in DMSO and in water (plus Triton X-100), there was a clear narrowing of the excitation spectra compared to absorption spectra due to aggregation evident in the latter. The proximity of the wavelength of each component of the Q band absorption to the Q band maxima of the excitation spectra for both complexes suggest that the nuclear configurations of the ground and excited states are similar and not affected by excitation, Table 1 [39]. Fluorescence emission peaks were observed at: 701 nm for **2**, 704 nm for **3** and 704 nm for **5** in DMSO (Table 1). The Stokes' shifts range from 11 to 15 nm, which is usual for ZnPc derivatives [40].

The fluorescence quantum yields (Φ_F) of **2**, **3** and **5** are given in Table 2. Fluorescence quantum yield (Φ_F) values for **2**, **3** and **5** in DMSO are lower than those for unsubstituted ZnPc ($\Phi_F = 0.20$, [40]) and are also lower than those of the ZnPc derivatives substituted with quaternized thiopyridine group in aqueous media containing small amounts of pyridine for monomerization [19]. This implies that the presence of quinoxalinyl and arylthio substituents caused some fluorescence quenching of the parent ZnPc. Complex **2** has higher fluorescence quantum yield (Φ_F) values than complex **3** in DMSO. While quaternized complex (**3**) has high Φ_F value in water (plus Triton X-100) compared to in DMSO due to aggregation in the latter solvent. Quaternized complex (**5**) showed similar Φ_F value in DMSO compared to in water (plus Triton X-100) (Table 2). For complexes **4** and **6** the Φ_F values are typical of MPc complexes as discussed in the literature [23].

3.4. Triplet quantum, yields and lifetimes

Triplet quantum yield (Φ_T) is the fraction of absorbing molecules that undergo intersystem crossing to the metastable triplet excited state. Therefore, factors which induce spin–orbit coupling will certainly populate the triplet excited state. Transient spectrum for complex **6** in DMSO is shown in Fig. 5, and shows a maximum at 490 nm, hence triplet lifetimes and yields were determined at this wavelength for complex. All complexes showed triplet absorption in the same region (490–500 nm). Fig. 6 displays the triplet decay curves of the complexes (using complexes **3** and **5** in water as examples). Complex **2** has longer triplet life times (τ_T) than complex **3** in DMSO and DMF. The triplet life time for complex **2** (171 µs), **3** (31 µs) and 60 µs (for **5**) in DMSO are lower than for unsubstituted ZnPc (350 µs) in DMSO [22] suggesting that the substituents quench the triplet state. In water (plus Triton X-100) the triplet lifetime of **5** was 12 µs, a value which is lower than the one determined in DMSO, due to aggregation since even in the

