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Photophysics of tetracarboxy-zinc phthalocyanine photosensitizers

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Zinc-tetracarboxy-phthalocyanine (ZnPc(COOH)₄) was synthesized by a melting method and basic hydrolysis. A ZnPc(COOH)₄/Fe₃O₄/Ch composite was prepared by immobilization of ZnPc(COOH)₄ onto Fe₃O₄/chitosan nanoparticles by a simple immersion method. The photophysical properties were studied using UV-vis spectrophotometry, fluorescence spectroscopy and time-correlated single photon counting (TCSPC) in different aqueous solutions. The UV-vis spectra of the ZnPc(COOH)₄/Fe₃O₄/Ch composite displays absorption by the aromatic rings, with a Q band exhibited at $\lambda_{\text{max}} = 702$ nm. Moreover, the ZnPc(COOH)₄/Fe₃O₄/Ch composite exhibits long triplet-state lifetimes of 1.6 μs and 12.3 μs , crucial for application as a photosensitizer. A triplet quantum yield of 0.56 for the ZnPc(COOH)₄/Fe₃O₄/Ch composite in DMSO/H₂O was achieved. FTIR showed that the conjugation of ZnPc(COOH)₄ with Fe₃O₄/chitosan nanoparticles was achieved by electrostatic interaction.

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Introduction

Metallophthalocyanine (MPc) derivatives are popular photodynamic therapy (PDT) photosensitizers (PSs). Research on a novel PS requires extensive human effort and a high cost investment over decades before clinical application. Nevertheless, some MPc derivatives, such as: aluminium phthalocyanine (Photosens®, Russia), used against skin, breast and lung malignancies, and cancers of the gastrointestinal tract;¹ silicon Pc (Pc 4, USA), for the sterilization of blood components against human colon, breast and ovarian cancers, and gliomas;² and a liposomal zinc phthalocyanine formulation, using a controlled organic solvent dilution against squamous cell carcinomas of the upper aerodigestive tract,³ have undergone clinical trials.

Current efforts are being made in the development of new photosensitizers (PSs) with improved solubility in body fluids and injectable solvents, photostability, enhanced permeability and retention effect, elimination and cumulative systemic toxicity.^{4–9} In the field of organic photosensitizers, metallophthalocyanines (MPcs) play an important role due to their excellent photo- and electro-chemical stability and exclusive light-harvesting capability in the red/NIR spectral regions.^{10–13}

The main disadvantages of MPcs in PDT are the lack of solubility and selectivity; therefore, the combination of magnetic iron oxide nanoparticles with a photosensitizer is a new and promising approach in PDT. Fe₃O₄ nanoparticles

have been successfully applied in tumor therapy by inducing hyperthermia and oxidative stress that lead to tumor cell damage.^{14–16} For application in PDT, magnetic nanoparticles (NPs) are usually coated with polymers, bound to the particle through organic linkers.¹⁷ Functionalization of Fe₃O₄ nanoparticles may lead to enhancement of their biocompatibility, colloidal stability, and an increase in the number of groups, through which the required antitumor effect can be obtained.

The major goal of this paper is to create a new photosensitizer with adequate solubility, especially in body fluids and injectable solvents, with greater tumor selectivity, enhanced hydrophilicity, and strong absorption in the NIR spectral region. Therefore, conjugation of an MPc derivative to a magnetic NP functionalized with a polymer is the first part of our research aimed at delivering PSs to tumor cells. The magnetic iron oxide nanoparticles will be used as the carrier of the photosensitizer because of: their ability to carry and deliver therapeutic photosensitizers into deep-seated tumours; the enhanced solubility of the hydrophobic PS with an appropriate size to accumulate in the tumour tissues *via* enhanced permeability and retention effect; and the ability to attack cancer cells selectively without harming other healthy cells. The Fe₃O₄ NPs will be functionalized with chitosan, which is a biodegradable, biocompatible polysaccharide and, in comparison with many other polymers, has many free –OH and –NH₂ groups that can serve as anchors for conjugation of therapeutics and targeting ligands.

Considering the above mentioned information, we focused our research on attaching functionalized ZnPc with carboxylic groups (–COOH) to an Fe₃O₄/chitosan system hoping to get a synergistic effect in the photodynamic parameters of the resulting composite.

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Materials and methods

Materials

All materials, trimellitic anhydride, zinc acetate dehydrate ($\text{Zn}(\text{CH}_3\text{COOH})_2 \cdot 2\text{H}_2\text{O}$), ammonium molybdate tetrahydrate ($(\text{NH}_4)_6\text{MO}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$), anhydrous sodium sulfate (Na_2SO_4), urea, 1-bromo-naphthalene, hydrochloric acid and acetic acid were purchased from Sigma-Aldrich, Inc., St. Louis, MO, USA and used as received. Dimethyl sulfoxide (DMSO), chitosan (Ch) and hydrogen peroxide (H_2O_2) were obtained from Alfa Aesar, Heysham, UK. Fe_3O_4 nanoparticles (Merck) were cleaned in a flux of hydrogen at room temperature for 20 minutes.

