

Newly synthesized peripherally octa-substituted zinc phthalocyanines carrying halogen terminated phenoxy-phenoxy moiety: comparative photochemical and photophysical features

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Abstract: This study reports the 3 new phthalonitrile derivatives, namely 4, 5 Bis-[4-(4-bromophenoxy) phenoxy] phthalonitrile (1), 4,5 Bis-[4-(4-chlorophenoxy) phenoxy]phthalonitrile (2), and 4, 5 Bis[4-(4-fluorophenoxy) phenoxy] phthalonitrile (3). Their octa-substituted zinc phthalocyanines (4, 5, 6) are reported for the first time in this study. The resulting compounds were characterized by utilizing some spectroscopic methods, such as UV-Vis, ¹HNMR, FT-IR spectroscopy, as well as mass spectra and elemental analysis. To show photosensitizer's potential, emission (F_p), singlet oxygen (1O_2), and photodegradation quantum yields (Φ_{Δ} , Φ_d) of octa-peripherally phthalocyanines (Pcs) were performed in the solutions, such as biocompatible solvent DMSO (dimethyl sulfoxide) as well as DMF (dimethylformamide) and THF (tetrahydrofuran). Solvent and octa-peripherally binding effect of the halogen (Br, Cl, F) terminated phenoxy-phenoxy groups on phthalocyanine rings for photophysical properties (4, 5, and 6) were compared with the tetra-peripherally and tetra nonperipherally substituted derivatives. The new dyes (4 to 6) may be evaluated in photodynamic therapy (PDT) of cancer as photosensitizers due to efficient 1O_2 from 0.55 to 0.75.

Key words: Photochemistry, photophysics, zinc phthalocyanine, octa-substituted, halogen substitution

1. Introduction

Phthalocyanines (Pcs) are known as macrocyclic compounds with different blue-green colors and unique spectroscopic properties. After being discovered in 1927 accidentally, Pcs have since found use in dyes [1,2], catalysis [3–5], optical-based electronics [6,7], electroensing [8], photovoltaic cells [9,10] and even medicine, such as PDT [11,12]. All of these uses of Pcs stem from their extended 18- π electron system, which contributes to the important chemical and physical properties of phthalocyanines, and also plays an important role in their theoretical or experimental work [13].

A Pc can be modified by one or a combination of three methods; these all maintain the core atomic configuration of the central Pc, which are metalation, axial substitution, and tetra- or octa-peripherally or nonperipherally substitution [14]. These binding types can give different properties to various applications, such as increasing the solubility of the phthalocyanine molecule and the design of the target molecules with the desired properties.

The most versatile method of modifying a Pc's properties comes from the Pc's 16 different perimeter substitution points (α and β), as these allow the addition of substituents of almost any composition, electron affinity, polarity, and size. These substituents are what allow Pcs to perform the host of functions that they are used for in the modern industry [15]. Substituents that carry properties affecting the electron distribution of the Pc can, however, affect the Pc's photophysical properties and are position sensitive [16].

In photodynamic therapy, phthalocyanines are used as second generation photosensitizer agents. Phthalocyanines bind to the amine groups of the antibody selected in accordance with the cancerous cell. When photosensitizer-bound antibody is delivered to the body, it only accumulates in diseased tumor cells without spreading throughout the body. When one of the electrons of the oxygen molecule receives energy from outside, it switches to a different orbital opposite to its direction of rotation and singlet oxygen (1O_2) forms. Photophysical and photochemical properties are very important studies to determine the potential of photosensitizer candidates, such as phthalocyanine, to be used in photodynamic therapy. Phthalocyanines are second generation compounds as photosensitizers that have the potential to be used in the treatment of cancer by PDT owing to their appreciate wavelength absorption and the ability to form singlet oxygen effectively [17–19].

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The properties of phthalocyanine compounds can be enriched with different substituents. Selected groups can be connected to the tetra-peripherally, tetra-nonperipherally or octa-peripherally or nonperipherally substituted positions at the Pc ring, and the desired photophysical and photochemical properties can be adjusted. The Pcs with the halogen atoms terminated phenoxy-phenoxy moiety at the octa-peripherally substituted were not performed before. Our recent articles show that synthesis, and photochemical and emission properties of tetra-substituted Zn(II) complexes bearing identical groups at nonperipherally and peripherally positions were discussed [20,21]. Octa-substituted phthalocyanines have been reported to have better solubility and lower aggregation tendency [22,23]. The goal of the study was to inspect the photosensitizer features of peripherally octa-binding versus tetra nonperipheral and tetra-peripheral positions for zinc phthalocyanine analogs.

2. Experimental design

All information about the used materials, equipment, synthesis, emission properties as photophysical and $^1\text{O}_2$ efficiency and photostability properties as photochemically are shown in the "Supplementary Information".

3. Results and discussion

3.1. Syntheses and characterization

The chemical synthesis routes to new octa-substituted zinc phthalocyanines (**4** to **6**) are represented in Scheme 1. The Pcs were obtained by the cyclotetramerization of the nitriles (**1**, **2**, and **3**) with dry zinc acetate in the presence of DBU catalyst in *n*-hexanol at reflux temperature under argon atmosphere.

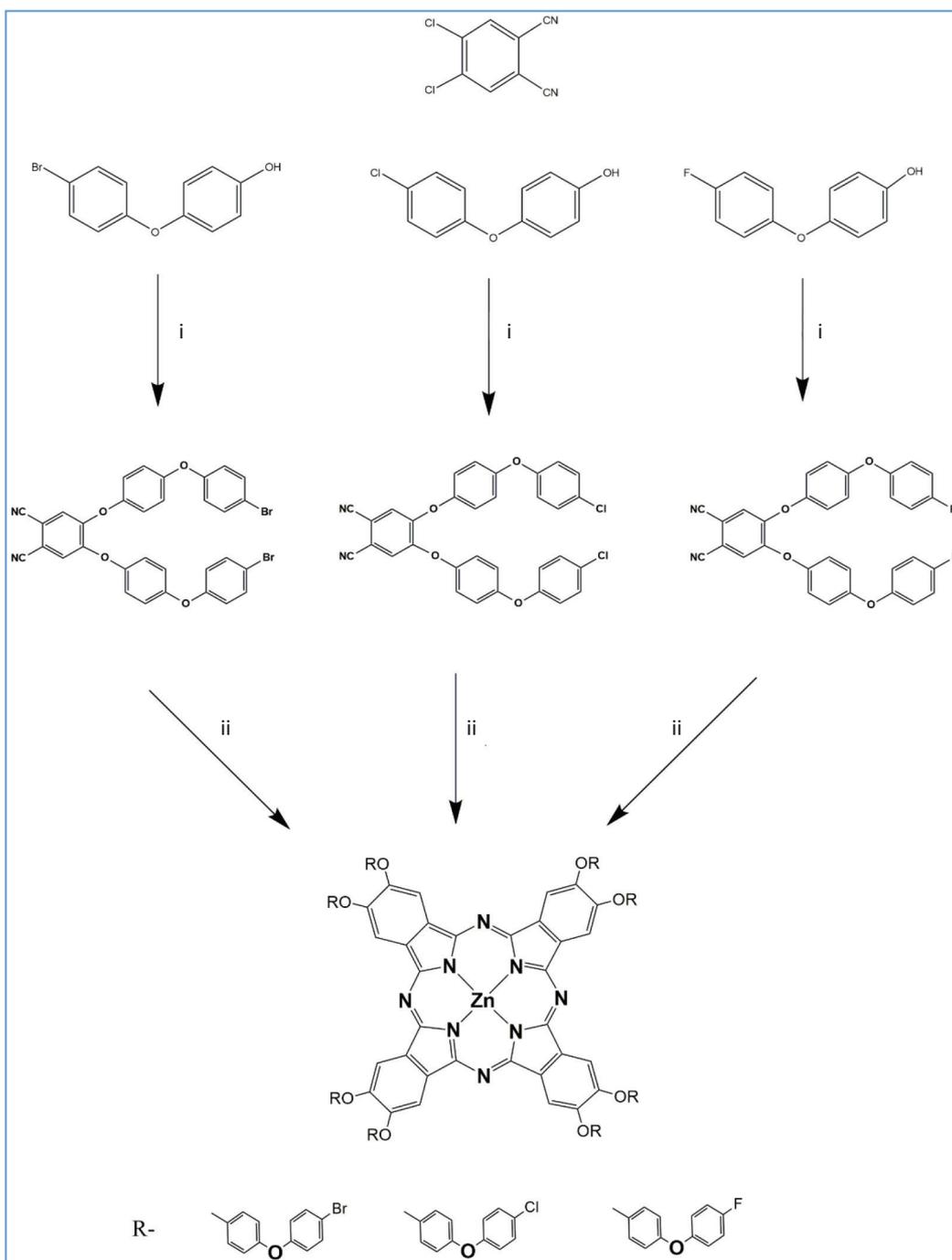
All the compounds were purified by column chromatography after thin layer chromatography studies. Their characterization were performed by using FTIR, ^1H NMR and UV-Vis spectroscopic techniques, together with mass spectra and elemental analysis.

Very characteristic FTIR vibrations of C=N triple bond were monitored at 2233 (for **1**), 2224 (for **2**), and 2226 (for **3**) cm^{-1} for the phthalonitriles. The vibration of ether bonds (C-O-C) for the nitriles were observed at 1240 cm^{-1} (**1**), 1205 cm^{-1} (**2**), and 1250 cm^{-1} (**3**), respectively. Aromatic C-H bond vibration peaks occurred at around 2970–3094 cm^{-1} for all the new nitriles. The ^1H NMR spectrum of the nitriles (**1** to **3**) gave for aromatic protons signals with δ between 7.90 and 6.94 (for **1**), 7.28 and 6.90 (for **2**), and 7.19 and 7.04 (for **3**), integrating for a total of 18 protons, respectively. The mass value of the phthalonitriles was obtained by the gas chromatography-mass (GC-MS) technique for **1**, and time-of-flight mass spectrometry (TOF-MS) technique for **2** and **3**. The molecular ion peaks were signed at m/z 654 for **1**, 587 for **2**, and 555 for **3**.