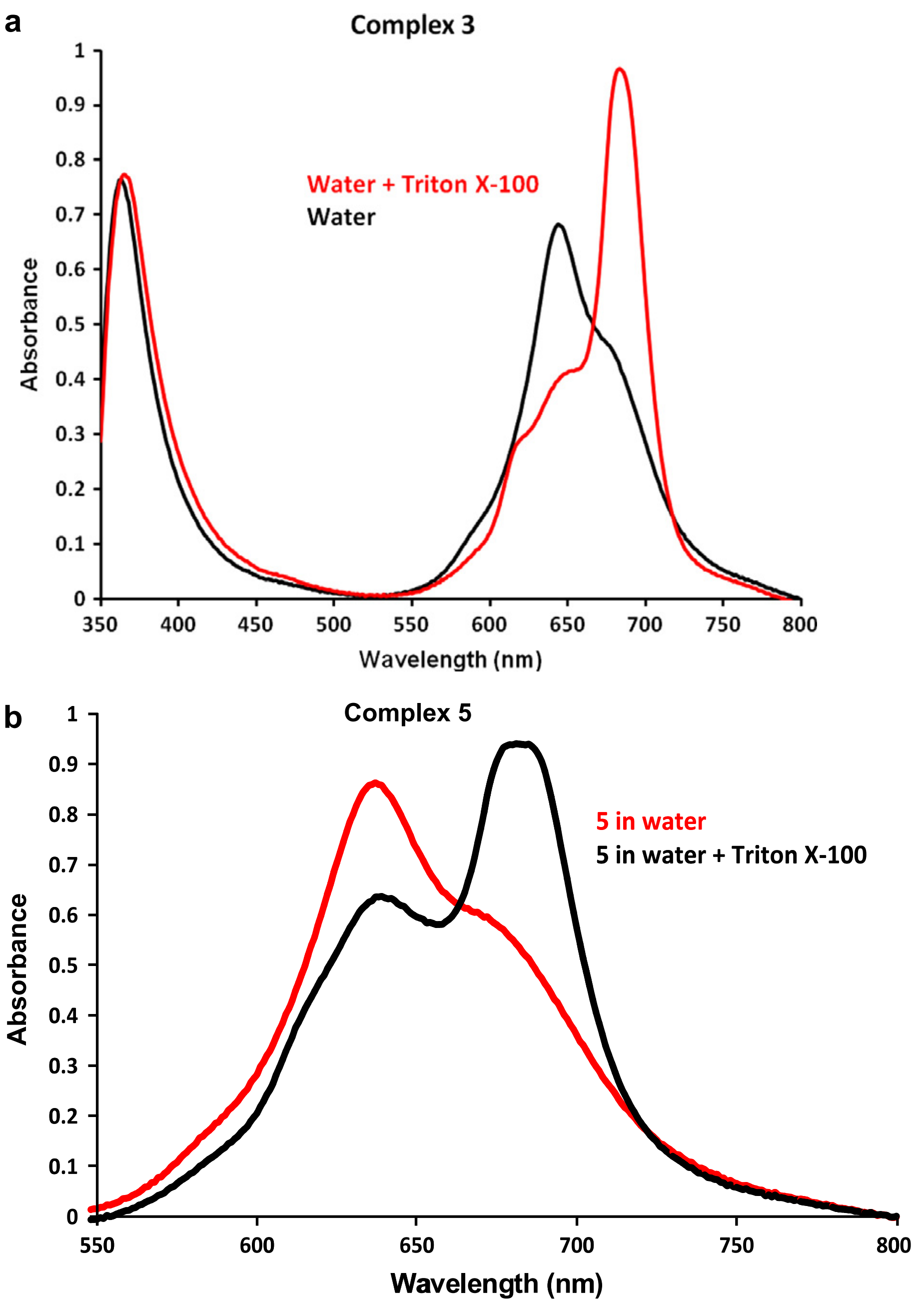


Fig. 3. UV–Vis absorption spectra (a) **3** in water and in water containing Triton X-100 and (b) **5** in water and in water containing Triton X-100 (c) **2**–**6** in DMSO.

presence of Triton X-100, aggregation still exists for **5** in water (Fig. 3b). The τ_T values value for complex **3** in aqueous media is higher than that of thiopyridine substituted ZnPc [19], though different monomerizing agents were employed.

The triplet quantum yields (Φ_T) for substituted complex **2** in DMSO ($\Phi_T = 0.79$) are high compared to complex **3** ($\Phi_T = 0.75$), complex **5** ($\Phi_T = 0.45$) and ZnPc standard in DMSO ($\Phi_T = 0.65$ for ZnPc in DMSO). While water soluble compound (**3**) bearing thioquinoline substituent showed high triplet quantum yield value in water (plus Triton X-100) ($\Phi_T = 0.80$), the other water soluble complex (**5**) bearing fluoro functional thiopyridine has low triplet quantum yield value ($\Phi_T = 0.32$) in the same solvent mixture. A low Φ_T value (=0.43) was obtained for the thiopyridine substituted ZnPc [19]. Triplet quantum yields and life times for complexes **4** and **6** in DMSO were discussed in the literature [23]. Complex **3** containing fluorinated substituents has a large triplet quantum yield due to the combination of enhanced intersystem crossing by the fluorines. Halogens are known to increase intersystem crossing [41].

3.5. Photochemical properties

3.5.1. Singlet oxygen quantum yields

Singlet oxygen quantum yield Φ_Δ is a measure of singlet oxygen generation and the Φ_Δ values were obtained using Eq. (5). Singlet oxygen quantum yields were studied in DMSO and water (for **3** and **5**) using a chemical method (DPBF and ADMA). Fig. 7 shows spectral changes observed during photolysis of complex **2** in DMSO in the presence of DPBF. The disappearance of DPBF was monitored using UV–Vis spectral changes. There were no changes in the Q