Equipment

The UV-vis spectra of the solutions were measured using a UV-vis spectrophotometer (Lambda 25, PerkinElmer, Inc., Shelton, CT, USA) from 200 nm to 1200 nm in 10 mm quartz cuvettes. The steady-state fluorescence spectroscopy was performed using a spectrometer (LS-55, PerkinElmer, Inc., Shelton, CT, USA) equipped with double-grating excitation and emission monochromators. Time-correlated single photon counting (TCSPC) was used to determine the fluorescence lifetime. The time-resolved fluorescence spectra were recorded on a spectrometer (FLS980, Edinburgh Instruments, Livingston EH54 7DQ, Oxford, UK). All the measurements were made at room temperature (295 ± 1 K). A Bruker D8 ADVANCE X-ray diffractometer (using Cu K_α radiation with $\lambda = 1.5406 \text{ \AA}$) was used for structural investigation of the magnetic nanoparticles. A Bruker FTIR spectrometer was used to provide information about the chemical composition.

Synthesis

The synthetic pathway of $\text{ZnPc}(\text{COOH})_4$

A mixture consisting of 4.35 g (0.022 mol) of trimellitic anhydride, 2.52 g of $\text{Zn}(\text{CH}_3\text{COOH})_2 \cdot 2\text{H}_2\text{O}$, 0.3 g of $(\text{NH}_4)_6\text{MO}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$, 0.5 g of Na_2SO_4 , 13.51 g (0.225 mol) of urea and 5 ml of 1-bromonaphthalene was heated at 200–205 °C for 8 h with continuous stirring. After 8 hours, the reaction mixture was cooled to room temperature and treated with methanol. The obtained suspension was filtered. The solid reaction product was washed on the filter with methanol, chloroform and, finally, with acetone. After drying, the product was crumbled and then refluxed for one hour in 5% hydrochloric acid (HCl) solution. After drying, the same procedure was carried out with 5% sodium hydroxide (NaOH) solution for one hour at 90 °C. Finally, the solution was acidified with HCl until the pH was equal to 2, and the precipitated final product was filtered and dried in the open air. 0.68 g of $\text{ZnPc}(\text{COOH})_4$ was obtained with a yield of 70% (Fig. 1).

Preparation of chitosan-functionalized magnetic nanoparticles

Chitosan and Fe_3O_4 were mixed in an appropriate proportion to form the chitosan-magnetic nanoparticles composite with amine groups by the reverse-phase suspension cross-linking

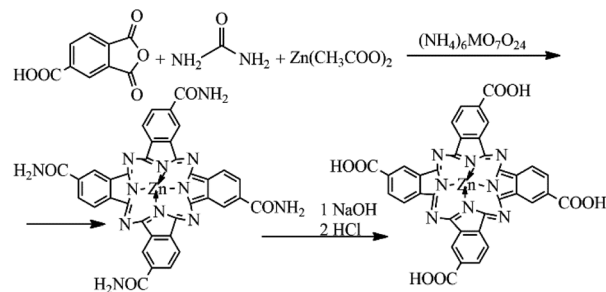


Fig. 1 Schematic diagram of $\text{ZnPc}(\text{COOH})_4$ synthesis.

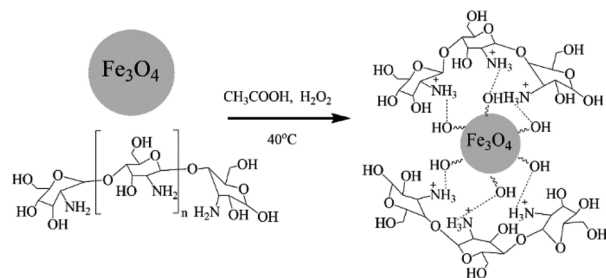


Fig. 2 Schematic diagram of the preparation of chitosan-functionalized magnetic nanoparticles.

method.¹⁸ Aqueous acetic acid solution was used as a solvent for the chitosan polymer and H_2O_2 was used as the cross-linker. In this specific procedure, a chitosan solution was prepared using a mixture of 2% acetic acid and 10% H_2O_2 solutions. Then 0.2 g Fe_3O_4 was added and stirred with strong ultrasonic agitation at room temperature for 4 h. At the end of this period, some of the chitosan- Fe_3O_4 nanocomposite particles were collected from the reaction mixture by using a permanent magnet. The product was washed with ethanol and dried in vacuum at 60 °C for 5 hours and used for XRD analysis (Fig. 2).

