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Highly efficient light-driven hydrogen evolution utilizing porphyrin-based nanoparticles†

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We developed dye-sensitized photocatalytic systems (DSPs) by utilizing porphyrins as a photosensitizer (PS) or as a photosensitizer–catalyst (PS/CAT) upon their chemisorption onto platinum-doped titanium dioxide nanoparticles (Pt-TiO₂ NPs). The DSPs coated with Pt-Tc₃CP (PS/CAT entity) exhibited a record-high stability (25 500 TONs) and H₂ evolution activity (707 mmol g^{−1} h^{−1}) compared to similar DSPs in the literature.

The prolonged and continuous utilization of fossil fuels as primary energy sources generated significant environmental complications, since their combustion is responsible for the exponential increase of greenhouse gas emissions.¹ Hence, it is of great importance to establish cost-competitive, low-carbon technologies aiming to develop sustainable systems based on renewable sources.² Green hydrogen (H₂) besides being a clean fuel is a chemical feedstock as well, which can be imperative for accomplishing multi-sector decarbonization.³ Light-driven H₂ production is an auspicious method because an abundant and clean energy (solar) is used to achieve an energy-rich storable compound (H₂) that can be used as a fuel.⁴

An efficient and facile approach toward light-driven H₂ evolution is the development of dye-sensitized photocatalytic systems (DSPs). Indeed, DSPs have received considerable attention recently due to their durability and tunability.^{5,6} In such photocatalytic schemes, a photosensitizer (PS) and a catalyst (CAT) are immobilized onto titanium dioxide nanoparticles (TiO₂ NPs) forming a heterogeneous photocatalyst. Using a light source, the PS absorbs photons and gets excited; subsequently, electrons are injected into

the conduction band of TiO₂. Finally, this flow of electrons reaches the CAT, which performs the reduction of H⁺ to H₂ and the oxidized PS is regenerated using a sacrificial electron donor (SED).

A great number of different photosensitizers (PSs) and catalysts (CATs) have been utilized in TiO₂-based DSPs over the last decade (Fig. 1a).^{6,7} In addition, by simply exchanging a molecular CAT with highly efficient Pt, researchers were able to develop schemes with greater stability and higher H₂ evolution activity (Fig. 1b).^{8,9} There are various examples of porphyrinoids being utilized either as the PS or as the CAT in photocatalytic H₂ evolution, mainly due to their straightforward structural modification, which enables them to adopt desirable chemical and physical properties.^{10,11} In spite of this fact though, only recently, our research group demonstrated a different approach (Fig. 1c), in which a single porphyrin (PS/CAT) was able to act as the light harvester and simultaneously as the catalyst.¹² Thus, in this approach, there is only one component (PS/CAT) that drives the photocatalytic H₂ evolution. Moving one step forward, herein we introduce an alternative approach, in which a PS/CAT derivative (a light harvester and a catalyst) is incorporated into Pt-TiO₂ NPs. The Pt-TiO₂ NPs act as a scaffold for the successful self-organization of the PS/CAT entities, an electron transport medium, and also as an additional photocatalyst. Thus, we combined metalated-porphyrin carboxylic acid derivatives with Pt-TiO₂ NPs and successfully developed highly efficient DSPs for H₂ evolution in aqueous media (Fig. 1d).

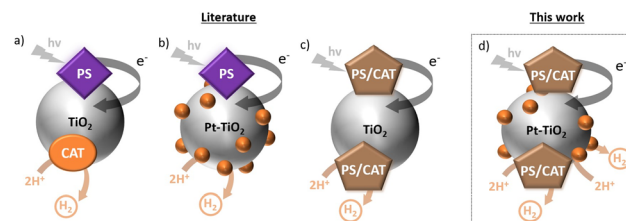


Fig. 1 The three established approaches in the literature to design DSPs for H₂ evolution: (a) PS and CAT on TiO₂ NPs, (b) PS onto Pt-TiO₂ NPs, and (c) PS–CAT onto TiO₂ NPs. (d) New approach: PS–CAT onto Pt-TiO₂ NPs.