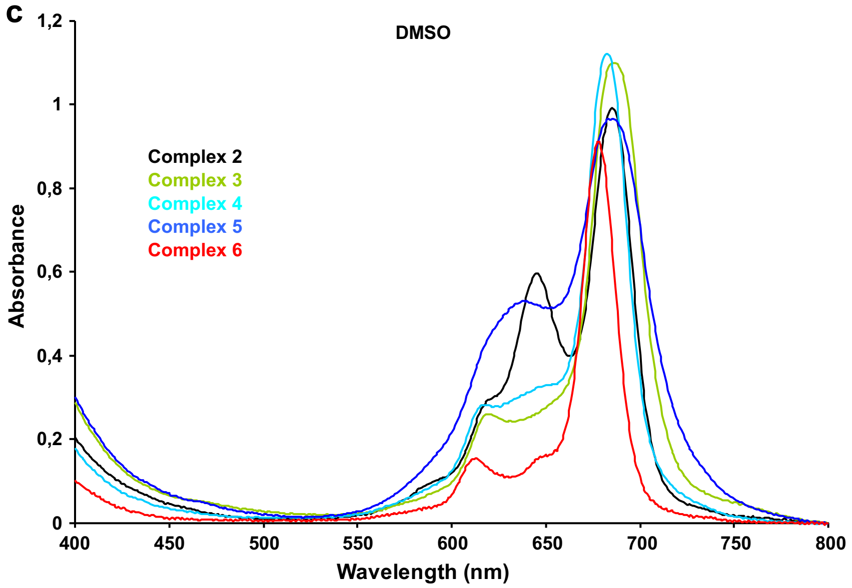


Fig. 3 (*continued*)

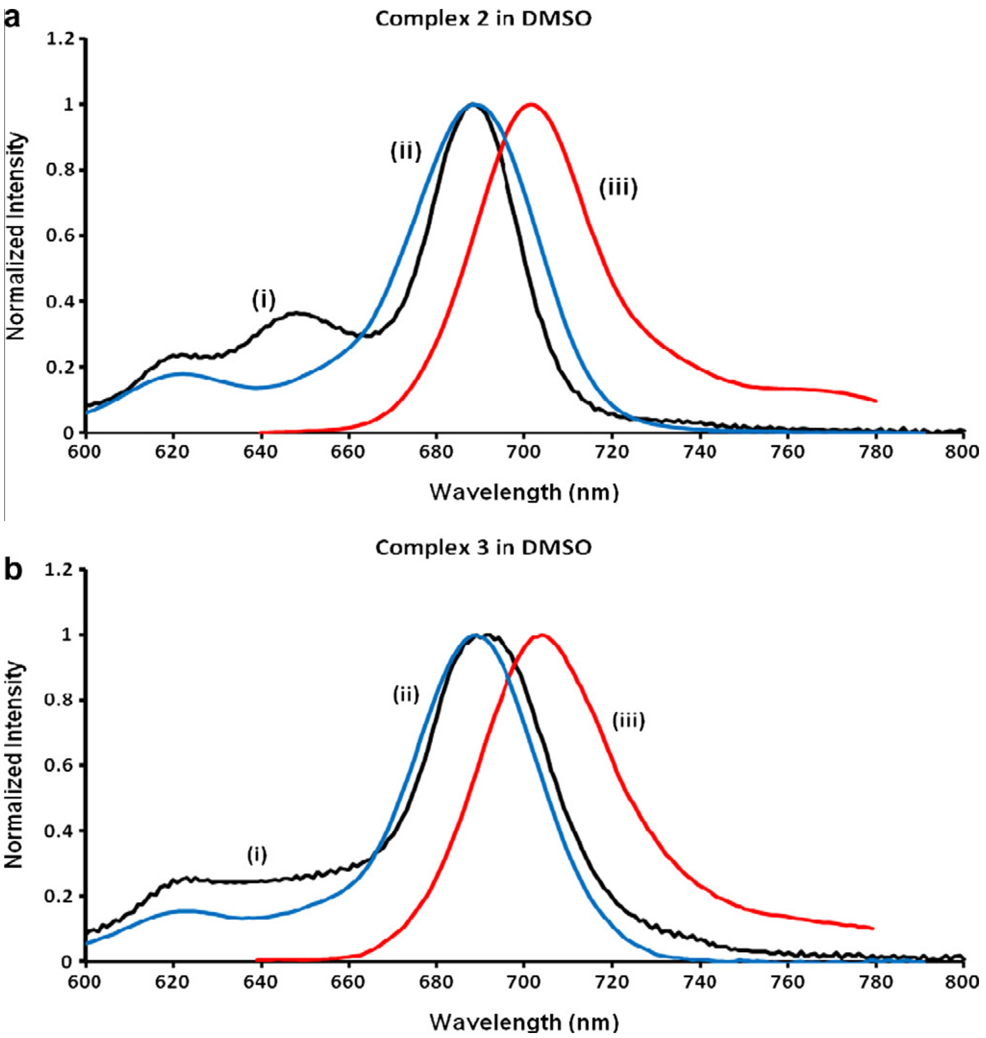


Fig. 4. Absorption (i), excitation (ii) and emission (iii) spectra of the compounds **2** (a) and **3** (b) in DMSO, (c) **3** in water containing Triton X-100 and (d) **5** in DMSO. Excitation wavelength = 688 nm for (**2**), 688 nm for (**3**) and 689 for (**5**) in DMSO and 686 nm for (**3**) in water containing Triton X-100.