Chitosan is able to interact with negatively charged molecules,¹⁹ such as the hydroxyl ($\text{Fe}-\text{OH}$) groups on the surface of magnetite nanoparticles. The presence of $-\text{OH}$ groups on the surface of the Fe_3O_4 nanoparticles was confirmed by the strong broad band with a maximum at 3431 cm^{-1} in the IR spectrum (Fig. 4), corresponding to $\nu(\text{O}-\text{H})$ oscillations. We suppose that ionic interactions occur between the negatively charged CH_3COO^- species and the positively charged (NH_3^+) groups of the chitosan molecules dissolved in the aqueous acetic acid solution.

The conjugation of $\text{ZnPc}(\text{COOH})_4$ to chitosan, Fe_3O_4 and $\text{Fe}_3\text{O}_4/\text{Ch}$ nanoparticles

Acetic acid is a weak acid and is a very common solvent for chitosan. A sample of 0.3 g of chitosan was dissolved in 50 ml of 2% concentrated acetic acid. Then 0.5 ml of 10% hydrogen peroxide was added to the solution for the destruction of intermacromolecular hydrogen bonds and interchain hydrogen bonds to make water-soluble chitosan. The appropriate ratio of chitosan to acetic acid in the chitosan-acetic acid solution was



1 : 0.5, and then $\text{ZnPc}(\text{COOH})_4$ was dissolved in a 1 : 1 DMSO/ H_2O solution. After that, both solutions were mixed, heated at 40 °C and stirred continuously for 40 min.

In a separate experiment, $\text{ZnPc}(\text{COOH})_4$ solution was mixed with a dispersion medium containing chitosan-functionalized magnetic nanoparticles at room temperature and stirred for 2 h using a mechanical stirrer.

Experiments where $\text{ZnPc}(\text{COOH})_4$ was dissolved in 1 : 1 DMSO/ H_2O solution and simply mixed with Fe_3O_4 were also performed.

Results and discussion

Structural analysis of the Fe_3O_4 and Fe_3O_4 /chitosan magnetic nanoparticles

The X-ray diffraction patterns of the Fe_3O_4 and Fe_3O_4 /chitosan nanoparticles, along with the standard pattern of Fe_3O_4 (JCPDS #75-0033), are shown in Fig. 3 and details of the peaks are given in Table 1. The similar XRD patterns reveal that Fe_3O_4 does not undergo any phase changes following functionalization with chitosan, a situation also confirmed by other reports.^{20,21}

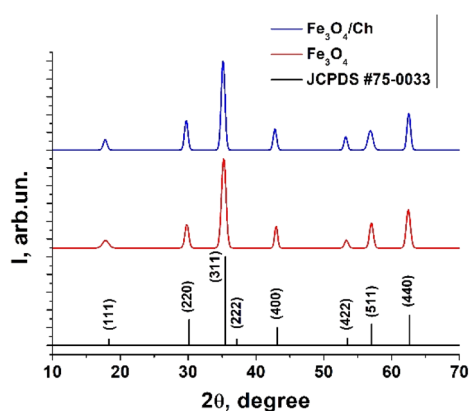


Fig. 3 XRD patterns of the Fe_3O_4 and Fe_3O_4 /chitosan nanoparticles, and the JCPDS #75-0033 card.

Table 1 Structural parameters of the Fe_3O_4 and Fe_3O_4 /chitosan nanoparticles

	2θ	FWHM	D , nm	D_{mean} , nm
Fe_3O_4	17.84	1.05	8.5	13.95
	29.81	0.67	13.7	
	35.25	0.79	11.	
	42.99	0.52	18.1	
	53.35	0.62	15.9	
	57.03	0.66	15.3	
	62.47	0.72	14.3	
$\text{Fe}_3\text{O}_4/\text{Ch}$	17.78	0.66	13.5	14.80
	29.72	0.61	15.0	
	35.16	0.66	14.1	
	42.81	0.60	15.8	
	53.24	0.59	16.7	
	56.88	0.86	11.7	
	62.54	0.61	16.8	

XRD diffraction analysis revealed a broad nature of the diffraction maxima, indicating that Fe_3O_4 has small crystallite sizes. The crystallite sizes were evaluated using the Debye-Scherrer formula:

$$D = (k\lambda/\beta \cos \theta) \quad (1)$$

where λ is the wavelength of the X-rays (1.5406 Å), β is the FWHM (full width at half maximum), θ is the diffraction angle, $k = 0.94$ and D is the crystallite size. The metal oxide nanoparticles have a mean crystallite size of 13.95 nm. During the coating process with chitosan, the crystallite size slightly increases, as the size of the individual crystallite is related to the thickness of the chitosan layer. The mean crystallite size of the nanoparticles with chitosan increases up to 14.80 nm.

