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β-Cyclodextrin-conjugated phthalocyanines as water-soluble and recyclable sensitisers for photocatalytic applications[†]

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Two zinc(II) phthalocyanines substituted with two and four permethylated β -cyclodextrin moieties at the α positions have been synthesised and immobilised on the surface of adamantane-modified silica nanoparticles through host-guest interactions. These molecular and supramolecular systems can catalyse the photooxygenation of 1-naphthol and 2-furoic acid in organic and aqueous media with high conversion efficiency and reaction yield, and photodegradation of 2-chlorophenol in water. Having a higher photostability and recyclability, the supramolecular nanosystems are particularly promising for these photocatalytic applications.

Being the lowest excited electronic state of molecular oxygen, singlet oxygen is a highly reactive species that can oxidise various compounds, degrade environmental pollutants and cause oxidative damage to microbials and tumours.¹ It is the predominant reactive oxygen species in the Type II photosensitised oxidation reactions in photodynamic therapy (PDT).² Owing to the high reactivity, it can react readily with nucleic acids (preferentially at the guanine), unsaturated lipids and proteins in the cellular constituents,³ leading to cell disruption. This species is also a highly versatile reagent for a range of chemical transformations, such as the [4+2] cycloaddition, [2+2] cycloaddition, ene reactions and heteroatom oxidation reactions, for example, of phenols and sulfides.^{1,4} Some of these reactions have been used as the key steps in the synthesis of some important natural products and drugs.5 The generation of singlet oxygen from chemical sources can occur through the oxidation of hypochlorite (ClO⁻) by H₂O₂, disproportionation of H₂O₂ catalysed by MoO₄²⁻, base-promoted disproportionation of peracids, decomposition of inorganic peroxides (e.g. CaO₂·2H₂O) and thermolysis of endoperoxides.⁶ Alternatively, singlet oxygen can also be generated photochemically

through dye-sensitised photoexcitation of ground-state triplet oxygen. Various functional dyes, such as porphyrins, boron dipyrromethenes, Rose Bengal, methylene blue, fullerenes, aggregation-induced emission dyes and ruthenium(II) and iridium(III) complexes have been used as singlet oxygen generators,^{2b,7} which can also be encapsulated in metal–organic frameworks to promote the sensitisation process and facilitate heterogeneous photocatalysis.⁸ Owing to the limited water solubility of these sensitisers, the photooxygenation reactions are usually carried out in organic solvents. Transformations involving singlet oxygen as an oxidant in aqueous media are relatively rare and may require a carrier for the photosensitisers.⁹

As an extension of our studies of advanced phthalocyaninebased photosensitisers for PDT,¹⁰ we previously examined the sensitising efficiency of a series of zinc(II) and silicon(IV) phthalocyanines towards the photooxygenation of 2-furoic acid, several alkenes and 1-naphthol in various organic solvents.¹¹ It was found that all these phthalocyanines were highly efficient in promoting these reactions and could be recycled through precipitation. We report herein an extension of this study using permethylated β-cyclodextrin substituents to increase the hydrophilicity of the phthalocyanine core and enable anchoring to silica nanoparticles through host-guest interactions that can allow the photocatalytic reactions to be performed in water and facilitate the recycling of the sensitisers. To our knowledge, using water-soluble phthalocyanines as sensitisers for photooxygenation reactions in aqueous media has rarely been reported.¹² Moreover, although β -cyclodextrins have been used to complex with water-soluble dyes to form supramolecular sensitisers,¹³ β-cyclodextrin-conjugated sensitisers have not been reported for this application.