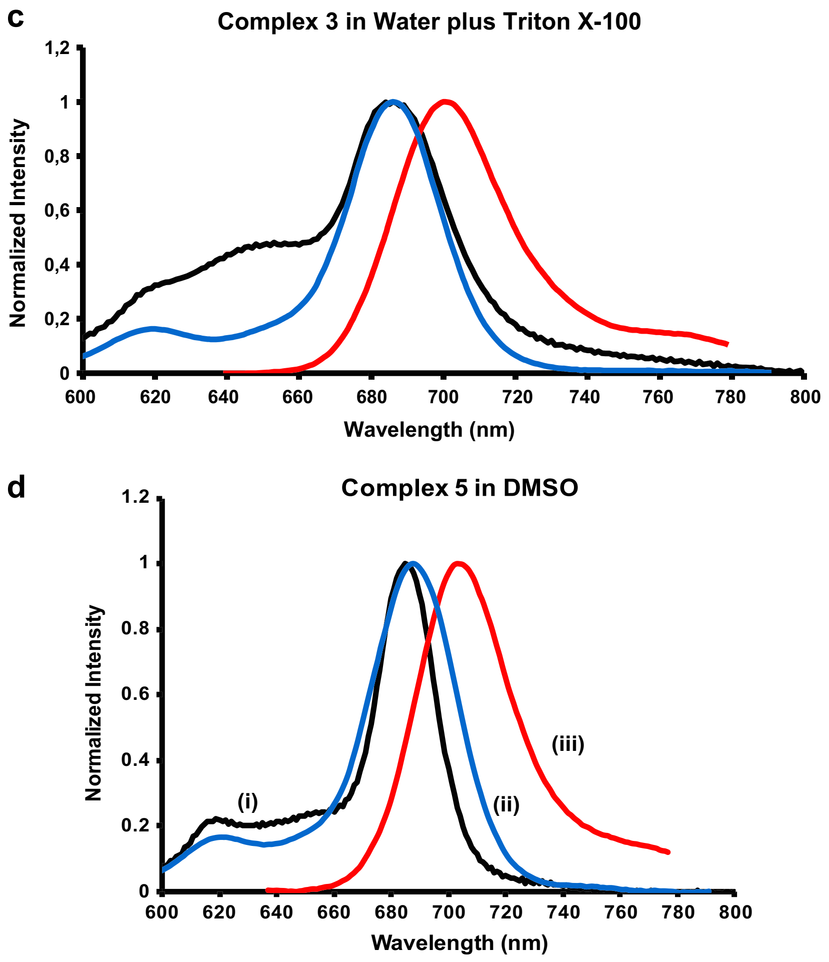


Fig. 4 (*continued*)

Table 2
Photophysical and photochemical properties of **2**–**6** in DMSO and aqueous media.

Complex	Solvent	Φ_F (±0.02)	τ_T (μs)	Φ_T (±0.03)	Φ_{IC}	Φ_d ($\times 10^{-5}$)	Φ_Δ (±0.01)	S_Δ
2	DMSO	0.10	171	0.79	0.11	3.98	0.56	0.71
3	DMSO	0.03	31	0.75	0.22	11	0.52	0.69
3	Water (Triton X[a])	0.08	110	0.80	0.12	18.7	0.34	0.43
4	DMSO	0.10[b]	140[b]	0.86[b]	0.04	3.57	0.68	0.79
5	DMSO	0.01	60	0.45	0.53	0.24	0.41	0.91
5	Water (Triton X[a])	0.02	12	0.32	0.67	7.05	0.24	0.75
6	DMSO	0.13[b]	210[b]	0.74[b]	0.13	0.74	0.63	0.85

[a] Triton X = Triton X-100.
[b] Values from Ref. [23].

band intensities during the Φ_Δ determinations, confirming that complexes are not degraded during singlet oxygen studies. The complexes (**4** and **6**) in this work were selected because they bore similar substituents, however they differed in their ether (C—O—C) and thio (C—S—C) bond linkages. We investigated the effect of this difference on the photophysicochemical properties. The Φ_Δ values are: **2** ($\Phi_\Delta = 0.56$), **3** ($\Phi_\Delta = 0.52$), **4** ($\Phi_\Delta = 0.68$), **5** ($\Phi_\Delta = 0.41$) and **6** ($\Phi_\Delta = 0.63$) in DMSO and for **3** ($\Phi_\Delta = 0.34$), **5** ($\Phi_\Delta = 0.24$) in water plus Triton X-100. The Φ_Δ values of complex **4** were higher than all complexes **3**–**6** in DMSO, Table 2. The Φ_Δ values for **2, 4** and **6** are lower or almost equal when compared to unsubstituted ZnPc in DMSO (0.67 [30]). Φ_Δ values of the arylthio-substituted complex **4** was larger than that of the aryloxy-substituted complex **6** (Table 2), corresponding to Φ_T values. As was the case for Φ_T values, the presence of sulfur atom may promote ISC, thus leading to higher singlet oxygen quantum yield for [42] **4**. The Φ_Δ values of complexes **3** and **5** in DMSO are higher than in water plus Triton X-100.