To achieve peripherally octa-substituted Zn(II)Pcs from their precursors, the template effect of $\text{Zn}(\text{OAc})_2$ was applied as central ion effect of Zn(II). Then cyclotetramerization of the nitriles, the distinctive carbon-nitrogen triple bond (C=N) vibration signals disappeared on the FTIR spectra of Pc complexes, the disappearing the peaks, the evidence of the made up of Pcs. The C-O-C vibrations were observed at 1232, 1187 cm^{-1} for **4**, 1203, 1186 cm^{-1} for **5**, and 1247, 1185 cm^{-1} for **6**, respectively. Aromatic carbon hydrogen single bond (CH) peaks occurred at 3107 (**4**), 3041 (**5**), and 3070 cm^{-1} (**6**) for phthalocyanines.

The purity of octa-substituted Zn(II)Pc derivatives were also checked by ^1H NMR with both of the groups, and Pc skeleton protons appeared in their respective regions. In the ^1H NMR spectrum of **4** to **6**, the aromatic Pc and substituent aromatic protons appeared between 7.60–6.55 ppm for **4**, 7.65–6.90 ppm for **5**, and 7.20–6.71 ppm for **6**. In the MS of peripherally octa-substituted Zn(II)Pcs, molecular (M) ion peak was observed at m/z 2682 $[\text{M}]^+$ (for **4**), (M+H) ion peaks were seen 2328 $[\text{M}+\text{H}]^+$ and 2196 $[\text{M}+\text{H}]^+$ for **5** and **6**, respectively (Figure S1), as confirmed the proposed structures. Elemental analysis data also supported the proposed chemical formulas for the precursors and their Pcs (**1** to **6**) as can be seen in the experimental part.

The electronic ground state spectra of Zn(II)Pcs (**4** to **6**) were performed in THF, DMF, and DMSO at room temperature (An example for **4**, **5**, and **6** in DMSO is given in Figure 1). The Q-bands of compounds (**4** to **6**) appeared at 681, 677, and 676 nm in DMF; 684, 680, and 680 nm in DMSO; and 678, 675, and 675 nm in THF, respectively (Table 1). Their B-bands were seen between 340 and 365 nm for all the compounds. The logarithmic molar absorption coefficient values of the bands are listed in Table 1. Additionally, the vibronic band peaks of **4**, **5** and **6** were recorded between 609 and 615 nm assigned to $n - \pi^*$ transitions for the complexes. Generally, the larger metal ions cause more red-shift of the Q-band. Axial ligation of metal ions also makes the Q-band shift to the red region. Moreover, Q-bands of the nonperipherally substituted [21] Pcs show up a bathochromic shift in comparison to those of their tetra- and octa-peripheral analogs. To conclude, the Q-bands of the MPcs (**4** to **6**) shift to the red region in the following order: **5** \leq **6** $<$ **4** in the solvents used. When compared to the previous tetra-peripheral and nonperipheral analogs [20,21] in DMSO, THF, and DMF, the Q-band values of peripherally



Scheme 1: Synthetic route of 3 phthalonitriles (**1**, **2**, and **3**), (i) DMF, K_2CO_3 , 24h; and their zinc phthalocyanines derivatives (**4**, **5** and **6**) (ii) anhydrous $Zn(Ac)_2$, hexanol 12h, DBU, argon atm.

octa-binding ones are blue-shifted relative to those of nonperipherally derivatives, but they have almost the same value as tetra-peripherally patterns. Type of halogen atoms (F, Cl, and Br) on the phenoxy-phenoxy substituent did not show a crucial change in the Q bands maximum for the Pc rings.

Aggregation behavior reduces the solubility of the Pcs in various solvents and subsequently weakens their performance in a wide range of scientific and technological fields requiring high soluble materials. Therefore, it matters to recognize and improve the factors affecting the aggregation behavior of Pcs. Change in concentration of Pcs, the solvent nature, and the temperature can alter aggregation as well as the size and position of the substituent. Spectral properties of Pcs as a function

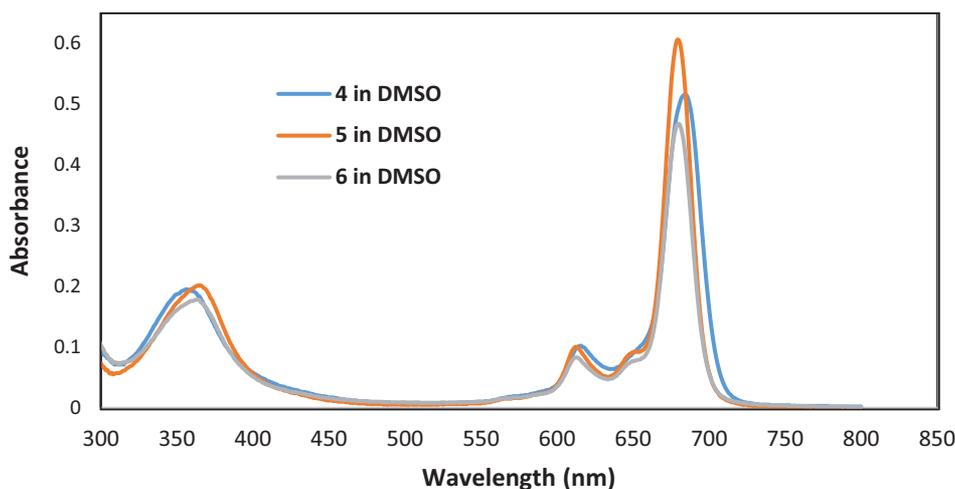


Figure 1. UV-Vis absorption spectra of 4, 5, and 6 in DMSO concentration at 2×10^{-6} moldm⁻³.

Table 1. Spectral parameters of 4, 5, and 6 in DMF, DMSO, and THF.

Comp.	Solvent	Q-band	(log ϵ)	Excitation	Emission	Stokes shift
		λ_{max} , (nm)		λ_{Ex} , (nm)	λ_{Em} , (nm)	Δ_{Stokes} , (nm)
4	DMF	678	5.39	679	689	11
	DMSO	684	5.39	682	689	5
	THF	675	5.27	673	686	11
5	DMF	678	5.14	676	691	13
	DMSO	680	5.16	681	690	10
	THF	675	5.17	676	684	9
6	DMF	678	5.39	690	690	12
	DMSO	680	5.33	692	692	12
	THF	675	5.42	687	687	12

of the electronic states change by enhancement of π -stacking which derange of the electronic states. Furthermore, the study of the electronic absorption spectra of Pcs is a useful approach for the measurement and management of the aggregation [24,25]. The concentration effect on aggregation properties of compounds 4, 5, and 6 was examined in different molarity of THF, DMSO, and DMF, ranging from 2×10^{-6} to 12×10^{-5} M. As concentration increased, the absorbance enhanced directly in a constant value, and no new band was observed. Since all compounds obey the Lambert-Beer law, aggregation does not rely on concentration at the studied range of concentration (Figures 2 and S2 were given for 4 in DMF).

4. Photophysical and photochemical properties

4.1. Emission spectra and fluorescence quantum yields

The emission properties of photosensitizing molecules are important measures for the evaluation of their application as biological imaging agents. Among a vast range of materials, Pcs include specific chemical and physical features that make them appropriate compounds in this respect. Therefore, the spectrophotometric and spectrofluorometric properties of Pcs are studied to determine the suitability of these molecules as biological imaging materials [26]. Fluorescence features of the complexes (4 to 6) were researched into in DMSO, THF, and DMF. The emission, excitation, and ground state spectra of the macrocyclic molecules (4 and 5) in DMSO are depicted in Figures 3 and S3. Octa-peripherally substituted zinc phthalocyanine derivatives showed similar emission, excitation, and absorbance characteristics with tetra-substituted peripheral and nonperipheral derivatives, except for minor differences in the wavelengths [20,21]. Maximum peak of the

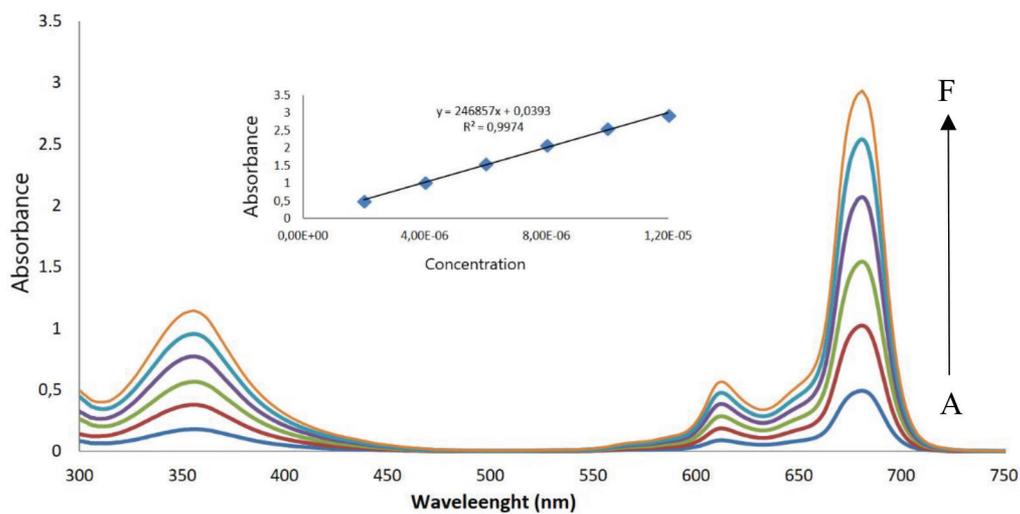


Figure 2. Absorption spectra of 4 in DMF at different concentration: 2×10^{-6} (A), 4×10^{-6} (B), 6×10^{-6} (C), 8×10^{-6} (D), 10×10^{-6} (E), 12×10^{-6} (F) mol/dm³.