Scheme 1 shows the synthetic route used to prepare the conjugates $\text{ZnPc}(\text{CD})_2$ (1) and $\text{ZnPc}(\text{CD})_4$ (2), which have two and four permethylated β -cyclodextrin moieties respectively. Treatment of mono-tosylated permethylated β -cyclodextrin 3¹⁴ with 3,6-dihydroxyphthalonitrile (4) and K₂CO₃ in *N*,*N*-dimethylformamide (DMF) gave the disubstituted product 5. Statistical condensation of this compound with 2 equiv. of unsubstituted

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Scheme 1 Synthesis of β -cyclodextrin-conjugated phthalocyanines 1 and 2.

phthalonitrile (6) in the presence of lithium and anhydrous zinc(II) acetate in *n*-pentanol at 150 °C led to the formation of 1 and 2, which could be isolated by column chromatography on silica gel followed by size-exclusion chromatography on Bio-Beads S-X1 beads in 9% and 6% yield respectively. Compound 2 is a crosswise-functionalised or ABAB-type phthalocyanine. Its formation was expected to be promoted by the bulky substituents at the di- α -positions of the phthalonitrile 5, which would hinder the self-condensation to form the AABB-type analogue.¹⁵ The use of these sterically hindered and hydrophilic substituents could also suppress the aggregation of the compounds and increase their water solubility. The experimental details and characterisation data are given in the ESI.[†]

The electronic absorption and fluorescence properties of 1 and 2 were studied in DMF and water (Fig. S1, ESI,† and Table 1). In DMF, the di- α -substituted phthalocyanine 1 exhibited a strong Q band at 692 nm, which was red-shifted to 717 nm for the tetra-α-substituted conjugate 2. The Q band was unshifted for 1 in water, but was further red-shifted to 726 nm for 2 in water. The red shift of the Q band by introducing substituents at the α positions has been well-documented.¹⁵ The sharp and intense Q band for these compounds indicated that they remained essentially non-aggregated in these media, which was supported by the linear relationship between the Q-band absorbance and the concentration of the conjugate (see Fig. S2, ESI,† for the spectra in water). Upon excitation at 610 nm, compound 1 showed a fluorescence band at 696 nm with a fluorescence quantum yield $(\Phi_{\rm F})$ of 0.17 in DMF with reference to unsubstituted zinc(II) phthalocyanine (ZnPc) ($\Phi_{\rm F} = 0.28$),¹⁴ whilst the emission of 2 was red-shifted (to 722 nm) with a relatively lower value of $\Phi_{\rm F}$

Table 1Photophysical properties of 1 and 2 in DMF and H_2O					
Compound	Solvent	$\lambda_{\max} (nm) \\ (\log \varepsilon)$	$\lambda_{\rm em}{}^a$ (nm)	${\Phi_{ m F}}^b$	${\Phi_\Delta}^c$
1	DMF	334 (4.73), 692 (5.30)	696	0.17	0.76
1	H_2O	342 (4.78), 692 (5.23)	702	0.16	—
2	DMF	341 (4.62), 717 (5.26)	722	0.12	0.65
2	HaO	342 (4 66)	729	0.12	_

^{*a*} Excited at 610 nm. ^{*b*} Using ZnPc as the reference ($\Phi_{\rm F}$ = 0.28 in DMF). ^{*c*} Using ZnPc as the reference (Φ_{Δ} = 0.56 in DMF).

726 (5.16)

(0.12). The fluorescence band was slightly red-shifted with a similar fluorescence quantum yield for both compounds in water (Table 1).

To evaluate the photosensitising efficiency of 1 and 2 in DMF, 1,3-diphenylisobenzofuran (DPBF) was used as the singlet oxygen scavenger and its absorbance at 415 nm was monitored during irradiation ($\lambda > 610$ nm), from which the singlet oxygen quantum yield (Φ_{Δ}) was determined (Table 1). It was found that both conjugates showed a higher Φ_{Δ} value (0.76 for 1 and 0.65 for 2) than ZnPc ($\Phi_{\Delta} = 0.56$).¹⁴ Interestingly, both compounds could also sensitise the photoconversion of DPBF to the corresponding endoperoxide in water, though the rate was slightly slower than that of ZnPc in DMF (Fig. S3, ESI[†]). The results showed that both compounds were efficient singlet oxygen generators in DMF and water that could enable them to serve as efficient sensitisers for photoreactions in organic and aqueous media.