FTIR analysis

The FTIR spectra of chitosan, the Fe_3O_4 and Fe_3O_4 /chitosan nanoparticles, $\text{ZnPc}(\text{COOH})_4$ and the $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ /chitosan composite are presented in Fig. 4 and 5. The intense peak observed at 636 cm^{-1} in the FTIR spectrum of Fe_3O_4 is attributed to the stretching vibration mode associated with Fe–O bonds in the crystalline lattice of the Fe_3O_4 nanoparticles. This

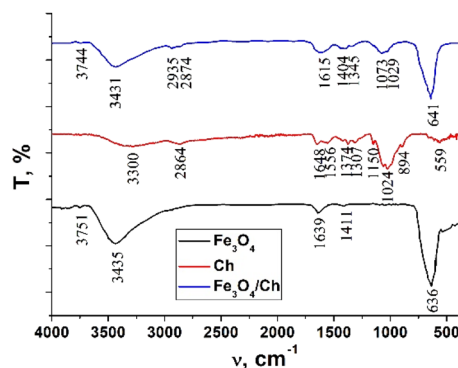


Fig. 4 FTIR spectra of chitosan, the Fe_3O_4 nanoparticles and the Fe_3O_4 /chitosan nanoparticles.

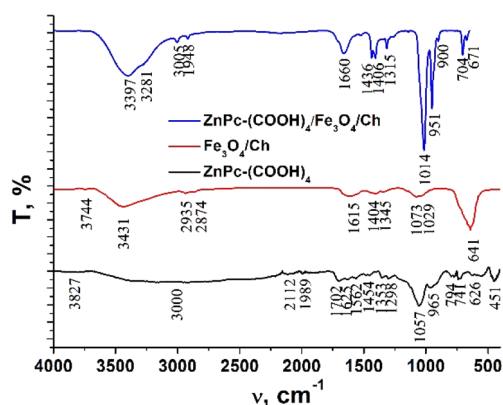


Fig. 5 FTIR spectra of $\text{ZnPc}(\text{COOH})_4$, Fe_3O_4 /chitosan and the $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ /chitosan composite.



vibration is shifted to 641 cm^{-1} in the FTIR spectrum of the Fe_3O_4 /chitosan nanoparticles. The modification and shift of the main characteristic bands (stretching C–O at 1024 cm^{-1} , bending NH_2 at 1648 cm^{-1} , stretching O–H 3300 cm^{-1} and C–H 2864 cm^{-1}) in the IR spectrum of chitosan to 1073 and 1029 cm^{-1} ($\nu(\text{C–O})$), 1615 cm^{-1} ($\delta(\text{NH}_2)$), 3431 cm^{-1} ($\nu(\text{O–H})$), and 2935 and 2874 cm^{-1} ($\nu(\text{C–H})$) in the IR spectrum of the Fe_3O_4 /chitosan system demonstrate the binding of chitosan to the Fe_3O_4 nanoparticles (Fig. 4). The result is consistent with similar investigations.^{22,23} The chemical interaction of $\text{ZnPc}(\text{COOH})_4$ with the Fe_3O_4 /chitosan system is confirmed by the shift of the signal from 1702 cm^{-1} ($\nu(\text{C=O})$) of the protonated COOH groups in the IR spectrum of $\text{ZnPc}(\text{COOH})_4$, associated with splitting, to 1660 cm^{-1} ($\nu_{\text{sym}}(\text{COO})$), and 1436 and 1406 cm^{-1} ($\nu_{\text{asym}}(\text{COO})$) that correspond to deprotonated carboxylic groups. This can be explained by the dissociation of carboxylic groups and formation of electrostatic interactions between NH_3^+ and COO^- fragments (Fig. 16a).

UV-vis and fluorescence analysis

Usually, MPcs give rise to electronic spectra with two strong absorption bands, one around 300 nm , called the “B” or Soret band, due to electronic transitions from the deeper π -HOMO to n^* -LUMO energy levels, while the other at 600 – 650 nm , called the “Q” band, due to electronic transitions from the π -HOMO to π^* -LUMO energy levels.²⁴ The UV-vis spectra of $\text{ZnPc}(\text{COOH})_4$ and $\text{ZnPc}(\text{COOH})_4/\text{Ch}$ in $\text{DMSO}/\text{H}_2\text{O}$ are presented in Fig. 6. The absorption spectra of the synthesized materials display absorption peaks in the visible region at around 700 nm . In the case of $\text{ZnPc}(\text{COOH})_4$ and $\text{ZnPc}(\text{COOH})_4/\text{Ch}$ dissolved in $\text{DMSO}/\text{H}_2\text{O}$, absorption maxima are situated at 640 and 697 nm , and 642 and 699 nm , respectively. The shifts of the Q band depend on the change in electron distribution in the phthalocyanine ring caused by the substituents and their position. The UV-vis spectra of $\text{ZnPc}(\text{COOH})_4$ immobilized on non-functionalized magnetic nanoparticles are shown in Fig. 7. The intensity of the absorption for the $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ material in a solution of $1:1:2$ $\text{DMSO}/\text{Ac.ac}/\text{phys.sol.}$ (where “Ac.ac” is acetic acid, and “phys.sol.” is a physiological NaCl solution) decreases when decreasing the molar concentration of $\text{ZnPc}(\text{COOH})_4$ from