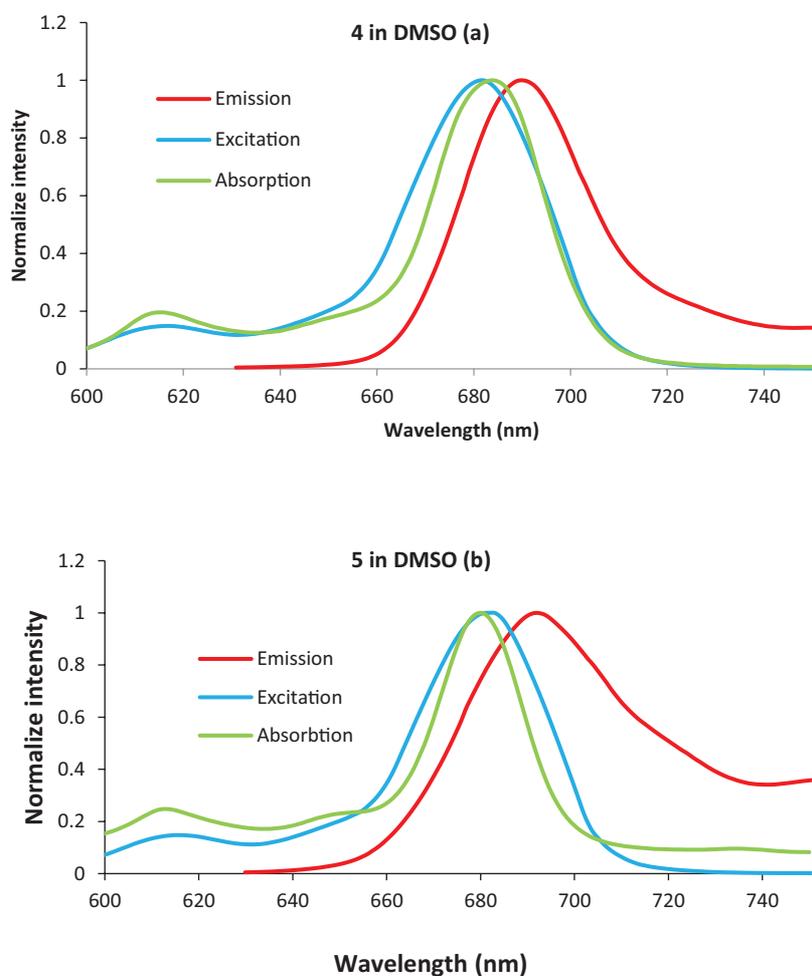


Figure 3. Absorption, excitation, and emission spectra of the compounds 4 (a) and 5 (b) in DMSO.

emission was seen at the following values: 689 nm for **4**, 691 nm for **5**, 690 nm for **6** in DMF; 689 nm for **4**, 690 nm for **5**, 692 nm for **6** in DMSO; and 686 nm for **4**, 684 nm for **5**, 687 nm for **6** in THF (Table 1), respectively. The excitation spectra were mirror images of the emission spectra for all Pcs.

The effect of substituent nature and solvent type on the values of Φ_F were examined, and the highest value was obtained for complex **5** in DMSO ($\Phi_F = 0.13$). Generally, nonperipherally substitution leads to lower values of Φ_F due to its proximity to the Pc ring, and the octa-substituted Zinc(II)Pc complexes (**4**, **5**, and **6**) have lower values of Φ_F in comparison to their ZnPc patterns [20,21]. Fluorescence quantum efficiencies of the octa-connected Pcs are higher than unsubstituted ZnPc; $\Phi_F = 0.18$ in DMSO [21]. Significant effect of halogen atom types (F, Cl, Br) on the Pcs on Φ_F values of **4**, **5** and **6** were not observed in the solutions. However, the F-substituted derivative showed higher fluorescence efficiency in all solvents.

4.2. Singlet oxygen quantum yields (Φ_Δ)

The effective singlet oxygen " 1O_2 " generation is the most important element of photodynamic therapy after combination of light, photosensitizers, and molecular oxygen. Due to the high reactivity of singlet oxygen, some biological macrosystems, such as nucleic acid, proteins, and lipid membranes, can be damaged and finally induce cell death. Energy transfer from photosensitizer to molecular oxygen should be as efficient as possible to obtain more singlet oxygen. This study aims to evaluate their effectiveness for the production of singlet oxygen since phthalocyanines containing phenoxy-phenoxy group with terminated halogen atoms (F, Cl, Br) seem to be suitable for inducing intersystem crossing. The effect of some factors consisting of the substituent, and the terminated halogens atom types on the " 1O_2 " quantum yields were investigated by applying a photochemical method based on the chemical quenching. The measurements " 1O_2 " yield are studied in the 3 solvents (DMF, THF, and DMSO) to determine whether the new Pcs were advisable for photodynamic therapy application. Figure 4 shows absorbance changes of DPBF observed during photolysis of zinc phthalocyanine complexes **4**, **5**, and **6** in DMSO by using UV-Vis spectroscopy. The degradation rate of DPBF is related to singlet oxygen production. No change in the Q band maxima of the Pcs was observed during the Φ_Δ determinations, which confirms that the sensitizers are not disrupted by 1O_2 attack (Figure S4) [26]. The Φ_Δ values are for **4** (0.69), **5** (0.61), **6** (0.67) in DMF; for **4** (0.60), **5** (0.55), **6** (0.67) in DMSO; for **4** (0.68), **5** (0.75), and **6** (0.73) in THF. The Φ_Δ values of 3 phthalocyanines were generally bigger in THF than DMF and DMSO. Chosen moiety on Pc skeleton increased the generation of 1O_2 compared to unsubstituted zinc phthalocyanine in DMF and THF (Table 1). When the effect of the halogen atom types was examined, there was no important difference depending on the halogen atom type. However, those with an F-end showed a higher singlet oxygen yield in DMSO, those with a Cl-end in THF, and those with a Br-end in DMSO. Octa-substituted zinc phthalocyanines (**4** to **6**) showed almost the same 1O_2 quantum yields compared to the previously obtained tetra-substituted peripherally and nonperipherally Zn(II)Pcs analogs bearing the same groups [20,21].

4.3. Photodegradation quantum yields under the light (Φ_d)

The effective photosensitizers during the photodynamic therapy applications should be stable under the applied light. This stability is necessary to maintain the efficiency of the photosensitizer molecule in terms of singlet oxygen production and to keep the drug concentration unchanged. Photodegradation is the oxidative degradation to determine the stability of a compound under photo irradiation applied and can be defined by photodegradation quantum yield. These processes were performed in THF, DMSO, and DMF by examining the falling away in the intensity of the maximum Q band of the complexes by the time. The photodegradation quantum yields are shown in Table 2. The obtained results show that synthesized complexes are stable to photochemical degradation and are much more resistant, especially compared to unsubstituted ZnPc. To measure Φ_d value, the absorbance (Q-band maxima) changes observed for **6** in DMF are shown in Figures 5 and S5. Highly stable phthalocyanine molecules give values of Φ_d as low as 10^{-6} , and for unstable Pcs values of Φ_d the order 10^{-3} have been reported [27]. The order of photochemical stabilities of the compounds were **4** > **5** > **6** in DMSO, and **6** > **4** > **5** in DMF, respectively. Φ_d of **4**, **5**, and **6** samples displayed high photostability under a light intensity of 2.50×10^{16} photons $s^{-1} cm^{-2}$ (Table 2). Not all of the complexes showed important photodegradation in measurements taken in THF. The complexes were highly stable in THF, while they showed the highest photochemical instability in DMF.

5. Conclusion

In this study, a new series of zinc phthalocyanine compounds carrying F (**6**), Cl (**5**), and Br (**4**) halogens terminated phenoxy-phenoxy moiety to octa-substituted position were successfully synthesized. Structural characterization of the resulting compounds (**1** to **6**) was performed using a number of diverse spectroscopic approaches. All data matched the proposed structures. Aggregation behaviors of the zinc Pcs were carried out at increasing molarity in THF, DMF, and DMSO. Additionally, the effect of solvent nature on the aggregation behavior of the zinc Pc was examined. As concentration increased, the absorbance enhanced directly in a constant value, and no new band was observed. Thus, nonaggregated behavior of the Pcs suggest that PDT applications are useful in the solutions. When the effect of the solvent

