ChemComm



COMMUNICATION

View Article Online



Cite this: Chem. Commun., 2023, 59, 1777

Received 9th December 2022, Accepted 17th January 2023

DOI: 10.1039/d2cc06730g

rsc.li/chemcomm

Lignin C-C bond cleavage induced by consecutive two-photon excitation of a metal-free photocatalyst†

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Photocatalytic lignin valorization has caught widespread attention; yet the reaction systems often employ noble metal complexes, hydrogen atom transfer (HAT) agents, and/or sacrificial electron donors/acceptors that do not comply with atom economy or environmental friendliness. Herein, we discovered that N-phenylphenothiazine (PTH) as a metalfree photocatalyst induced the cleavage of the lignin C_{α} – C_{β} bond under ambient conditions free of those additional agents with a high yield and selectivity toward benzoic acid. Transient spectroscopic investigations revealed that the energy-demanding $C_{\alpha}-C_{\beta}$ bond cleavage was induced by the potent oxidant, ²PTH^{•+*}, that was derived from consecutive twophoton excitation of PTH.

Lignin, rich in aromatic carbon units, is a renewable energy source to replace the use of fossil fuels on a large scale. Yet breaking the profuse C-O and C-C bonds selectively into small value-added compounds is challenging. Currently, various strategies have been reported for the valorization of lignin, including pyrolysis, gasification, acid or base treatment, hydrogenolysis, etc. 1-5 These methods often require harsh reaction conditions such as high temperature, high pressure, corrosive solvents, etc., so better methods are urgently needed. Photocatalysis, typically considered as a green and mild method for organic redox synthesis, has gained increasing popularity for biomass valorization. 6-14 However, cleavage of the high energy C-C or C-O bonds requires potent photooxidants or photoreductants, among which noble-metal-containing ruthenium or iridium coordination compounds are often used. 15-19 Furthermore, hydrogen atom transfer (HAT) agents and sacrificial electron or hole donors are often used as necessary additives in an inert atmosphere to complete the catalytic cycle. 15,16,18,20-25 These additives generate unproductive waste to the extent that the value of the obtained small aromatic compounds may not offset it. Therefore, it is highly desirable to find a photocatalytic strategy

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† Electronic supplementary information (ESI) available. See DOI: https://doi.org/ 10.1039/d2cc06730g

that can selectively cleave lignin C-C bonds into high-value-added aromatic compounds in an ambient environment without metalcontaining photocatalysts, sacrificial reagents or other additives.

Herein, we report that N-phenylphenothiazine (PTH) as a metal-free photocatalyst surprisingly induces the selective cleavage of lignin C_{α} – C_{β} bonds under ambient conditions without any other additives. Though a mild photooxidant in its singlet excited state, the doublet excited state of the radical cation (2PTH***) is a potent photooxidant to induce the oxidative cleavage of the C_α-C_β bond in lignin models through consecutive two-photon excitation (Scheme 1). Two-color two-pulse laser flash photolysis experiments revealed a rapid subnanosecond electron transfer process likely through a static quenching mechanism.26-28 A wide scope of major lignin units were successfully cleaved in high yields through simple steady state illumination of PTH, demonstrating the potential utility of this simple, commercially-available, metal-free photocatalyst for lignin valorization in an environmentally-friendly manner.

PTH showed mainly UV absorption in the ground state (Fig. 1a). Electrochemical oxidation of PTH in CH3CN resulted in PTH⁺ formation showing three distinctive visible to near IR absorption bands (λ_{max} = 514 nm, 772 nm, and 864 nm) (Fig. S1, ESI†) that were consistent with the literature. 29 PTH was air-stable as the absorption was retained upon solution exposure to the air. When the PTH solution was irradiated with 390 nm light in ambient air, a similar absorption change attributed to the formation of PTH^{•+} was also observed (Fig. S2, ESI†). Molecular oxygen dissolved in CH3CN

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✓ No noble metals ✓ No HAT agents ✓ No electron donors/acceptors

Scheme 1 Photocatalytic cleavage of the $C_{\alpha} - C_{\beta}$ bond of lignin model substrates

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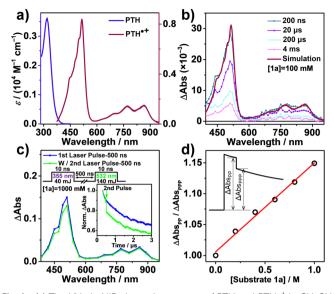


Fig. 1 (a) The UV-vis-NIR absorption spectra of PTH and PTH $^{\bullet+}$ in CH₃CN. (b) Full TA spectra of PTH obtained after 355 nm pulsed-laser excitation in the presence of 100 mM 1a in aerated CH₃CN at the indicated time delays. (c) Absorption difference spectra of PTH in the presence of 1000 mM 1a in a two-color two-pulse TA experiment at 500 ns time delay before the second laser pulse (blue) and after the second laser pulse (green). Inset: Transient kinetic data monitored at the probe wavelength of 510 nm for PTH $^{\bullet+}$ with a two-color two-pulse laser excitation sequence shown in the laser pulse scheme above (kinetics in green) or with only the first 355 nm pulsed-laser excitation (kinetics in blue). (d) Stern–Volmer-type plot based on the two-color two-pulse TA experiment at different concentrations of 1a. The subscript PP stands for pump-probe and PPP pump–pump–probe. The inset shows the meaning of ΔAbs_{PPP} and ΔAbs_{PPP}.