The magnitude of the S_Δ ($=\Phi_\Delta/\Phi_T$) represents the efficiency of quenching of the triplet excited state by singlet oxygen. Compound **2** displayed S_Δ near unity in DMSO. However, complex **3** showed lower values of S_Δ suggesting less efficient transfer of energy to the ground state oxygen, Table 2. This resulted in a lower singlet oxygen quantum yield even though complex **3** had a high ($\Phi_T = 0.80$) triplet quantum yield. Compounds **4**, **5** and **6** displayed S_Δ of near unity in DMSO implying efficient quenching of the triplet states by singlet oxygen (Table 2).

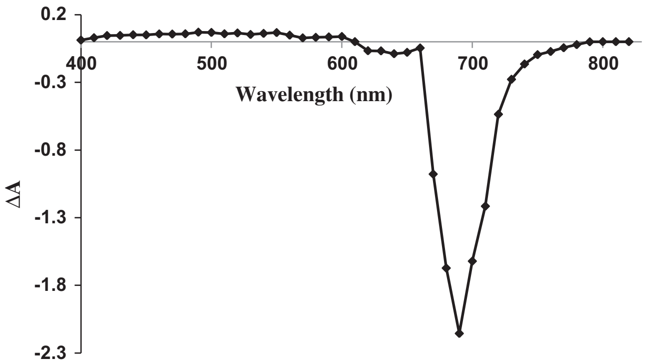


Fig. 5. Transient difference spectrum of complex **6** in DMSO.

3.5.2. Photodegradation quantum yields

Photodegradation is a process where a phthalocyanine is degraded under light irradiation. It can be used to determinate MPcs stability and this is especially important for those molecules intended for use as photocatalysts. The photobleaching stabilities of complexes **2**–**6** were determined in DMSO and in water for **3** and **5** by monitoring the decrease in the intensity of the Q band under irradiation with increasing time. The spectral changes observed for the complexes **2**–**6** during irradiation are shown in Fig. 8 (using complex **2** as an example in DMSO). There was no phototransformation into products which absorb in the visible region. The photodegradation quantum yield (Φ_d) values for the complexes are shown in Table 2 and are of the order of 10^{-5}–10^{-4}. These values show that the molecules are of moderate stability in all solvents used. Stable ZnPc molecules show values as low as 10^{-6} and for unstable molecules, values of the order 10^{-3} have been reported [43]. Photobleaching quantum yield value of complex **2** is lower than complex **3** in both DMSO, hence complex **2** are more stable than complex **3** in same solvent. Stability of complex **3** in water is lower than in DMSO, while complex **5** is more stable in DMSO than in water. In both cases, the observation contradicts what is expected in terms of singlet oxygen quantum yields, where high Φ_Δ values should result is higher degradation, since it is believed that photodegradation is a singlet oxygen mediated process [33]. The arylthio-substituted complex **4** is less stable than the corresponding aryloxy-substituted complex **6** in DMSO. The electronic effect of the substituents could explain the slight variation in the Φ_d values, i.e. the arylthio groups are more electron-donating than their corresponding aryloxy groups and thus tend to enhance the probability of the photobleaching process [44]. While the most stable complex among the all complexes in DMSO is **5**, complex **3** is the least stable complex in the solvent.

4. Conclusion

In this study, we have described the syntheses, spectral and photophysicochemical properties of soluble peripheral tetrakis [2-thioquinoine]-substituted zinc phthalocyanines (**2**) and its quaternized derivative (**3**) and quaternized 4-(*tetra*-5-(trifluoromethyl)-2-thiopyridinephthalocyaninato) zinc(II) (**5**). While complex **2** has good solubility in common organic solvents and is monomeric in solution (except in DMSO), complexes **3** and **5** are highly soluble in water as well as DMSO and DMF. It is important to mention here that for high-technological applications the