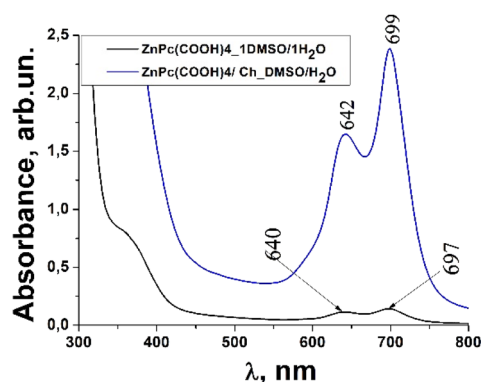


Fig. 6 Absorbance spectra changes of the $\text{ZnPc}(\text{COOH})_4$ compound and $\text{ZnPc}(\text{COOH})_4/\text{Ch}$ in $\text{DMSO}/\text{H}_2\text{O}$ solvent.

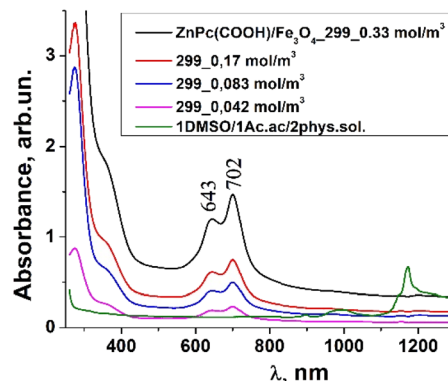


Fig. 7 Absorbance spectra changes of $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ in $\text{DMSO}/\text{Ac.ac}/\text{phys.sol.}$ solution, $1:1:2$ ratio, at different molar concentrations.

0.33 mol m^{-3} to 0.042 mol m^{-3} . The conjugation of $\text{ZnPc}(\text{COOH})_4$ with the chitosan-functionalized Fe_3O_4 nanoparticles gives rise to similar positions of the maxima in the Q band absorbance spectra (Fig. 8) as in the case when $\text{ZnPc}(\text{COOH})_4$ is mixed with the non-functionalized Fe_3O_4 nanoparticles. A difference appears in the width of the bands, with a narrower band being found for $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$ than for $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$.

In Fig. 7, Fe_3O_4 was dissolved in a physiological solution of 0.9% NaCl and 2% acetic acid. For the Fe_3O_4 /chitosan solution measurements shown in Fig. 8, 2% acetic acid and 10% hydrogen peroxide were used. The Q band extends into the 580 – 800 nm region and exhibited two peaks at $\lambda_{\text{max}} = 645\text{ nm}$ and 702 nm in the case of the Fe_3O_4 nanoparticles linked to chitosan (Fig. 8), almost the same values as when Fe_3O_4 is not bound to chitosan (Fig. 7). Both the $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$ and $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ spectra (Fig. 9) show similar specific absorption peaks of the phthalocyanine aromatic ring. The chitosan had no obvious absorption peak in the visible region, but leads to an increased intensity of the 702 nm peak and a narrower Q band. The comparison in Fig. 9 allows us to suppose that the Q absorption band could be assigned to the π -

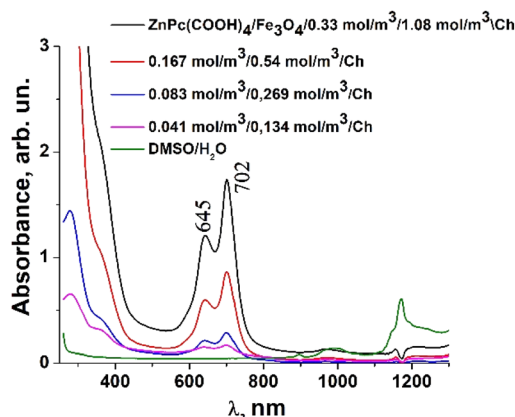


Fig. 8 Absorbance of the $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$ composite in $\text{DMSO}/\text{H}_2\text{O}$ solution at different molar concentrations.

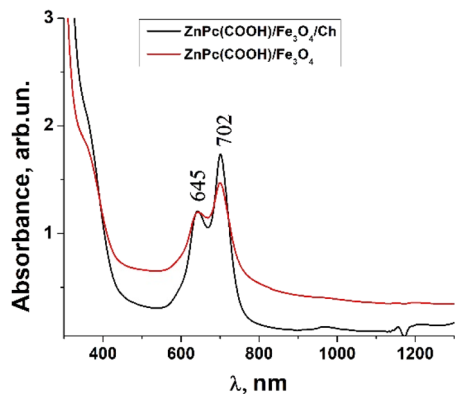


Fig. 9 Comparison of the absorbance of the $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ and $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{Ch}$ composites in DMSO/phys.sol. 0.9% and DMSO/ $\text{H}_2\text{O}_2/\text{Ac.ac}$ solutions.