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We prepared two series of porphyrin derivatives metalated with zinc (Zn), palladium (Pd), and platinum (Pt) and introduced carboxylic acid units at their periphery as anchoring groups for their successful attachment onto Pt-TiO₂ NPs. As illustrated in Fig. S1 (ESI[†]), the carboxylic acid units were introduced either on a three-carbon alkyl chain (*c*₃) at the *para*-position of the phenyl ring (for the **M-Tc₃CP** porphyrins) or at the *para*-position of the phenyl ring (for the derivatives **M-TCP**). The leading reasons to specifically modify these porphyrinoids in such a manner were derived from the results of our previous investigations.¹² Namely, **Pd-Tc₃CP** and **Pt-Tc₃CP** were able to self-organize onto TiO₂ NPs acting as both the PS and the CAT. In stark contrast, **Zn-Tc₃CP** acted only as the PS, and as expected it did not produce any H₂. Although these DSPs demonstrated great stability and efficiency, the best conditions for H₂ evolution should be an organic/aqueous solvent mixture with 15% of triethanolamine as the SED. Thus, to explore their catalytic properties onto Pt-TiO₂ DSPs, we prepared three metalated **M-Tc₃CP** (with Zn, Pd, and Pt, Fig. S1, ESI[†]) together with their respective **M-TCP** derivatives. More importantly, all these porphyrin-based Pt-TiO₂ DSPs operate in aqueous medium, rendering them as “greener” DSPs compared to the previous ones.¹²

The synthesis of **M-Tc₃CP** was carried out following the procedures reported in the literature,^{12–14} whereas **M-TCP** derivatives were prepared according to the synthetic approach described in detail in the ESI[†] (Scheme S1 and Fig. S2–S13). The absorption spectra of **M-TCP** and **M-Tc₃CP** in freshly distilled toluene/ethanol solutions (ratio 1:1) are illustrated in Fig. 2. Their absorption coefficient numbers and their absorption data (λ_{max} of Soret and Q bands) are listed in Table S1 (ESI[†]). In all cases, typical absorption features for such metalated porphyrinoids¹⁵ are observed. The electrochemical properties of all **M-Tc₃CPs** were investigated by means of cyclic voltammetry (Table S2, ESI[†]). The driving force regarding the electron injection from the porphyrins to TiO₂ (ΔG_{inj}), as well as their regeneration from the SED (ΔG_{reg}) indicate that both processes are thermodynamically favorable (see the ESI[†] for details; Table S2).

The initial step for the light-driven H₂ evolution experiment is the chemisorption of the complexes onto the Pt-TiO₂ NPs. Various initial concentrations of metalated porphyrins were utilized in order to optimize the chemisorption of the porphyrins onto Pt-TiO₂ NPs (see the ESI[†]). All the absorption spectra before and after their chemisorption are available in the ESI[†] (Fig. S14–S16) and the respective dye loadings (DLs) for each complex are listed in Tables S3–S8 (ESI[†]). In Fig. 2c, the absorption spectra of **Pt-Tc₃CP** before

and after chemisorption onto Pt-TiO₂ NPs are presented. It is worth noting that by using this initial concentration (*viz.* 1.0×10^{-5} M), a quantitative loading of the porphyrin (DL = 100%) was achieved in all different cases.

In a typical H₂ evolution experiment, 5 mg of the porphyrin-sensitized Pt-TiO₂ NPs were dispersed in an aqueous solution (see the ESI[†] for details). The dispersions were prepared in a glass vial, sealed with a rubber septum, and irradiated using a 40 W light-emitting diode lamp (LED lamp, Fig. S17, ESI[†]). Upon photo-irradiation, all different metalated porphyrins (**M-TCP** and **M-Tc₃CP**) demonstrated H₂ production. The photocatalytic activity of the porphyrin-based DSPs was strongly dependent on the amount of the adsorbed porphyrin onto the TiO₂ NPs (Tables S2–S7, ESI[†]). By considering the best photocatalytic data for each DSP (Table 1), we can safely conclude that all the **M-Tc₃CP** derivatives outperform their respective **M-TCP** ones, in terms of both stability (TONs) and efficiency (total H₂ evolution, mmol g^{−1} h^{−1}). Nevertheless, **Zn-TCP** and **Zn-Tc₃CP** demonstrated almost identical TONs (~1100) and nearly the same amount of H₂ evolution (~400 mmol g^{−1} h^{−1}). This indicates that the photocatalytic activity of Zn-porphyrin derivatives is not affected by the different anchoring groups (the rigid carboxylic acid group *vs.* flexible *c*₃-carboxylic acid), confirming their sole role as PSs.