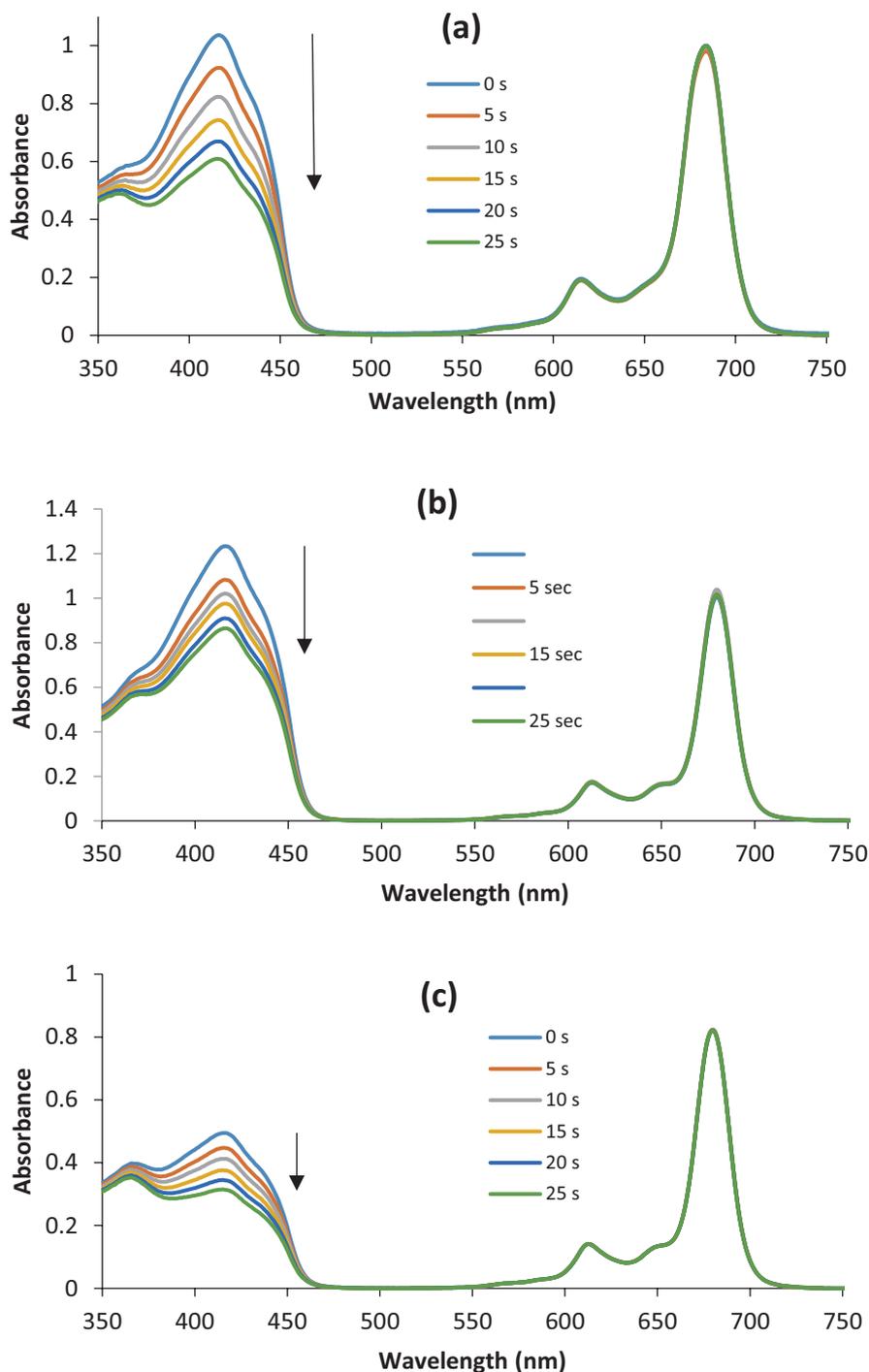
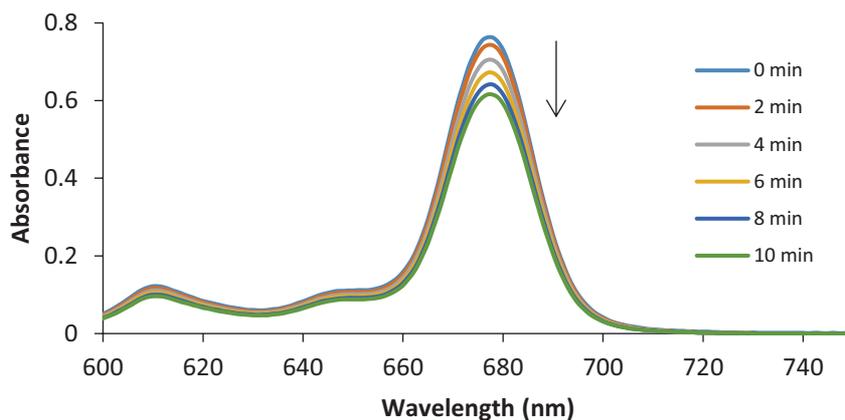


Figure 4. A typical spectrum for the determination of singlet oxygen quantum yield of for complex **4** (a), **5** (b), **6** (c) in DMSO at a concentration 6×10^{-6} mol dm $^{-3}$. The light intensity of 7.05×10^{15} photons s $^{-1}$ cm $^{-2}$ was used for Φ_D with 5 s intervals.

on singlet oxygen production was examined, admirable photophysicochemical results were obtained among the 3 solvents used. Photophysical and photochemical properties of zinc complexes bearing the same substituent terminated different halogens (F, Cl, and Br) at octa-peripherally positions were also studied comparatively to their tetra-peripherally and nonperipherally patterns. Important increases in the 1O_2 quantum yields were realized in the presence of the selected group and diamagnetic zinc atom as the central atom. Compared to the type of halogen atoms via phenoxy-phenoxy groups

Table 2. Photophysical and photochemical properties of **4**, **5**, and **6** in DMF, DMSO, and THF.

Compound	Solvent	Φ_F	$\Phi_d (10^{-4})$	Φ_Δ
4	DMF	0.07	11.0	0.69
	DMSO	0.03	0.40	0.60
	THF	0.10	----	0.68
5	DMF	0.08	15.0	0.61
	DMSO	0.13	1.00	0.55
	THF	0.10	-----	0.75
6	DMF	0.10	8.0	0.67
	DMSO	0,11	6.0	0.67
	THF	0.09	-----	0.73

**Figure 5.** A typical spectrum for the determination of photodegradation of complex **6** in DMF.

improve photophysicochemical properties. The results of photochemical measurements show that the complexes have suitable photodegradation stability with applicative “ 1O_2 ” efficiencies ranging from 0.55 to 0.75.

Acknowledgments

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References

1. Dahlen MA. The phthalocyanines a new class of synthetic pigments and dyes. *Industrial & Engineering Chemistry* 1939; 31: 839-847. doi: 10.1021/ie50355a012
2. Mahapatra NN. *Textile Dyeing*. New Delhi, India: Woodhead Publishing,, , 2018.
3. Rongrong C, Haixia L, Deryn C, Guofeng W. Unraveling oxygen reduction reaction mechanisms on carbon-supported Fe-phthalocyanine and Co-phthalocyanine catalysts in alkaline solutions. *The Journal of Physical Chemistry C* 2009; 113 (48): 20689-20697. doi: 10.1021/jp906408y
4. Norman H, Stucky GD, Chadwick T. Shape selectivity in hydrocarbon oxidations using zeolite encapsulated iron phthalocyanine catalysts. *Journal of the Chemical Society, Chemical Communications* 1986; 20: 1521-1522. doi: 10.1039/C39860001521
5. Helen JM, Peter MB, Neil BM. Catalysis by microporous phthalocyanine and porphyrin network polymers. *Journal of Materials Chemistry* 2008; 18 (5): 573-578. doi: 10.1039/B715660J

6. Sezer MB, Şener K, Koca A, Erdoğan A, Avciata U. Synthesis, electrochemistry, spectroelectrochemistry and electrocolorimetry of phthalocyanine-anthraquinone hybrids. *Synthetic Metals* 2010; 160: 2155-2166. doi: 10.1016/j.synthmet.2010.08.002
7. Simon J, Sirlin C. Mesomorphic molecular materials for electronics, optoelectronics, iono-electronics: octaalkyl-phthalocyanine derivatives. *Pure and Applied Chemistry* 1989; 61 (9): 1625-1629. doi: 10.1351/pac198961091625
8. González-rodríguez D, Torres T, Dirk MG, Rivera J, Herranz MÁ. Subphthalocyanines: tuneable molecular scaffolds for intramolecular electron and energy transfer processes. *Journal of American Chemical Society* 2004; 36 (2): 1-36. doi: 10.1021/ja039883v
9. Vogel M, Doka S, Breyer C, Lux-Steiner M, Fostiropoulos K. On the function of a bathocuproine buffer layer in organic photovoltaic cells. *Applied Physics Letters* 2006; 89 (16): 163501. doi: 10.1063/1.2362624
10. Peumans P, Forrest SR. Very-high-efficiency double-heterostructure copper phthalocyanine/C60 photovoltaic cells. *Applied Physics Letters* 2001; 79 (1): 126-128. doi: 10.1063/1.1384001
11. Raymond B. Photosensitizers of the porphyrin and phthalocyanine series for photodynamic therapy. *Chemical Society Reviews* 1995; 24 (1): 19-33.
12. John DS. Phthalocyanines as photosensitizers in biological systems and for the photodynamic therapy of tumors. *Photochemistry and Photobiology* 1986; 43 (6): 691-699. doi: 10.1039/CS9952400019
13. Michael H, Danilo D, Markus B, Sergej V. Conjugated macrocycles as active materials in nonlinear optical processes: optical limiting effect with phthalocyanines and related compounds. *The Chemical Record* 2002; 2 (3): 129-148. doi: 10.1002/tcr.10024
14. Keleş T, Bıyıklıoğlu Z, Gültekin E, Bekircan O. Synthesis and electrochemical properties of peripheral, nonperipheral tetra [2-(3,5-diphenyl-1H-1,2,4-triazol-1-yl)ethoxy] substituted cobalt(II), manganese(III) phthalocyanines. *Inorganica Chimica Acta* 2019; 487: 201-207. doi: 10.1016/j.ica.2018.12.010
15. Schumann S, Hatton RA, Jones TS. Organic photovoltaic devices based on water-soluble copper phthalocyanine. *The Journal of Physical Chemistry C* 2011; 115 (11): 4916-4921. doi: 10.1021/jp109544m
16. John M, Martin JS. Transition assignments in the ultraviolet-visible absorption and magnetic circular dichroism spectra of phthalocyanines. *Inorganic Chemistry* 2001; 40 (4): 812-814. doi: 10.1021/ic0009829
17. Durmuş M, Erdoğan A, Oğunsipe A, Nyokong T. The synthesis and photophysical and photochemical behaviour of novel water-soluble cationic indium (III) phthalocyanine. *Dyes and Pigments* 2009; 82: 244-250. doi: 10.1016/j.dyepig.2009.01.008
18. Erdoğan A, Arıcı M. Novel soluble octa-substituted phthalocyanines bearing chloro and long alkyl chain containing fluorine: synthesis, characterization and photophysical and photochemical properties. *Journal of Fluorine Chemistry* 2014; 166: 127-133. doi: 10.1016/j.jfluchem.2014.08.005
19. Güzel E, Atmaca GY, Erdoğan A, Burkut MK. Novel sulfonated hydrophilic indium(III) and gallium(III) phthalocyanine photosensitizers: preparation and investigation of photophysical and photochemical properties. *Journal of Coordination Chemistry* 2017; 70: 2659-2670. doi: 10.1080/00958972.2017.1366471
20. Kırbaç E, Erdoğan A, Atmaca GY. Novel highly soluble fluoro, chloro, bromo-phenoxy-phenoxy substituted zinc phthalocyanines: synthesis, characterization and photophysical and photochemical properties. *Journal of Organometallic Chemistry* 2014; 751: 115-122. doi: 10.1016/j.jorganchem.2013.12.005
21. Kırbaç E, Erdoğan A. New non-peripherally substituted zinc phthalocyanines: synthesis, and comparative photophysical and photochemical properties. *Journal of Molecular Structure* 2020; 1202: 127392. doi: 10.1016/j.molstruc.2019.127392
22. Erdoğan A, Nyokong T. New soluble methylenedioxy-phenoxy-substituted zinc phthalocyanine derivatives: synthesis, photophysical and photochemical studies. *Polyhedron* 2009; 28: 2855-2862. doi: 10.1016/j.poly.2009.06.019
23. Uğur AL, Erdoğan A, Koca A, Avciata U. Synthesis, spectroscopic, electrochemical and spectroelectrochemical properties of metal free, manganese, and cobalt phthalocyanines bearing peripherally octakis-[4-(thiophen-3-yl)-phenoxy] substituents. *Polyhedron* 2010; 29: 3310-3317. doi: 10.1016/j.poly.2010.09.008
24. Ahmetali E, Atmaca GY, Karaoğlu HP, Koçak MB, Erdoğan A. Photophysical and photochemical properties of newly synthesized zinc(II) and chloroindium(III) phthalocyanines substituted with 3,5-bis (trifluoromethyl)phenoxy groups. *J Porphyrins Phthalocyanines* 2019; 23: 960-968. doi: 10.1142/S108842461950055X
25. Korkmaz E, Ahmetali E, Atmaca GY, Karaoğlu HP, Erdoğan A et al. Investigation of photophysical and photochemical properties of phthalocyanines bearing fluorinated groups. *Monatshefte für Chemie* 2020; 151: 181-190. doi: 10.1007/s00706-019-02543-y
26. Koca B, Hamuryudan E, Catak S, Erdoğan A, Monari A et al. Exploring the photophysics of polyfluorinated phthalocyanine derivatives as potential theranostic agents. *The Journal of Physical Chemistry C* 2019; 123: 24417-24425. doi: 10.1021/acs.jpcc.9b07053
27. Nyokong T. Effects of substituents on the photochemical and photophysical properties of main group metal phthalocyanines. *Coordination Chemistry Reviews* 2007; 251: 1707-1722. doi: 10.1016/j.ccr.2006.11.011