π^* transition on the ZnPc macrocycle. Introducing the peripheral $-\text{COOH}$ substituent onto the macrocycle of ZnPc led to a significant bathochromic shift of the absorption spectra due to an increased destabilization of the HOMO electron state versus the LUMO state.

The low energy peak is due to the monomer, while the high energy peak is caused by the aggregation. The aggregation

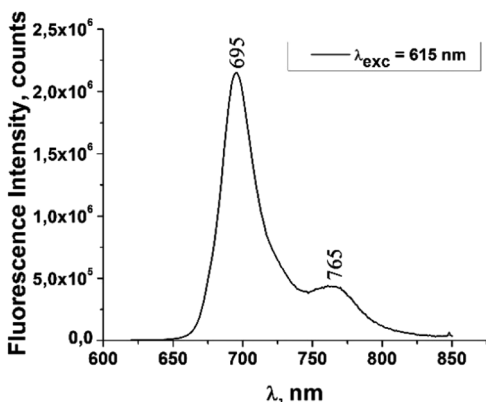


Fig. 10 Emission spectrum of $\text{ZnPc}(\text{COOH})_4$ in DMSO/ H_2O solution.

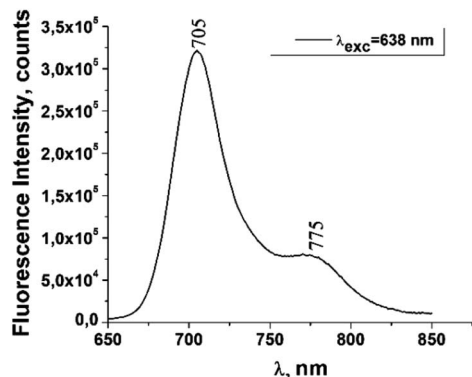


Fig. 11 Emission spectrum of $\text{ZnPc}(\text{COOH})_4/\text{chitosan}$ in DMSO/ H_2O solution.

species persisted more when the Fe_3O_4 nanoparticles were not bound to chitosan.

The fluorescence emission spectrum of $\text{ZnPc}(\text{COOH})_4$ in DMSO/ H_2O is shown in Fig. 10. The fluorescence spectrum after excitation at 615 nm shows two emission bands situated at 695 nm and 765 nm. The fluorescence spectrum of the $\text{ZnPc}(\text{COOH})_4/\text{chitosan}$ system (Fig. 11) after excitation at 638 nm also shows two bands, as in Fig. 10, but they are both shifted 10 nm into the near-infrared region. The fluorescence

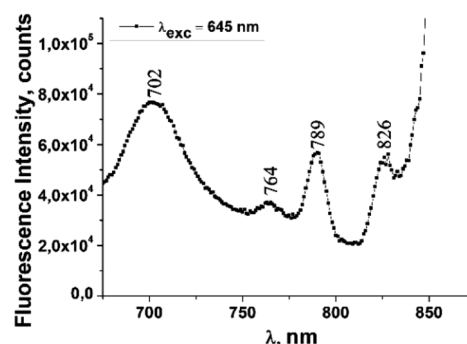


Fig. 12 Emission spectrum of $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4$ in DMSO/phys.-sol. 0.9% solution.

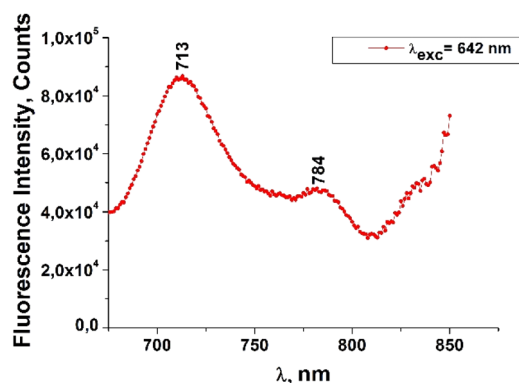


Fig. 13 Emission spectrum of $\text{ZnPc}(\text{COOH})_4/\text{Fe}_3\text{O}_4/\text{chitosan}$ in DMSO/ $\text{H}_2\text{O}_2/\text{Ac.ac}$ solution.

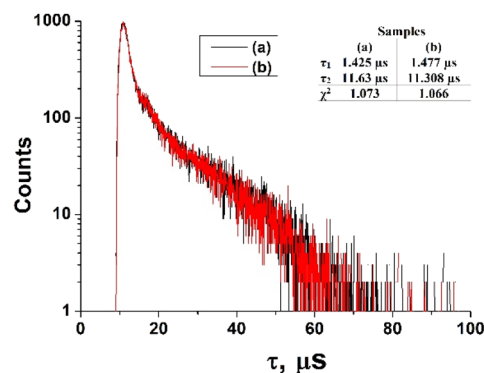


Fig. 14 The fluorescence lifetimes of $\text{ZnPc}(\text{COOH})_4$ (a) and $\text{ZnPc}(\text{COOH})_4/\text{chitosan}$ (b) in DMSO/ H_2O solution.