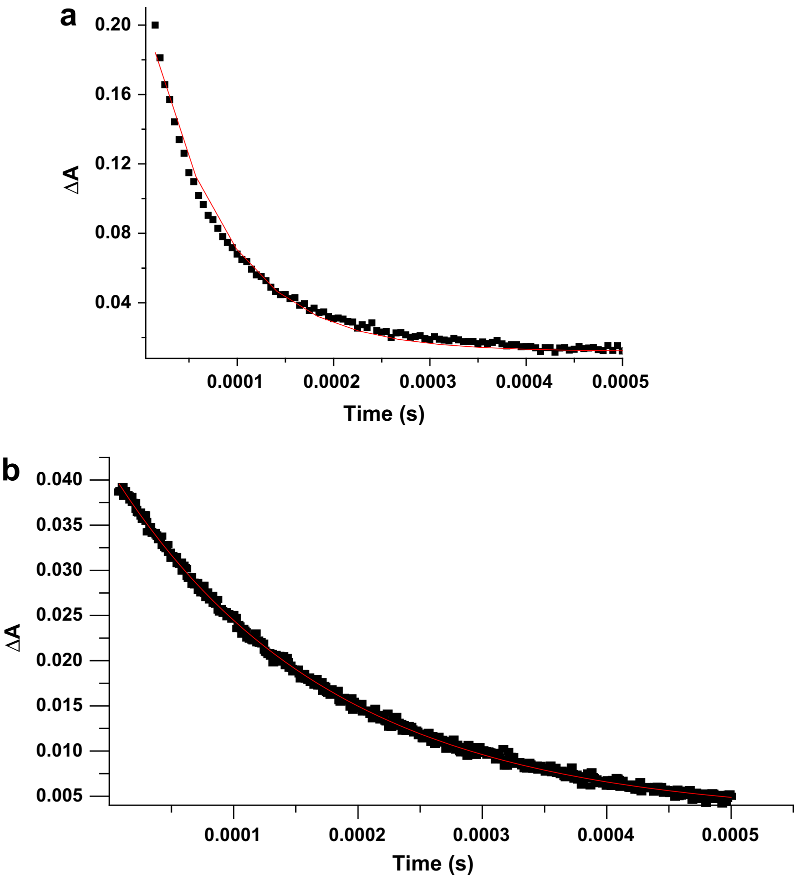


Fig. 6. Mono-exponential triplet decay profile for complex **3** (a) and complex **5** (b) in water.

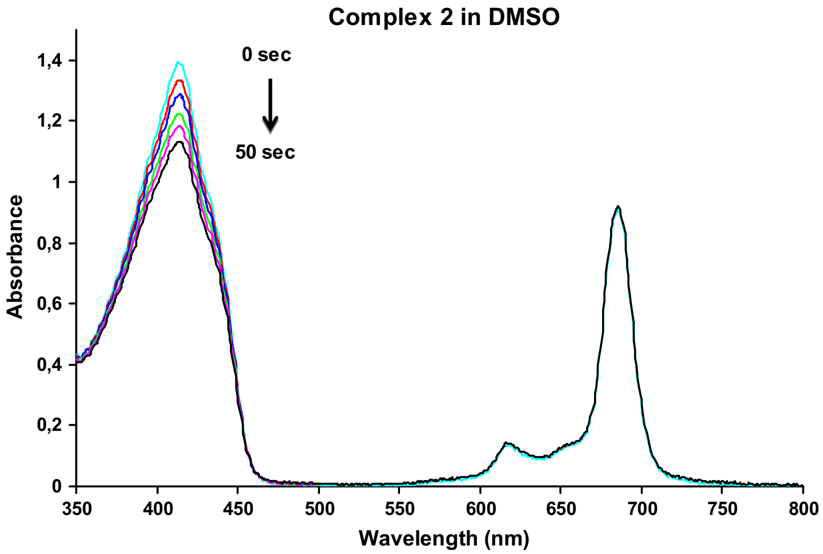


Fig. 7. A typical spectra for the determination of singlet oxygen quantum yield. This figure was for complex **2** in DMSO at a concentration of 6×10^{-6} mol dm^{-3}.