In contrast, both **Pd-Tc₃CP** and **Pt-Tc₃CP** exhibited superior TONs and H₂ evolution rates compared to their counterparts **Pd-TCP** and **Pt-TCP**, respectively (Table 1). More specifically, **Pd-Tc₃CP** achieved 7722 TONs and 593 mmol g^{−1} h^{−1} of H₂ evolution, the values of which are significantly greater than those of **Pd-TCP** (1147 TONs and 256 mmol g^{−1} h^{−1} of H₂, respectively). In a similar manner, nonetheless reaching even greater results, **Pt-Tc₃CP** demonstrated 11 607 TONs and 458 mmol g^{−1} h^{−1} of H₂ evolution, outperforming **Pt-TCP** (2525 TONs and 378 mmol g^{−1} h^{−1} of H₂). A possible explanation for the enhanced performance of the **M-Tc₃CP** derivatives compared to that of the **M-TCP** ones is that the adsorption *via* four anchoring groups leads to a well-oriented self-organization of the **M-Tc₃CPs**. This was indeed verified by scanning electron microscopy (SEM) experiments, which demonstrated that **Pt-Tc₃CP** undergoes a well-oriented self-organization in spherical nanostructures (Fig. S18b, ESI[†]). In contrast, both **Zn-TCP** (Fig. S18c, ESI[†]) and **Pt-TCP** (Fig. S18d, ESI[†]) self-aggregate

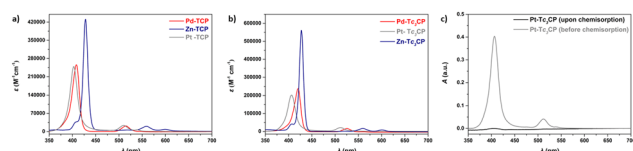


Fig. 2 Extinction coefficient (ϵ) of (a) **M-TCP** and (b) **M-Tc₃CP** derivatives (M: Zn, Pd, or Pt) in freshly distilled toluene/ethanol (1:1 ratio) solutions. (c) Absorption spectra of **Pt-Tc₃CP** (1.0×10^{-5} M) before and after chemisorption onto Pt-TiO₂ NPs.

Table 1 The best photocatalytic data for each porphyrin-based DSP are listed below

Porphyrin	TONs <i>vs.</i> PS ^a	TONs <i>vs.</i> CAT ^b	H ₂ evolution rate ^c
Zn-TCP	1192	1686	360
Zn-Tc₃CP	1031	1972	421
Pd-TCP	1147	814	256
Pd-Tc₃CP	7722	2097	593
Pt-TCP	2525	1772	378
Pt-Tc₃CP	11 607	1216	707

^a TON in 24 hours *vs.* PS = porphyrin (see the ESI for details). ^b TON in 24 hours *vs.* CAT. In the cases of **Zn-TCP** and **Zn-Tc₃CP**: CAT = PtTiO₂. However, in the cases of **Pd-TCP**, **Pd-Tc₃CP**, **Pt-TCP**, and **Pt-Tc₃CP**: CAT = PtTiO₂ and Pt- or Pd-porphyrin (see the ESI for details). ^c H₂ evolution rate (mmol g^{−1} h^{−1}) *vs.* total g of CAT in 24 hours (see the ESI for details).



on the top of the spherical Pt-TiO₂ NPs (Fig. S18a, ESI†). In addition, the strong binding of **Pt-Tc₃CP** is illustrated in Fig. S19 (ESI†), since the peaks correlated with the $\nu(\text{C}=\text{O})$ and the $\nu(\text{C}-\text{O})$ stretching of the unbound carboxylic acid group at ~ 1700 and 1200 cm^{-1} , respectively disappeared in the FT-IR spectrum of the chemisorbed sample (**Pt-Tc₃CP@Pt-TiO₂**). In perfect agreement with our recent report, these catalytic results underline again the diverse behavior of both Pd- and Pt-porphyrins acting as PS/CAT entities, in contrast to the respective Zn-porphyrins, which act as PSs.¹²