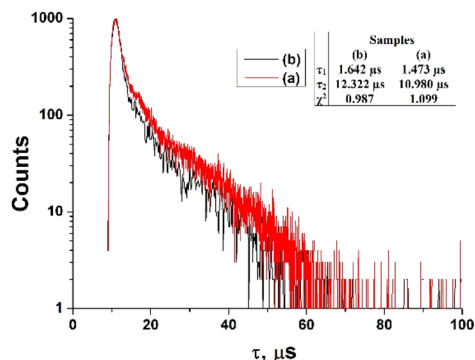


Fig. 15 The fluorescence lifetimes of ZnPc(COOH)₄/Fe₃O₄ in DMSO/phys.sol. 0.9% (a) and ZnPc(COOH)₄/Fe₃O₄/chitosan in DMSO/H₂O₂/Ac.ac (b) solutions.

spectrum of ZnPc(COOH)₄ immobilized on the Fe₃O₄ magnetic nanoparticles shows broad and structured fluorescence at 702 nm, 764 nm, 789 nm and 826 nm, and shows an increase in intensity at 850 nm, when excited at 645 nm (Fig. 12). The limits of the measurement equipment did not allow us to record fluorescence above 850 nm. The spectrum of ZnPc(COOH)₄ immobilized on the Fe₃O₄/chitosan magnetic nanoparticles shown in

Fig. 13 displayed less structured fluorescence. Only two broad bands situated at 713 nm and 784 nm shifted to the near-infrared region are revealed. The resultant red-shift was associated with the electrostatic interaction between ZnPc(COOH)₄ and the chitosan-functionalized Fe₃O₄ nanoparticles.

The fluorescence lifetimes of ZnPc(COOH)₄ and ZnPc(COOH)₄/chitosan in DMSO/H₂O solution are presented in Fig. 14.

The fluorescence decays of ZnPc(COOH)₄ and ZnPc(COOH)₄/chitosan in DMSO/H₂O solutions at about the same interval of excitation wavelengths ($\lambda_{\text{exc}} = 684\text{--}772$ nm) show a bi-exponential behaviour with lifetime values being 1.42 μs and 11.63 μs for the solution without chitosan, while, for the solution with chitosan, values of 1.47 μs and 11.31 μs are reported. The presence of chitosan does not induce significant variations in the fluorescence decay times. Thus, because the NH₂ groups in chitosan can form the same ionic bonds with the COOH groups, even in the absence of Fe₃O₄, but only in the presence of Fe₃O₄, the fluorescence decay time changes. So, the presence of Fe₃O₄ NPs is vital for the main result of the chemical reactions of the developed composite.

In Fig. 15, the fluorescence lifetimes of ZnPc(COOH)₄/Fe₃O₄ and ZnPc(COOH)₄/Fe₃O₄/chitosan in DMSO/phys.sol. 0.9% and DMSO/H₂O₂/Ac.ac solutions are illustrated. The fluorescence

Table 2 Photophysical parameters: triplet quantum yields (Φ_T) and the triplet-state lifetimes (τ_T) for all compounds

	Solvent	λ_{abs} , nm	λ_{emis} , nm	Φ_T	τ_T , μs
ZnPc(COOH) ₄	DMSO/H ₂ O	697	765	0.25	11.63
ZnPc(COOH) ₄ /chitosan	DMSO/H ₂ O	699	775	0.27	11.31
ZnPc(COOH) ₄ /Fe ₃ O ₄	DMSO/phys.sol. 0.9%	702	826	0.23	10.98
ZnPc(COOH) ₄ /Fe ₃ O ₄ /chitosan	DMSO/H ₂ O ₂ /Ac.ac	702	784	0.56	12.32