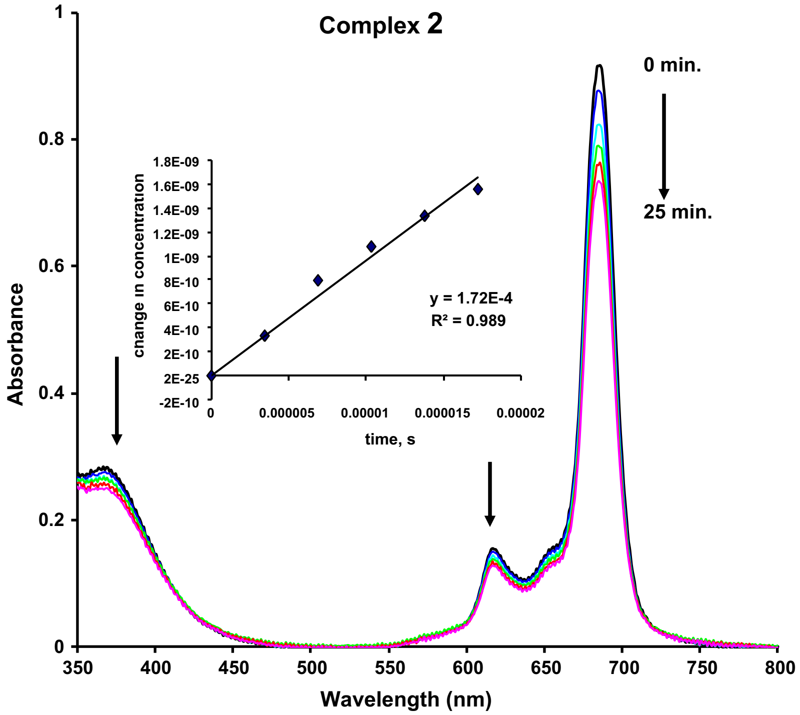


Fig. 8. The photodegradation of compound **2** in DMSO showing the disappearance of the Q band at 5 min intervals.

solubility of phthalocyanines is important. The introduction of [2-thioquinoine] and with-drawing fluoro-functional groups with thio and oxo linkages on the ring results in high triplet quantum yields (ranging from 0.32 to 0.86 in DMSO and water (for **3** and **5**)) and high singlet oxygen quantum yields (0.56 for **2**, 0.68 for **4** and 0.63 for **6** in DMSO). Quaternized complex **5** showed lower triplet quantum and singlet oxygen quantum yields values than unquaternized **4** and **6** in DMSO ($\Phi_T = 0.45$, $\Phi_\Delta = 0.41$ for **5**) and water ($\Phi_T = 0.32$, $\Phi_\Delta = 0.24$, for **5**) due to aggregation. Singlet oxygen quantum yields, which give indication of the potential of the complexes as photosensitizers in applications where singlet oxygen is required (Type II mechanism) ranged from 0.34 to 0.68. Thus, these complexes show potential as Type II. Photophysical and photochemical properties of the phthalocyanines complexes **2**–**6** are very useful for PDT. Complexes **3** and **5** are even more appropriate due to water solubility.

Acknowledgements

This work was supported by the Department of Science and Technology (DST) and National Research Foundation (NRF), South Africa through DST/NRF South African Research Chairs Initiative for Professor of Medicinal Chemistry and Nanotechnology as well as Rhodes University.