SUPPLEMENTARY INFORMATION

**Newly synthesized peripherally octa-substituted zinc phthalocyanines
carrying halogen terminated phenoxy-phenoxy moiety; comparatively
photochemical and photophysical features**

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1. Materials and equipment

Dimethylsulfoxide (DMSO), 1-pentanol, methanol, n-hexane, chloroform (CHCl_3), tetrahydrofuran (THF), acetone, K_2CO_3 , ethanol, and dimethylformamide (DMF) were purchased from Merck, 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), 1,3-diphenylisobenzofuran (DPBF), 4,5-dichlorophthalonitrile, zinc acetate, zinc phthalocyanine, 4-(4-bromophenoxy)phenol, 4-(4-chlorophenoxy)phenol and 4-(4-fluorophenoxy)phenol were purchased from Sigma Aldrich. Column chromatography was performed on silica gel 60 (0.04–0.063mm).

FT-IR spectra (KBr pellets) were measured with a Perkin Elmer Spectrum One Spectrometer. Absorption spectra in the UV-Visible region were obtained with a Shimadzu 2001 UV spectrophotometer. Elemental analyses were recorded with a Thermo Flash EA 1112 Series.

Fluorescence spectra were done using a Varian Eclipse spectrofluorometer using 1 cm pathlength cuvettes at room temperature. ^1H NMR spectra were recorded in CDCl_3 solutions on a Varian 500 MHz spectrometer.

Photo-irradiations were done using a General Electric quartz line lamp (300W). A 600 nm glass cut off filter (Schott) and a water filter was used to filter off ultraviolet and infrared radiations respectively. An interference filter (Intor, 700 nm with a bandwidth of 40 nm) was additionally placed in the light path before the sample. Light intensities were measured with a POWER MAX5100 (Molelectron detector incorporated) power meter. The mass spectra were acquired on a Bruker Daltonics (Bremen, Germany) MicroTOF mass spectrometer equipped with an electrospray ionization (ESI) source. The instrument was operated in positive ion mode using a m/z range of 50–3000. The capillary voltage of the ion source was set at 6000 V and the capillary exit at 190 V. The nebulizer gas flow was 1 bar and drying gas flow 8 mL/min.

2. Photophysical and Photochemical Studies

2.1. Fluorescence quantum yields

Fluorescence quantum yields (Φ_F) were determined by the comparative method (Eq. 1) [S1],

$$\Phi_F = \Phi_{F(\text{Std})} \frac{F \cdot A_{\text{Std}} \cdot n^2}{F_{\text{Std}} \cdot A \cdot n_{\text{Std}}^2} \quad (1)$$

where F and F_{Std} are the areas under the fluorescence emission curves of the samples (**4** to **6**) and the standard, respectively. A and A_{Std} are the respective absorbances of the samples and standard at the excitation wavelengths, respectively. n^2 and n_{Std}^2 are the refractive indices of solvents used for the sample and standard, respectively. Unsubstituted ZnPc (in DMSO) ($\Phi_F = 0.20$) [S2], (in DMF) ($\Phi_F = 0.17$) [S3], (in THF) ($\Phi_F = 0.25$) [S4] was employed as the standard. Both the samples and standard were excited at the same wavelength. The absorbance of the solutions at the excitation wavelength ranged between 0.04 and 0.05.

2.2. Singlet oxygen quantum yields

Singlet oxygen quantum yield (Φ_Δ) determinations were carried out using the experimental set-up described in the literature [S5-S8]. Quantum yields of singlet oxygen photogeneration were determined in air (no oxygen bubbled) using the relative method with ZnPc as reference and DPBF as chemical quencher for singlet oxygen, using equation 2

$$\Phi_{\Delta} = \Phi_{\Delta}^{\text{Std}} \frac{R \cdot I_{\text{abs}}^{\text{Std}}}{R^{\text{Std}} \cdot I_{\text{abs}}} \quad (2)$$

where $\Phi_{\Delta}^{\text{Std}}$ is the singlet oxygen quantum yields for the standard ZnPc ($\Phi_{\Delta}^{\text{Std}} = 0.67$ in DMSO [S8] and 0.56 for ZnPc in DMF [S9], and 0.53 for ZnPc in THF [S10]) R and R^{Std} are the DPBF photobleaching rates in the presence of the respective samples (**4**, **5** and **6**) and standard, respectively. I_{abs} and $I_{\text{abs}}^{\text{Std}}$ are the rates of light absorption by the samples (**4**, **5** and **6**) and standard, respectively. To avoid chain reactions induced by DPBF in the presence of singlet oxygen [S9], the concentration of quencher (DPBF) was lowered to $\sim 3 \times 10^{-5} \text{ mol dm}^{-3}$. Solutions of sensitizer (containing DPBF) were prepared in the dark and irradiated in the Q band region using the setup described above. DPBF degradation at 417 nm was monitored. The light intensity of $7.05 \times 10^{15} \text{ photons s}^{-1} \text{ cm}^{-2}$ was used for Φ_{Δ} determinations.

2.3. Photodegradation quantum yields

Photodegradation quantum yield (Φ_d) determinations were carried out using the experimental set-up described in the literature [S6-S7]. Photodegradation quantum yields were determined using formula 3,

$$\Phi_d = \frac{(C_0 - C_t) \cdot V \cdot N_A}{I_{\text{abs}} \cdot S \cdot t} \quad (3)$$

where “ C_0 ” and “ C_t ” are the sample (**4**, **5** and **6**) concentrations before and after irradiation respectively, “ V ” is the reaction volume, “ N_A ” the Avogadro’s constant, “ S ” the irradiated cell area and “ t ” the irradiation time, “ I_{abs} ” is the overlap integral of the radiation source light

intensity and the absorption of the samples (**4**, **5** and **6**). A light intensity of 2.50×10^{16} photons $\text{s}^{-1} \text{cm}^{-2}$ was employed for Φ_a determinations.

3. Synthesis

3.1. 4,5 Bis-[4-(4-bromophenoxy)phenoxy]phthalonitrile (**1**)

The 4,5-dichlorophthalonitrile (0.39 g 1.97 mmol) was dissolved in dry DMF (10 ml) under inert argon atmosphere and 4-(4-bromophenoxy) phenol (1.00 g 3.77 mmol) was added. After stirring for 30 min at room temperature, finely ground anhydrous potassium carbonate (2.0 g 14.47 mmol) was added in portions during two hours with efficient stirring. The reaction mixture was stirred under argon atmosphere at room temperature for 24 h. Then the mixture was dumped into 100 ml cold water, and the precipitate was filtered off, and crystallized in methanol and then dried. Finally, the pure powder was dried in a vacuum. Yield: 0.27 g (22%). IR spectrum (cm^{-1}): 2970 (Ar-CH), 2233 ($\text{C}\equiv\text{N}$), 1478 ($\text{C}=\text{C}$), 1240, 1095 (C-O-C), 824 (C-Br). ^1H NMR (CDCl_3): δ = 7.88-7.90 (m, 2H, Ar-H), 7.46-7.52 (m, 4H, Ar-H), 7.04-7.12 (m, 10H, Ar-H). 6.94-7.00 (m, 2H, Ar-H). The results of elemental analysis, Calcd for $\text{C}_{32}\text{H}_{18}\text{Br}_2\text{N}_2\text{O}_4$: C, 58.74; H, 2.77; N, 4.28%; Found: C, 58.70; H, 2.75; N, 4.23%. MS (GC-MS) m/z : Calc. 654.30; Found: 654.0 $[\text{M}]^+$.

3.2. 4,5 Bis-[4-(4-chlorophenoxy)phenoxy]phthalonitrile (**2**)

The synthesis of **2** was similar to that of **1**, except 4-(4-chlorophenoxy) phenol (1.00 g 4.53 mmol) was employed instead of (1). The amounts of the other reagents were: 4,5-dichlorophthalonitrile, 0.45 g (2.28 mmol) and anhydrous potassium carbonate, 2 g (14.47 mmol).

Yield: 0.23 g (17%). IR spectrum (cm^{-1}): 3094 (Ar-CH), 2224 ($\text{C}\equiv\text{N}$), 1586 ($\text{C}=\text{C}$), 1205, 1087 (C-O-C), 826 (C-Cl). ^1H NMR (CDCl_3): δ = 6.90-6.94 (m, 4H, Ar-H), 6.98 (m, 4H, Ar-H), 6.98 (m, 8H, Ar-H), 7.10 (m, 2H, Ar-H), 7.25-7.28 (m, 4H, Ar-H). The results of elemental

analysis, Calcd for $C_{32}H_{18}Cl_2N_2O_4$: C, 67.98; H, 3.21; N, 4.95%; Found: C, 68.04; H, 3.19; N, 4.91%. MS (TOF-MS) m/z: Calc. 564.1; Found: 587 $[M+Na]^+$.