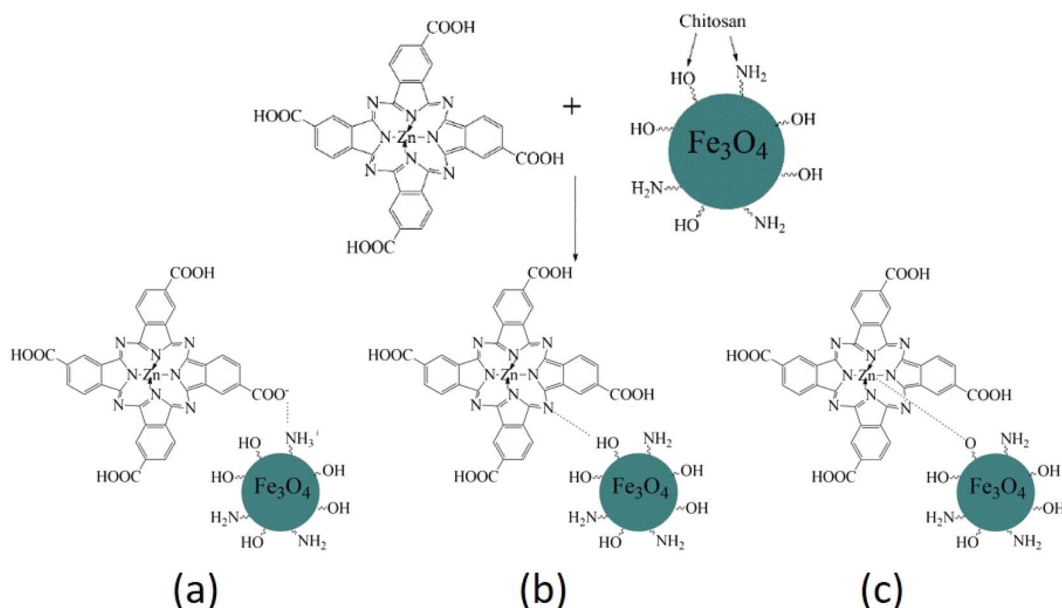


Fig. 16 Scheme of the possible interactions (electrostatic (a), hydrogen (b) and coordination bonds (c)) of ZnPc(COOH)₄ with the chitosan-functionalized Fe₃O₄ nanoparticles.



decay curve for ZnPc(COOH)₄/Fe₃O₄ yielded two lifetimes of 1.47 μs and 10.98 μs. The values are smaller than those of the ZnPc(COOH)₄/Fe₃O₄/chitosan composite, although the contribution of the shorter lifetime component is less than 13%. The longer lifetime in the ZnPc(COOH)₄/Fe₃O₄/chitosan composite can be explained by the magnetic nanoparticles' functionalization with chitosan. The fluorescence quantum yield values of the ZnPc(COOH)₄/Fe₃O₄ or ZnPc(COOH)₄/Fe₃O₄/chitosan composites in DMSO/phys.sol. 0.9% and DMSO/H₂O₂/Ac.ac solutions of 1 : 1 ratio were found to be lower than that for non-substituted ZnPc in non-diluted DMSO (0.67 in ref. 25) due to increased intersystem crossing in the presence of the Fe₃O₄ NPs. The photophysical parameters: triplet (Φ_T) quantum yields and the triplet-state lifetimes (τ_T), for ZnPc(COOH)₄ linked to magnetic nanoparticles are presented in Table 2.

So, we suppose that the surface interaction between the amino groups of the chitosan/Fe₃O₄ and the carboxylic groups of ZnPc(COOH)₄ most probably forms an electrostatic interaction. In addition to the electrostatic interaction between charged surfaces of ZnPc(COOH)₄ and chitosan/Fe₃O₄, coordination bonds between the Zn²⁺ ions of phthalocyanine and the oxygen atoms of chitosan/Fe₃O₄ can be formed.^{26,27} Also, hydrogen bonds between the nitrogen atoms of phthalocyanine and the hydrogen atoms of chitosan/Fe₃O₄ are also possible, as shown in the scheme presented in Fig. 16.

So, significant efforts have been made to develop the ZnPc(COOH)₄/Fe₃O₄/chitosan composite that has strong absorption of long-wavelength light and a triplet quantum yield of 0.56 that can be promising for PDT. But further studies will continue to improve the triplet-state lifetime and the triplet quantum yield, and elucidate the physicochemical processes in this composite. Moreover, *in vitro* and *in vivo* studies are required to elucidate the PDT effects.

Conclusions

In this study we have developed:

(1) a soluble ZnPc(COOH)₄ photosensitizer in DMSO/H₂O, ratio 1 : 1, with high absorption at 702 nm, excitation/emission wavelengths of 615/765 nm and fluorescence lifetimes of 1.42 μs and 11.63 μs.

(2) Fe₃O₄/chitosan magnetic nanoparticles with a mean crystallite size of the nanoparticles up 14.80 nm using the suspension cross-linking technique.

(3) ZnPc(COOH)₄ immobilized on chitosan-functionalized Fe₃O₄ nanoparticles through an immersion method with the aid of DMSO/H₂O₂/Ac.ac solution, exhibits higher triplet lifetimes of 1.6 μs and 12.3 μs.

The values of the triplet quantum yield (0.56) and the triplet-state lifetimes of ZnPc(COOH)₄/Fe₃O₄/Ch make this composite a promising candidate for PDT.

Author contributions

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Popusoi and I. Lungu; writing – original draft preparation: T. Potlog and S. Robu; writing – review and editing: I. Bulimestru, T. Potlog and S. Robu; supervision: T. Potlog. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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