References

[1] M. Bouvet, The Porphyrin Handbook, vol. 19, Academic Press, New York, 2003. p. 1–36.
[2] C.C. Leznoff, A.B.P. Lever, Phthalocyanines: Properties and Applications, vols. 1–4, VCH, Weinheim, 1989–1996.
[3] A. Bilgin, B. Ertem, Y. Gok, Eur. J. Inorg. Chem. 12 (2007) 1703–1712.
[4] K. Langa, J. Mosinger, D.M. Wagnerova, Coord. Chem. Rev. 248 (2004) 321–350.
[5] N. Bhardwaj, J. Andraos, C.C. Leznoff, Can. J. Chem. 80 (2002) 141–147.
[6] E. Agar, S. Sasmaz, N. Akdemir, I. Keskin, Dalton Trans. (1997) 2087–2090.
[7] B. Ertem, A. Bilgin, Y. Gök, H. Kantekin, Dyes Pigments 77 (2008) 537–544.
[8] S. Unlu, M.N. Yaraşır, M. Kandaz, A. Koca, B. Salih, Polyhedron 27 (2008) 2805–2810.
[9] A. Bilgin, Y. Gök, Supramol. Chem. 18 (2006) 491–499.
[10] S. Wie, D. Huang, L. Li, Q. Meng, Dyes Pigments 56 (2003) 1–6.
[11] M. Durmuş, A. Erdoğmuş, A. Ogunsipe, T. Nyokong, Dyes Pigments 82 (2009) 244–250.
[12] P. Zimcik, M. Miletin, Z. Musil, K. Kopecky, L. Kubza, D. Brault, J. Photochem. Photobiol. A: Chem. 183 (2006) 59–69.
[13] M.P. de Filippis, D. Dei, L. Fantetti, G. Roncucci, Tetrahedron Lett. 41 (2000) 9143–9147.
[14] I. Scalise, E.N. Durantini, Bioorg. Med. Chem. 13 (2005) 3037–3045.
[15] S.R. Wood, J.A. Holroyd, S.B. Brown, Photochem. Photobiol. 65 (1997) 397–402.
[16] A.P. Castano, T.N. Demidova, M.R. Hamblin, Photodiagn. Photodynam. Ther. 1 (2004) 279–293.
[17] P. Tau, T. Nyokong, Dalton Trans. (2006) 4482–4490.
[18] P. Tau, T. Nyokong, J. Porphyr. Phthalocyan. 10 (2006) 1040–1048.
[19] S. Moeno, T. Nyokong, J. Photochem. Photobiol. A: Chem. 203 (2009) 204–210.
[20] N. Sehlotho, M. Durmuş, V. Ahsen, T. Nyokong, Inorg. Chem. Commun. 11 (2008) 479–483.
[21] S. Abdurrahmanoğlu, A.R. Ozkaya, M. Bulut, O. Bekaroglu, J. Chem. Soc. Dalton Trans. (2004) 4022–4029.
[22] M. Selcukoğlu, E. Hamuryudan, Dyes Pigments 74 (2007) 17–20.
[23] A. Erdoğmuş, S. Moeno, C. Litwinski, T. Nyokong, Photochem. Photobiol. A: Chem. 210 (2010) 200–208.
[24] T.D. Smith, J. Livorness, H. Taylor, J. Chem. Soc. Dalton Trans. (1983) 1391–1400.
[25] S. Fery-Forgues, D. Lavabre, J. Chem. Ed. 76 (1999) 1260–1264.
[26] J. Fu, X.Y. Li, D.K.P. Ng, C. Wu, Langmuir 18 (2002) 3843–3847.
[27] A. Ogunsipe, J.Y. Chen, T. Nyokong, New J. Chem. 7 (2004) 822–827.
[28] P. Kubát, J. Mosinger, J. Photochem. Photobiol. A: Chem. 96 (1996) 93–97.
[29] T.H. Tran-Thi, C. Desforge, C.C. Thiec, J. Phys. Chem. 93 (1989) 1226–1233.
[30] A. Harriman, M.C. Richoux, J. Chem. Soc. Faraday Trans. 2. 76 (1989) 1618–1626.
[31] N.A. Kuznetsova, N. Gretsova, E. Kalmykova, E. Makarova, S. Dashkevich, V. Negrimovskii, O. Kaliya, E. Luk'yanets, Russ. J. Gen. Chem. 70 (2000) 133–140.
[32] N.A. Kuznetsova, N.S. Gretsova, V.M. Derkacheva, O.L. Kaliya, E.A. Lukyanats, J. Porphyr. Phthalocyan. 7 (2003) 147–154.
[33] W. Spiller, H. Kliesch, D. Wohrle, S. Hackbarth, B. Roder, G. Schnurpfeil, J. Porphyr. Phthalocyan. 2 (1998) 145–158.
[34] D. Wöhrle, O. Suvorova, R. Gerges, O. Bartels, Ł. Łapok, N. Baziakina, S. Makarov, A. Słodek, J. Porphyr. Phthalocyan. 8 (2004) 1020–1041.
[35] Z. Odabas, A. Altındal, A.R. Ozkaya, M. Bulut, B. Salih, O. Bekaroglu, Polyhedron 26 (2007) 695–707.
[36] V. Manivannan, W.A. Nevin, C.C. Leznoff, A.B.P. Lever, J. Coord. Chem. 19 (1988) 139–158.
[37] H. Enkelkamp, R.J.M. Nolte, J. Porphyr. Phthalocyan. 4 (2000) 454–459.
[38] H.S. Nalwa, J.S. Shirk, in: C.C. Leznoff, A.B.P. Lever (Eds.), Phthalocyanines: Properties and Applications, vol. 4, VCH Publishers, New York, 1996, pp. 79–181.
[39] M. Durmuş, T. Nyokong, Inorg. Chem. Commun. 10 (2007) 332–338.
[40] A. Ogunsipe, D. Maree, T. Nyokong, J. Mol. Struct. 650 (2003) 131–140.
[41] X.-F. Zhang, H.-J. Xu, J. Chem. Soc. Faraday Trans. 89 (1993) 3347–3351.
[42] P. Tau, T. Nyokong, J. Mol. Catal. A: Chem. 273 (2007) 149–155.
[43] S. Maree, T. Nyokong, J. Porphyr. Phthalocyan. 5 (2001) 782–792.
[44] A.K. Sobbi, D. Wöhrle, D. Schleettwein, J. Chem. Soc. Perkin Trans. 2 (1993) 481–488.