3.3. 4,5 Bis[4-(4-fluorophenoxy) phenoxy]phthalonitrile (3)

The synthesis of **3** was similar to that of **1**, was employed instead of 4-(4-fluorophenoxy)phenol (1.0 g 4.90 mmol). The amounts of the other reagents were: 4,5-dichlorophthalonitrile, 0.48 g (2.43 mmol) and anhydrous potassium carbonate, 2 g (14.47 mmol). Yield: 0.28 g (21 %). IR spectrum (cm^{-1}): 3095 (Ar-CH), 2226 ($C\equiv N$), 1585 ($C=C$), 1250, 1084 (C-O-C), 843 (C-F); 1H NMR ($CDCl_3$): δ = 7.04-7.12 (m, 14H, Ar-H), 7.19 (m, 4H, Ar-H). The results of elemental analysis, Calcd for $C_{32}H_{18}FN_2O_4$, The results of elemental analysis, Calcd for $C_{32}H_{18}F_2N_2O_4$, C, 72.18; H, 3.41; N, 5.26%; Found: C, 72.23; H, 3.45; N, 5.31%. MS (TOF-MS) m/z: Calc. 532.0; Found: 555 $[M+Na]^+$.

3.4. (3,4)-Octo[(bromophenoxy) phenoxy] phthalocyaninato zinc(II) (4)

A mixture of 4,5 Bis-[4-(4-bromophenoxy)phenoxy]phthalonitrile (**1**) (0.10 g 0.15 mmol), DBU (0.2 ml, 1.33 mmol) and zinc acetate (0.05 g, 0.50 mmol) in n-hexanol (4.0 ml) was refluxed and stirred under argon atmosphere for 12 h. The resulting green suspension was cooled. The crude product was precipitated by addition of n-hexane, collected by centrifuged and washed with hot hexane, ethanol and methanol. The green product was further purified by column chromatography over a silica gel using a mixture of $CHCl_3$: MeOH (100/ 5 v/v) as eluent. Yield: 0.037 g (36%). UV-Vis (DMF): λ_{max} nm (log ϵ) 681 (5.39), 613 (4.68), 356 (4.98); UV-Vis (DMSO): λ_{max} nm (log ϵ) 684 (5.39), 615 (4.71), 356 (4.99); (THF): λ_{max} nm (log ϵ) 678 (5.27), 611 (4.53), 351 (4.84). FT-IR ν_{max}/cm^{-1} (KBr pellet): (3107 (Ar-CH), 1600 ($C=C$), 1480 ($C=N$), 1254, 1232, 1187 (C-O-C) 1H NMR ($CDCl_3$): δ = 6.96-67,90 (44H, m, Ar-H)., The results of elemental analysis, Calcd for $C_{128}H_{72}Br_8N_8O_{16}Zn$: C, 57.31; H, 2.71; N, 4.18%; Found: C, 57.39; H, 2.68; N, 4.25%. MS (MALDI-MS) m/z: Calc: 2682.0; Found: 2682 $[M]^+$.

3.5. (3,4)-Octo [chlorophenoxy] phenoxy phthalocyaninato zinc(II) (5)

Synthesis and purification was as outlined for **4** except 4-5 bis [4-(4-chlorophenoxy) phenoxy] phthalonitrile (0.10 g 0.17 mmol), (**2**) was employed instead of **1**. Amounts of reagents used in DBU (0.2 ml, 1.33 mmol), zinc acetate (0.1 g, 0.50 mmol) in n-hexanol (4.0 ml). Yield: 0.026 g (25 %). UV-Vis (DMF): λ_{\max} nm (log ϵ) 677 (5.14), 611 (4.32), 365 (4.65); UV-Vis (DMSO): λ_{\max} nm (log ϵ) 680 (5.16), 612 (4.38), 364 (4.69); (THF): λ_{\max} nm (log ϵ) 675 (5.17), 609 (4.36), 357 (4.69). FT-IR $\nu_{\max}/\text{cm}^{-1}$ (KBr pellet): 3041 (Ar-CH), 1592 (C=C), 1481 (C=N), 1203, 1186 (C-O-C) (Pc skeletal). ^1H NMR (CDCl_3): δ = 7.65-6.90 (44H, m, Ar-H). The results of elemental analysis, Calcd for $\text{C}_{128}\text{H}_{72}\text{Cl}_8\text{N}_8\text{O}_{16}\text{Zn}$: C, 66.07; H, 3.12; N, 4.82%; Found: C, 66.16; H, 3.16; N, 4.87%. MS (MALDI-MS) m/z: Calc. 2327; Found: 2328 $[\text{M}+\text{H}]^+$.

3.6. (3,4)-Octo [fluorophenoxy] phenoxy phthalocyaninato zinc(II) (6)

Synthesis and purification was as outlined for **4** except 4,5 Bis[4-(4-fluorophenoxy) phenoxy]phthalonitrile (0.1 g 0.18 mmol), (**3**) was employed instead of **1**. The amounts of the reagents employed were: DBU (0.20 ml, 1.33 mmol), zinc acetate (0.01 g, 0.50 mmol) in n-hexanol (4 ml). Yield: 0.032 g (31 %). UV-Vis (DMF): λ_{\max} nm (log ϵ) 676 (5.39), 610 (4.64), 362 (4.97). UV-Vis (DMSO): λ_{\max} nm (log ϵ) 680 (5.33), 613 (4.60), 365 (4.89); (THF): λ_{\max} nm (log ϵ) 675 (5.42), 609 (4.67), 356 (5.00).

FT-IR $\nu_{\max}/\text{cm}^{-1}$ (KBr pellet): 3070 (Ar-CH), 1605 (C=C), 1486 (C=N), 1247, 1185 (C-O-C) (Pc skeletal) ^1H -NMR (CDCl_3): δ = 7.20-6.70 (44H, m, Ar-H). The results of elemental analysis Calc. for $\text{C}_{128}\text{H}_{72}\text{F}_8\text{N}_8\text{O}_{16}\text{Zn}$: C, 70.03; H, 3.31; N, 5.10%; Found: C, 70.11; H, 3.35; N, 5.16%. MS (MALDI-MS) m/z: Calc. 2195.0; Found: 2196 $[\text{M}+\text{H}]^+$.

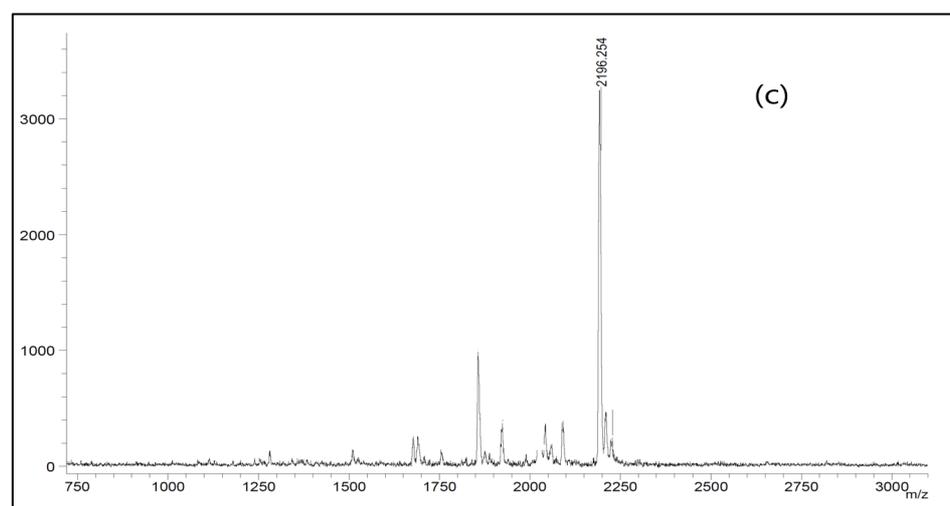
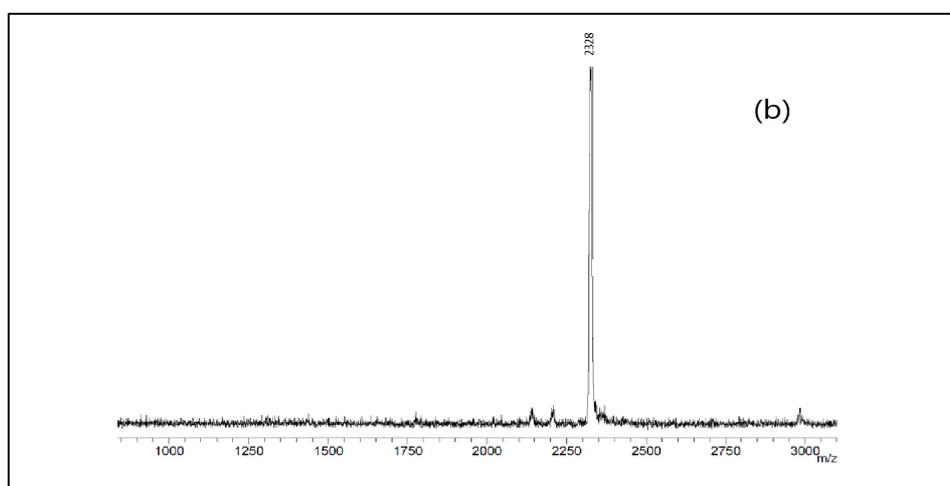
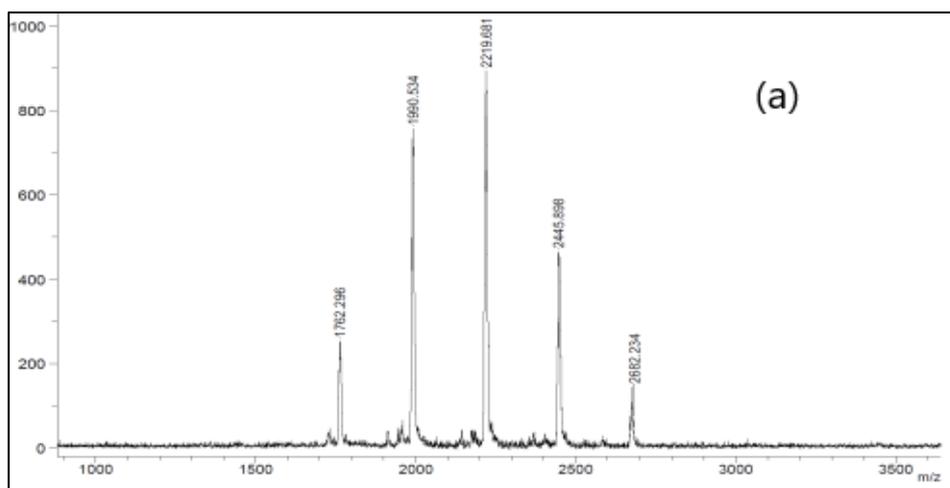


Figure S1. Compounds of mass spectrum of **4** ($2682 [M]^+$) (a), **5** ($2328 [M+H]^+$) (b), and **6** ($2196 [M+H]^+$) (c).