To verify this hypothesis, the photocatalytic activity of **1** in photooxygenation of 1-naphthol was first examined in CHCl₃ under different reaction conditions. According to the results summarised in Table 2, a higher oxygen content could increase the percentage of conversion and a higher catalyst loading could also slightly increase the reaction yield. However, increasing the power of the light irradiation seemed not to be a favourable condition. Under the optimised conditions, *i.e.* by using 0.1 mol% of **1** and irradiation with a halogen lamp at 100 W for **1** h with continuous bubbling of oxygen, 1-naphthol could be converted into 1,4-naphthoquinone with 85% conversion and 92% isolated yield (entry 6).

Similar results were obtained when the solvent was changed to tetrahydrofuran (THF), CH₃CN or water (with 1% CH₃CN added to facilitate the dissolution of 1-naphthol) (Table S1, ESI†). The promising results for the aqueous reactions could be attributed to the bulky and hydrophilic β -cyclodextrin substituents that can preserve the photosensitising property of the phthalocyanine core in water. The photosensitising efficiency of the tetra- α -substituted analogue 2 was also evaluated and similar results were obtained (Table S1, ESI†). These results showed that both 1 and 2 were indeed efficient photosensitisers

Table 2 Photooxygenation of 1-naphthol in CHCl_3 using 1 as the photosensitiser*

$\begin{array}{c} \begin{array}{c} & 1 \\ \hline & O_2 \ hv \end{array} \end{array} \xrightarrow[]{} \begin{array}{c} & 0 \\ \hline & 0 \\ \end{array}$						
Entry	Light power (W)	Atmosphere	1 (mol%)	Time (h)	Conv. (%)	Yield (%)
1	300	Open air	0.001	6	30	85
2	300	Bubbled air	0.001	4	50	87
3	300	Bubbled air	0.01	2	52	89
4	300	Bubbled O ₂	0.01	2	70	88
5	100	Bubbled O_2	0.01	2.5	88	84
6	100	Bubbled O ₂	0.1	1	85	92

^{*a*} The mixtures were irradiated ($\lambda > 610$ nm) at ambient temperature. The percentage of conversion and reaction yield were calculated based on the amounts of starting material recovered and isolated product respectively.

Table 3 Photooxygenation of 2-furoic acid using 1 and 2 (0.1 mol%) as the photosensitisers a

ССООН	$\frac{1 \text{ or } 2}{O_2, hv}$	HOOOO	
c 1		G (01)	

Photosensitiser	Solvent	Conv. (%)	Yield (%)
1	CHCl ₃	80	75
2	CHCl ₃	85	88
1	H ₂ O	34	85
2	H_2O	38	90

^{*a*} The mixtures were bubbled with O₂ and irradiated (100 W, $\lambda > 610$ nm) at ambient temperature for 2 h. The conversion efficiency and percentage yield were determined by ¹H NMR spectroscopy using 2,5-dimethylfuran as an internal standard.

for photooxygenation of 1-naphthol both in organic and in aqueous media.

The photooxygenation reaction of 2-furoic acid to 5-hydroxy-2(5H)-furanone was also studied using **1** and **2** as the photosensitisers in CHCl₃ and in water (Table 3). The reactions proceeded smoothly in CHCl₃ for both compounds with comparable percentage of conversion and reaction yield as those for the photooxygenation of 1-naphthol, but their conversion efficiency was significantly lower in water (<40%). As shown in Table S2 (ESI†), a longer irradiation time (to 4 h) could not improve the result. By increasing the loading of photosensitiser to 2 mol%, a moderate conversion efficiency of *ca.* 50% could be achieved.