In an effort to provide an even more fair assessment for the porphyrin-based DSPs developed herein, we explored their catalytic activity under the same dye loading (DL = 100%) by utilizing initial porphyrin solutions of $1.0 \times 10^{-5}\text{ M}$ in all cases (see Tables S3–S8, ESI†). As illustrated in Fig. 3, **Pt-Tc₃CP** and **Pd-Tc₃CP** reached 10 819 and 7722 TONs and H₂ evolution rates of 707 and 342 mmol g⁻¹ h⁻¹, respectively, outperforming their **M-TCP** counterparts and the respective Zn-porphyrinoids. Similar to the behavior during the best performing photovoltaic experiments (Table 1), using these DSPs (with DL = 100%), the photocatalytic response of **Zn-Tc₃CP** and **Zn-TCP** was yet again almost identical (~ 1100 TONs and $\sim 50\text{ mmol g}^{-1}\text{ h}^{-1}$ of H₂). Furthermore, by comparing the **M-TCP** derivatives, evidently **Pt-TCP** (2018 TONs and 82 mmol g⁻¹ h⁻¹ of H₂) is a better photocatalyst compared to **Pd-TCP** (1096 TONs and 49 mmol g⁻¹ h⁻¹ of H₂). It may be well argued that **Pd-TCP** acts as a photosensitizer in this case, since the photocatalytic values are almost the same as the Zn-porphyrin-based DSPs (~ 1100 TONs and $\sim 50\text{ mmol g}^{-1}\text{ h}^{-1}$ of H₂). In contrast, **Pt-TCP** reached almost double values concerning the TONs and the H₂ evolution rates (2018 TONs and 82 mmol g⁻¹ h⁻¹, respectively) emphasizing once more the PS/CAT nature of the Pt-porphyrin-based DSPs.¹²

To evaluate the stability of our best performing system (**Pt-Tc₃CP@PtTiO₂**), we performed long-term photocatalytic experiments. As illustrated in Fig. S20a (ESI†), the DSPs coated with **Pt-Tc₃CP** exhibited great stability reaching 25 500 TONs, and high H₂ evolution activity ($316\text{ mmol g}^{-1}\text{ h}^{-1}$ of H₂). Upon 48 h

of continuous visible light irradiation, the H₂ evolution was stopped and the DSPs reached a plateau. In an effort to investigate the reason for deactivation, in four different experiments, we added either (a) **Pt-Tc₃CP**, (b) AA 1M, (c) Pt-TiO₂, or (d) **Pt-Tc₃CP@Pt-TiO₂**; however, we did not observe any reactivation of the H₂ production (Fig. S20b, ESI†). Only when both the photocatalytic NPs (**Pt-Tc₃CP@Pt-TiO₂**) and the SED (AA) were added, H₂ production was detected. These experiments demonstrate that both the SED and the **Pt-Tc₃CP@Pt-TiO₂** photocatalyst have been converted into non-active compounds/materials. Indeed, the absorption spectrum of the SED before and after the catalytic experiment significantly changes (Fig. S20c, ESI†). In contrast, the SEM experiments demonstrated that the morphology of Pt-TiO₂ is not affected at all upon photocatalysis (Fig. S21, ESI†). More specifically, similar to our previous study,¹⁹ **Pt-Tc₃CP** exhibits a spherical self-organization on the Pt-TiO₂ NPs which is retained even upon the 48 h of photocatalysis. Hence, we concluded that the deactivation of the **Pt-Tc₃CP@Pt-TiO₂** system can be attributed to the degradation of the porphyrin and the SED, rendering them the limiting factors of our DSPs.

In addition, we evaluated the correlation between the amount of porphyrin and the H₂ evolution rate for all **M-Tc₃CP** and **M-TCP** (M: Zn, Pt, and Pd, Fig. S22, ESI†). Interestingly, for all **M-TCP** porphyrins and **Zn-Tc₃CP**, a linear correlation between the amount of the porphyrin and the H₂ evolution rate is observed. In particular, in all cases, the higher H₂ evolution rate was detected for the greater porphyrin quantity ($\sim 3.0 \times 10^{-7}\text{ mol}$). In stark contrast, the respective experiments for **Pt-Tc₃CP** and **Pd-Tc₃CP** revealed that the highest H₂ production rate is not associated with the greater amount of the porphyrin. In the case of **Pd-Tc₃CP**, the highest H₂ production rate of $1.5 \times 10^{-7}\text{ mol}$ was detected, whereas for the **Pt-Tc₃CP** it was $3.0 \times 10^{-8}\text{ mol}$ of the porphyrin. These findings confirm once more the hypothesis that the enhanced catalytic efficiency of **Pt-Tc₃CP** and **Pd-Tc₃CP** can be accredited to the well-oriented self-organization of the porphyrinoids on the surface of the Pt-TiO₂ performing as PS/CAT entities.