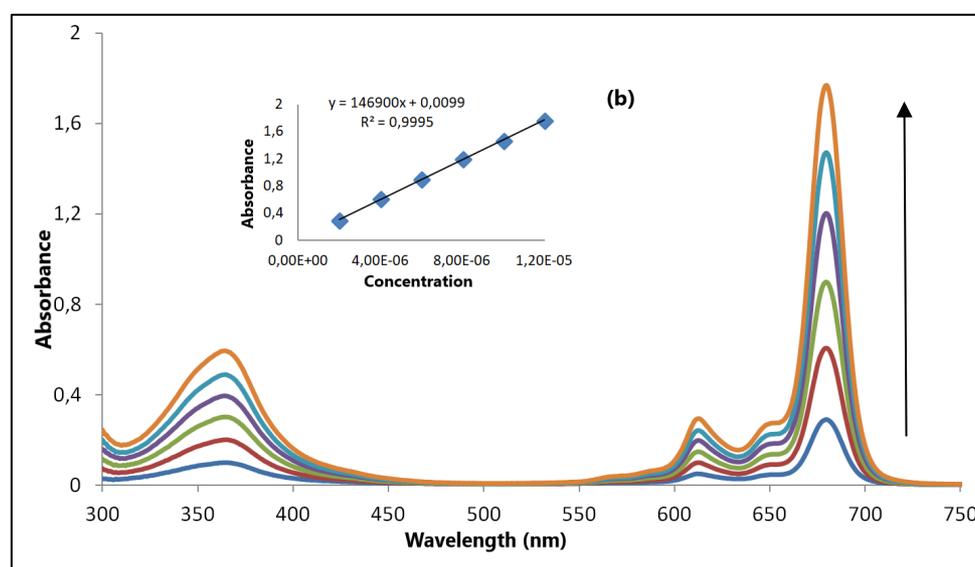
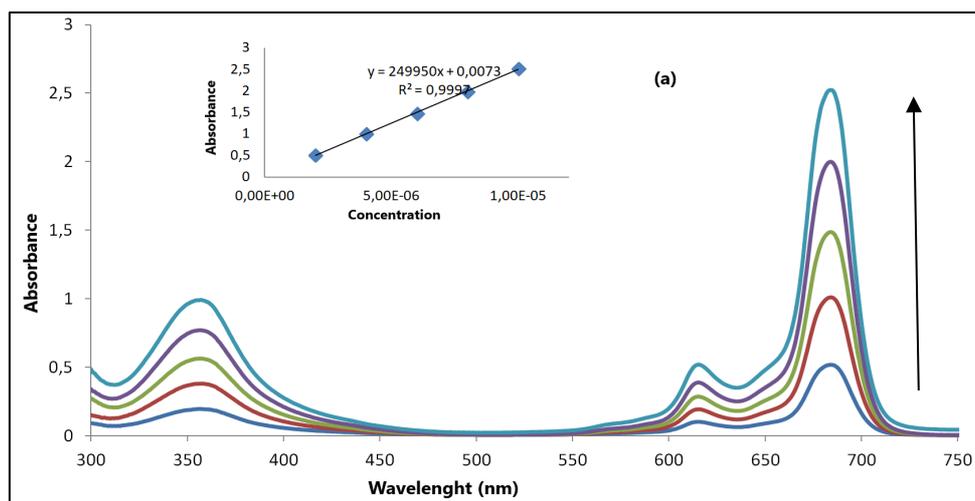


Figure S2. Absorption spectra of **4** (a) in DMSO and **5** (b) in DMF at different concentration: 2×10^{-6} , 4×10^{-6} , 6×10^{-6} , 8×10^{-6} , 10×10^{-6} , 12×10^{-6} mol dm⁻³

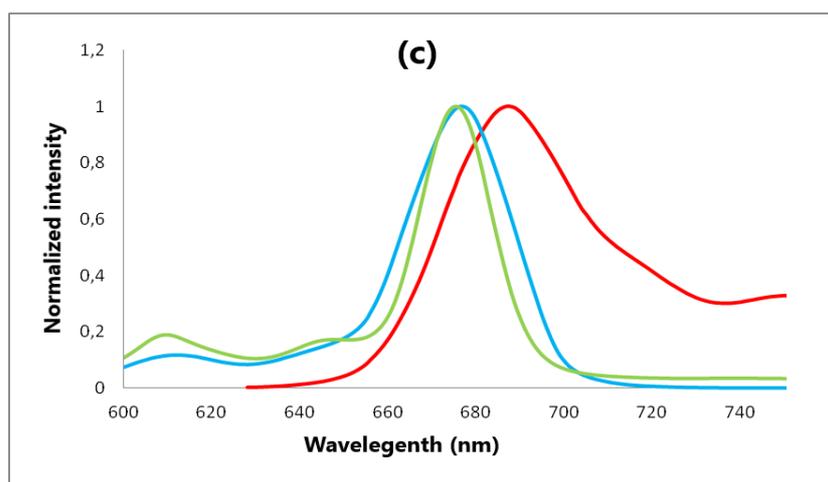
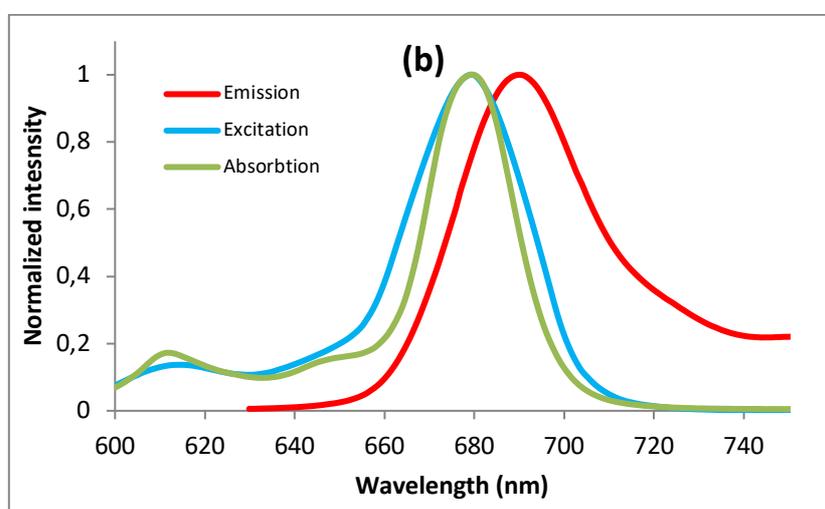
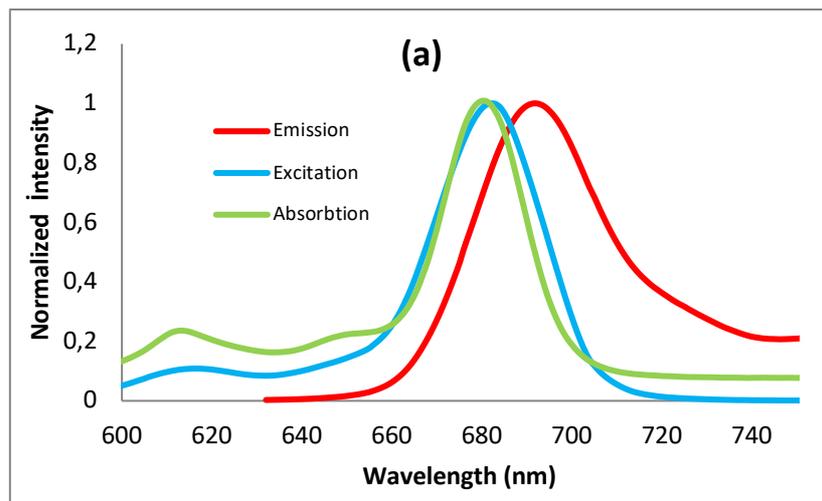


Figure S3. Absorption, excitation and emission spectra of the compounds **4** in DMSO (a), **4** in DMF (b), **6** and in THF (c)