As an important parameter of photocatalysts, the photostability of 1 and 2 was examined in different solvents by monitoring the change in Q-band absorbance during the irradiation time. As shown in Fig. S4 (ESI⁺), the absorbance remained essentially unchanged for both compounds in THF and CH3CN over 6 h. By contrast, the compounds underwent photo-bleaching in CHCl₃, DMF and water, and the absorbance almost vanished after irradiation for 3 h. The decrease in absorbance was moderate for CH₃OH. These results suggested that the photostability of these two compounds was similar and followed the order: THF \approx CH₃CN > MeOH > $CHCl_3 \approx DMF \approx$ water. It is worth noting that despite the relatively low photostability in CHCl₃ and water, as mentioned above, both 1 and 2 could sensitise the photooxidation of 1-naphthol and 2-furoic acid effectively. This observation could also explain why a higher power and a longer light irradiation time could not promote the reactions in CHCl₃ (Table 2) and water (Table S2, ESI⁺).

To address the photostability issue in water, the compounds were immobilised on silica nanoparticles functionalised with adamantane molecules on the surface *via* host–guest interactions.¹⁶ It was believed that the immobilisation could enhance the photostability of the compounds and enable the photooxygenation reactions to be carried out heterogeneously, which can facilitate the recycling of the photosensitisers by simple centrifugation. To prepare these phthalocyanine-modified nanoparticles, adamantane-functionalised silica nanoparticles¹⁷ were mixed with **1** or **2** (0.1 mg mL⁻¹) in water. After stirring at ambient temperature for 24 h, the mixtures were centrifuged and the solid obtained was washed thoroughly with water to give **1**@SiO₂ and **2**@SiO₂ as a greenish powder. The transmission electron microscope (TEM)

images of both nanosystems showed a uniform morphology with a diameter of 100–200 nm (Fig. S5, ESI[†]). Dynamic light scattering analysis also revealed a hydrodynamic diameter of 194 nm with a polydispersity index of 0.04–0.05 for both nanosystems (Fig. S6, ESI[†]). The loading of phthalocyanine was determined by sonicating the nanoparticles in DMF to fully extract the phthalocyanine into the solution, of which the concentration was quantified spectroscopically. The loading was found to be 1.8 wt% (or 5.4 nmol mg⁻¹) for 1@SiO₂ and 1.9 wt% (or 5.3 nmol mg⁻¹) for 2@SiO₂.

These phthalocyanine-modified nanoparticles showed the characteristic Q band of phthalocyanines in water at 692 nm (for $1@SiO_2$) or 725 nm (for $2@SiO_2$). The position was virtually unshifted compared with that of free **1** and **2** (Table 1), but the absorbance and fluorescence were significantly weaker (Fig. 1a and b). These nanoparticles could also generate singlet oxygen upon excitation in water, though the efficiency was slightly lower than that of the free counterparts (Fig. S3, ESI†). Interestingly, the photostability of these nanoparticles in water was significantly improved compared with the free phthalocyanines. As shown in Fig. 1c, the Q-band absorbance remained almost unchanged for $1@SiO_2$ and $2@SiO_2$ upon irradiation with a 100 W halogen lamp for 6 h, whilst that of **1** and **2** vanished after irradiation for 3 h.

These phthalocyanine-modified silica nanoparticles were then used to catalyse the photooxygenation of 1-naphthol and 2-furoic acid in water. A smaller amount of CH_3CN (0.2% *vs.* 1% used in the above studies) was added in order to avoid detachment of the phthalocyanines from the nanoparticles. As shown in Table 4, both the percentage of conversion and isolated yield could reach *ca.* 90% in just 1 h for the photooxygenation of 1-naphthol, which were comparable with those for the free phthalocyanines (Table S1, ESI†). For the photooxygenation of 2-furoic acid, the percentage of conversion was significantly



Fig. 1 (a) Electronic absorption and (b) fluorescence ($\lambda_{ex} = 610$ nm) spectra of **1**, **2**, **1**@SiO₂ and **2**@SiO₂ in water. The phthalocyanine concentration was fixed at 2 μ M. (c) Change in the Q-band absorbance of **1**, **2**, **1**@SiO₂ and **2**@SiO₂ in water upon irradiation (100 W, $\lambda > 610$ nm) at ambient temperature. (d) Photocatalytic decomposition of 2-chlorophenol (initial concentration = 4 mM) using **1**, **2**, **1**@SiO₂ or **2**@SiO₂ (at 1 mol% of phthalocyanine) as the photosensitiser in water (with 0.2% CH₃CN) in open air and upon irradiation with the above light source.