To sum up, we demonstrated that dispersion of porphyrin-based DSPs in an aqueous medium is an auspicious method to develop highly performing photocatalytic nanoparticles. Unlike the reported research works to date, the utilized porphyrins herein are able to act at the same time as a light harvester and a catalyst (PS/CAT). Hence, we introduced a more facile – in terms of preparation protocols – approach, compared to more complex structures (PS-dyads) or a combination of two entities (PS + CAT) that were reported in other studies.^{9–13,16–21} We prepared different metalated tetra-carboxylic acid porphyrins to explore the impact of two significant factors: (i) the different metals and (ii) the position of the anchoring group in light-driven H₂ production. Interestingly, in contrast to Pd- and Pt-porphyrins, the catalytic properties of the respective Zn-porphyrins were not affected by the different anchoring groups. It is worth mentioning that the different positioning of the anchoring groups strongly impacted the H₂ evolution of both Pd- and Pt-porphyrin-based DSPs. We can safely assume that the **M-TCP** derivatives use maximum two carboxylic acids to

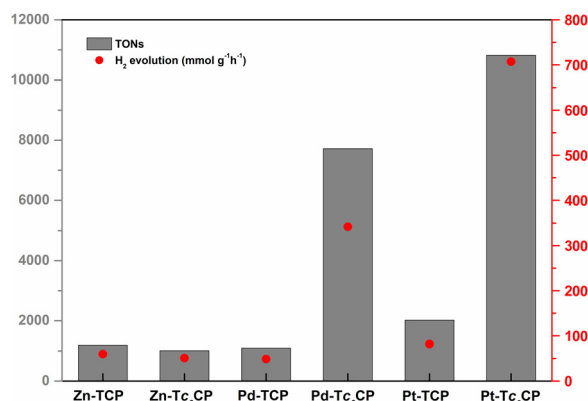


Fig. 3 Comparison of all the **M-TCP** and **M-Tc₃CP** derivatives (M: Zn, Pd, or Pt) concerning their catalytic activity (TONs and H₂ evolution rates). In all cases, the concentration of the initial porphyrin solution used for the chemisorption of the porphyrin was $1.0 \times 10^{-5}\text{ M}$ and the resulting dye-loading percentage was DL = 100%.



Table 2 Comparison between the best porphyrin-based DSPs in the literature and this work. In all the reports below, a porphyrinoid (or a porphyrin-based dyad) was utilized as the PS, Pt-TiO₂ NPs as the catalysts, and an aqueous solution as the solvent

PS	SED	TONs	Irr. time	H ₂ evolution ^b	Publication
Pt-Tc ₃ CP	AA (1M)	25 500 ^a	24/48	707	This work
YD2- <i>o</i> -C8	AA (0.5M)	11 900	120	272	28
BDP-Por-BDP(Im)	AA (1M)	18 600	72	225	31
ZnP-dyad	AA (0.5M)	12 800	120	173	28
LGtT	TEOA 20%	14 792	5	7.4	29
LG-DtT	TEOA 20%	13 282	5	6.7	29
LG-5	TEOA 20%	6582	5	3.3	29
PdTHPP	TEOA 10%	158	5	2.0	30
ZnTHPP	TEOA 10%	92	5	1.3	30
THPP	TEOA 10%	39	5	0.6	30
SnTPyP	EDTA	7.5	4	0.2	27
Sn(IV)TCPP	C ₆ H ₁₂ ^c	—	5	0.5 ^d	26

^a TON in 48 hours vs. PS = porphyrin (see the ESI for details). ^b H₂ evolution rate (mmol g⁻¹ h⁻¹) vs. total g of CAT in 24 hours. CAT = PtTiO₂ and Pt-Tc₃CP (see the ESI for details). ^c The oxygenation of cyclohexene (C₆H₁₂) was studied instead of the presence of a SED. ^d In μmol g⁻¹ h⁻¹.

bound onto the NPs, whereas the chemisorption of **M-Tc₃CP** can be achieved *via* four carboxylic acids.^{22–25} This multisided anchoring mode of **M-Tc₃CP** derivatives resulted in their enhanced photocatalytic activity (Table 1).

In Table 2, a thorough comparison between our work and the highest performing porphyrin-based DSPs in the literature is given. In all these reports, a porphyrinoid or a porphyrin-based dyad was utilized as the PS and Pt-TiO₂ NPs as the catalyst entity, and the photocatalytic reaction was performed in an aqueous solvent. Remarkably, the H₂ evolution rate of our DSPs developed with **Pt-Tc₃CP** is more than two times greater (707 mmol g⁻¹ h⁻¹) compared to other porphyrin-based DSPs reported in the literature (Table 1). In addition, besides the high efficiency, the developed DSPs herein exhibited a greater stability as well, reaching 25 500 TONs. Overall, we showed stable and efficient DSPs for H₂ evolution by utilizing PS-CAT derivatives in aqueous media. In the future, several aspects should be explored targeting the development of earth-abundant dispersions with high stability and efficiency.

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Conflicts of interest

There are no conflicts to declare.

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