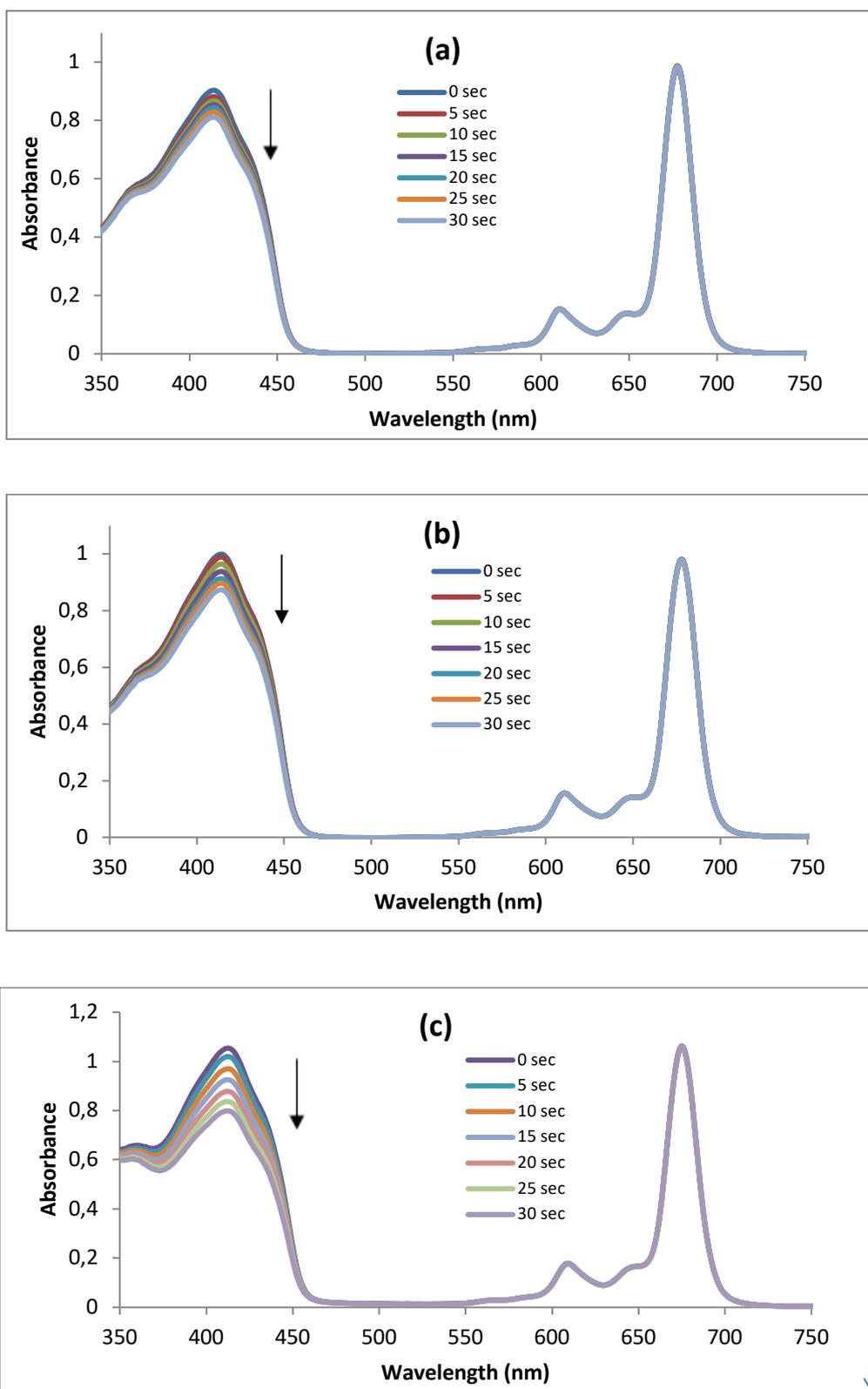


Figure S4. A typical spectrum for the determination of singlet oxygen quantum yield of for complex **5** (a) in DMF, **6** (b) in DMF and **4** (c) in THF at a concentration $6 \times 10^{-6} \text{ mol dm}^{-3}$

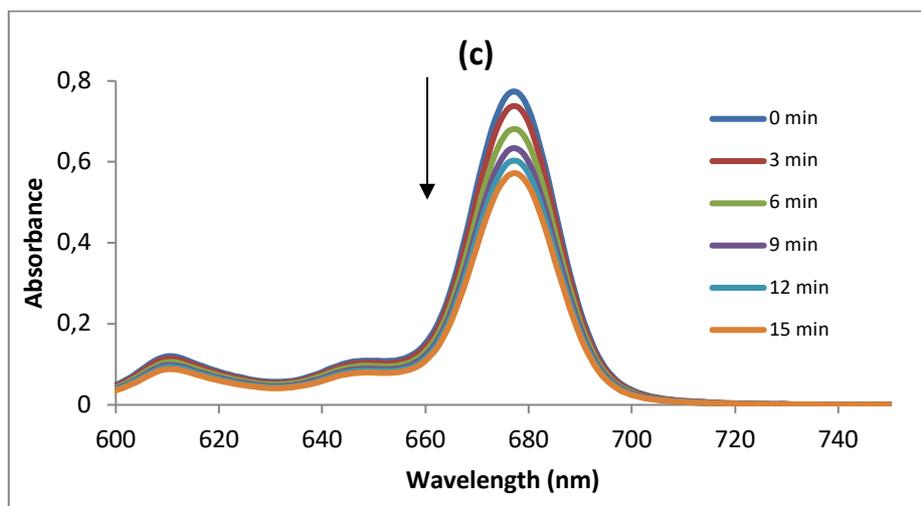
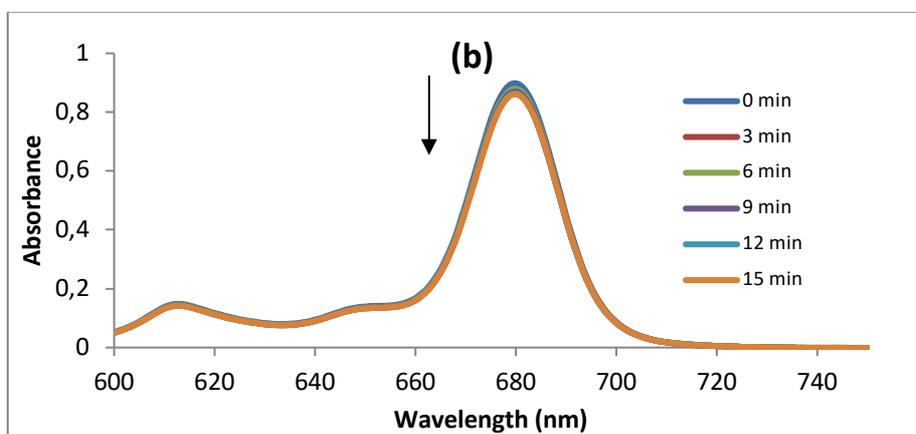
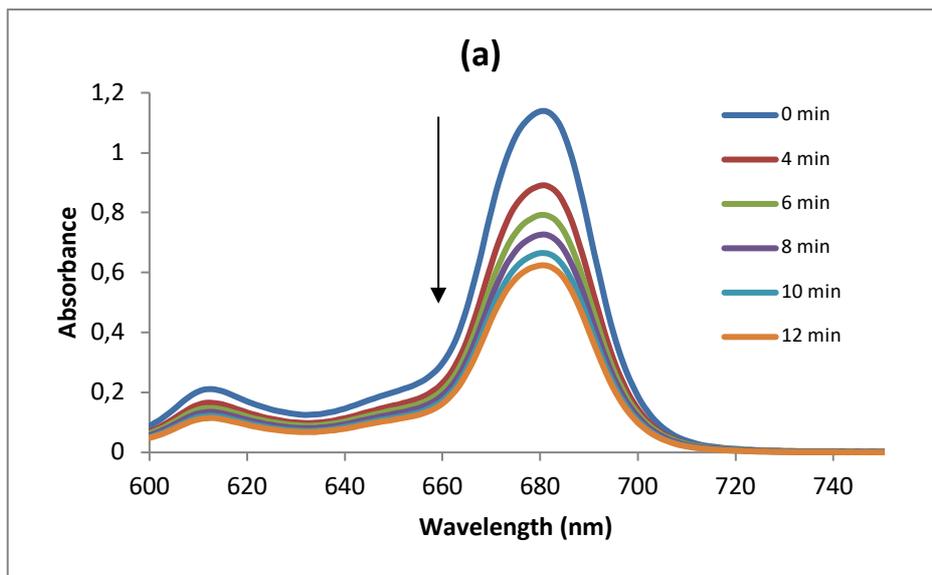


Figure S5. A typical spectrum for the determination of Photodegradation. This figure was for complex **4** in DMF (a), **5** in DMSO (b) and **5** in DMF (c)

References

- S1. Frey-Forgues S, Lavabre D. Are fluorescence quantum yields so tricky to measure? A demonstration using familiar stationary products. *Journal of Chemical Education* 1999; 76: 1260-1264. doi: 10.1021/ed076p1260
- S2. Ogunsipe A, Chen JY, Nyokong T., Photophysical and photochemical studies of zinc(II) phthalocyanine derivatives effects of substituents and solvents. *New Journal of Chemistry* 2004; 25: 822-827. doi: 10.1039/B315319C
- S3. Durmus M, Nyokong T. Photophysicochemical and fluorescence quenching studies of benzyloxyphenoxy-substituted zinc phthalocyanines. *Spectrochim Acta A*. 2008; 69: 1170-1177. doi: 10.1016/j.saa.2007.06.029
- S4. Saka ET, Durmus M, Kantekin H. Solvent and central metal effects on the photophysical and photochemical properties of 4-benzyloxybenzoxy substituted phthalocyanines. *Journal of Organometallic Chemistry* 2011; 696: 913-924. doi: 10.1016/j.jorganchem.2010.10.024
- S5. Brannon JH, Madge D. Picosecond laser Photophysics. group 3A phthalocyanines. *Journal of the American Chemical Society* 1980;102: 62-65
- S6. Ogunsipe A, Nyokong T. Photophysical and photochemical studies of sulphonated non-transition metal phthalocyanines in aqueous and non-aqueous media. *Journal of Photochemistry and Photobiology A: Chemistry* 2005; 173: 211-220. doi: 10.1016/j.jphotochem.2005.03.001
- S7. Seotsanyana-Mokhosi I, Kuznetsova N, Nyokong T. Photochemical studies of tetra-2,3-pyridinoporphyrazines. *Journal of Photochemistry and Photobiology A: Chemistry* 2001; 140: 215-222. doi:10.1016/j.jphotochem.2005.03.001
- S8. Kuznetsova N, Gretsova N, Kalmykova E, Makarova E, Dashkevich S, Negrimovskii V, Kaliya O, Luk'yanets E. Structure-photochemical properties relationship for porphyrins and related compounds, *Russ. J. Gen. Chem.* 2000; 133:133-140.
- S9. Spiller W, Kliesch H, Wohrle D, Hackbarth S, Roder B, Schnurpfeil G, Singlet oxygen quantum yields of different photosensitizers in polar solvents and micellar solutions. *Journal of Porphyrins and Phthalocyanines* 1998; 2: 145-149. doi:10.1002/(SICI)1099-1409(199803/04)2:2<145::AID-JPP60>3.0.CO;2-2
- S10. Ogunsipe A, Maree D, Nyokong T. Solvent effects on the photochemical and fluorescence properties of zinc phthalocyanine derivatives. *Journal of Molecular Structure* 2003; 650: 131-140. doi:10.1016/S0022-2860(03)00155-8