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Table 4 Photooxygenation of 1-naphthol and 2-furoic acid using 1@SiO₂ and 2@SiO₂ as the photosensitisers in water (with 0.2% CH₃CN)^a

Photosensitiser	Substrate	Time (h)	Conv. (%)	Yield (%)
1@SiO ₂ 2@SiO ₂ 1@SiO ₂	1-Naphthol 1-Naphthol 2-Furoic acid	1 1 8	87 89 89	94 92 85
$2 \otimes SiO_2$	2-Furoic acid	8	76	89

^a The mixtures containing the photosensitisers (at 1 mol% of phthalocyanine) were bubbled with O₂ and irradiated (100 W, $\lambda > 610$ nm) at ambient temperature.

improved to 89% (or to 76%) after immobilising 1 (or 2) on the silica nanoparticles and extending the reaction time to 8 h. That the latter could be done was due to the enhanced photostability of the nanoparticles.

As these reactions proceeded in a heterogeneous way, the photocatalysts could be recovered readily by centrifugation after the reactions. The nanoparticles recovered were then washed with water thoroughly with sonication and then used in another run of the photooxygenation reactions. As shown in Table S3 (ESI[†]), for the reaction of 1-naphthol, the yield of the product was decreased by only 9% (for 1@SiO₂) or 6% (for 2@SiO₂) after recycling 5 times (*i.e.* irradiation for a total of 5 h). For the reaction of 2-furoic acid, the decrease in reaction yield was slightly higher to 16% (for 1@SiO₂) or 23% (for 2@SiO₂) after 5 cycles due to the longer reaction time (*i.e.* irradiation for a total of 40 h). The results showed that these nanoparticle-based photocatalysts exhibited significantly higher photostability than the free counterparts, enabling them to serve as improved and recyclable photocatalysts.

To extend the application of these photocatalytic systems, their efficiency in photocatalytic decomposition of 2-chlorophenol was examined. Chlorophenols are toxic organic pollutants in wastewater released from the dye, herbicide and pharmaceutical industries. Owing to their bio-resistant nature, the decomposition of this material inevitably relies on advanced chemical methods.¹⁸ To perform the photo-decomposition, a mixture of 2-chlorophenol and a catalytic amount of 1, 2, 1@SiO2 or 2@SiO2 (at 1 mol% of phthalocyanines) in water (with 0.2% CH₃CN) was irradiated (100 W) at ambient temperature, and then the concentration of 2-chlorophenol was monitored by HPLC at its absorbance at 275 nm. As shown in the degradation curves (Fig. 1d), the degradation of 2-chlorophenol was slightly faster for free 1 and 2 compared with the nanosystems 1@SiO₂ and 2@SiO₂. However, all the photocatalysts could eventually remove virtually all the 2-chlorophenol over a period of 4 h. Based on the trend of the curves, the two nanosystems appeared to exhibit more sustained photocatalytic activity as a result of their higher photostability. These nanosystems could also be recovered and reused for the next run of photodegradation.

In summary, two zinc(II) phthalocyanines substituted with two and four β -cyclodextrin moieties were prepared (compounds 1 and 2). With these bulky and hydrophilic substituents at the α positions, these compounds remained non-aggregated and could function as efficient photosensitisers in aqueous media. The presence

of β-cyclodextrin moieties could also facilitate the immobilisation on the surface of adamantane-modified silica nanoparticles through host-guest interactions, giving the nanosystems 1@SiO2 and 2(a)SiO₂. All these molecular and supramolecular systems served as efficient sensitisers for photooxygenation of 1-naphthol and 2-furoic acid, as well as photodegradation of 2-chlorophenol. The nanosystems exhibited higher photostability and recyclability, and hence are particularly promising for photocatalytic applications in aqueous media.

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Conflicts of interest

There are no conflicts to declare.

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