was presumably the electron acceptor responsible for quenching the PTH excited state (Fig. S3, ESI†).³⁰

Cyclic voltammetry (CV) was performed to evaluate the redox properties of PTH and the lignin model substrate 1,2-diphenylethanol (1a). PTH showed a reversible redox wave at $E^{\circ}(\text{PTH}^{\bullet+/0}) = 0.92 \text{ V}$ vs. NHE (Fig. S4, ESI†) and an irreversible peak at $E_{\text{p/2}} = 1.59 \text{ V}$ attributed to PTH $^{2+/\bullet+}$. The oxidation of 1a was also irreversible with $E_{\text{p/2}} = 1.9 \text{ V}$, which was more positive than $E_{\text{p/2}}(\text{PTH}^{2+/\bullet+})$. CV of the PTH and 1a mixture did not show any catalytic current for the oxidation of 1a as expected due to unfavourable thermodynamics (Fig. S4, ESI†).

A steady-state fluorescence quenching experiment was carried out to test whether the PTH excited state could oxidize 1a. Unsurprisingly, titration of 1a up to 100 mM did not lead to any measurable PTH fluorescent quenching (Fig. S5, ESI†). The excited state of PTH apparently lacked the oxidative power to initiate the oxidation of 1a.

Nanosecond transient absorption (TA) spectroscopy was employed to explore the electron transfer dynamics between PTH and **1a**. Fig. 1b shows the full TA spectra of PTH in the presence of **1a** in aerated CH₃CN after nanosecond pulsed-laser excitation ($\lambda_{\rm ex}$ = 355 nm). The positive absorption bands from the visible to near infrared region corresponded to the absorption of PTH^{•+}, which was consistent with the oxidation of PTH from both the spectroelectrochemistry and photolysis data (Fig. S2 and S6, ESI†).

The visible to NIR absorption of PTH^{•+} allowed it to absorb a second photon to reach the doublet excited state, PTH***. Prior studies have shown that PTH*+* is a potent photooxidant with $E^{\circ}(PTH^{\bullet+*/0}) = 2.31 \text{ V.}^{27} \text{ It was of great interest to study the}$ PTH•+* reactivity towards the degradation of lignin models with redox potential around 2.0 V. Nanosecond two-color two-pulse TA experiments were carried out to investigate the quenching of PTH^{•+*} by **1a**. The first laser pulse ($\lambda_{ex} = 355$ nm) generated PTH* that subsequently transferred an electron to O2 to form the long-lived PTH++ as the spectral simulation showed in Fig. 1b. The second laser pulse (λ_{ex} = 532 nm) was delayed by 500 ns relative to the first and selectively excited the transiently formed PTH•+. The second laser pulse resulted in significant bleaching of the PTH^{•+} absorption signal monitored at 510 nm in the presence of 1000 mM 1a (Fig. 1c inset). Absorption difference spectra of PTH recorded from 390 nm - 950 nm in oxygen-saturated CH3CN after two pulsed-laser excitations are displayed in Fig. 1c. Upon titration of increasing concentrations of 1a, the bleach signal of delta absorbance monitored at 510 nm gradually increased right after the second laser pulse excitation. For the control sample that was in the absence of 1a, the second laser pulse did not result in the bleaching of the PTH^{•+} absorption (Fig. S7, ESI[†]). A Stern–Volmer-type plot for the quenching of PTH^{•+}* by 1a was obtained by plotting ΔAbs_{PP}/ΔAbs_{PPP} as a function of increasing concentrations of 1a (Fig. 1d). The plot showed a linear regression, from which the slope was equal to 0.15 M^{-1} . Considering that the lifetime of PTH^{•+*} was only 36 ps,²⁹ it was highly unlikely that the reductive quenching approached through bimolecular diffusion, but rather ground state association of PTH ** and 1a with the equilibrium constant of 0.15 M^{-1} .

Steady-state photolysis of PTH and 1a was carried out in CH₃CN under ambient air conditions. Deviations from the standard condition along with the reaction conversions and product yields are also listed in Table 1. First, we optimized the photocatalyst PTH concentration and chose 15 mol% as the standard reaction concentration since concentration as high as 20 mol% did not result in a significant increase in the product yield (Table 1, entries 1-3). Three major products were detected including benzoic acid (1b), benzaldehyde (1c), and diphenylethanone (1d). The formation of 1b and 1c clearly demonstrated that PTH under light promoted oxidative cleavage of the C_{α} - C_{β} bond in appreciable yields (entry 1). Note that 100% selective C_{α} - C_{β} bond cleavage in **1a** would theoretically result in 200% yield of 1b and 1c combined. Nevertheless, the combined yield of 96% was still among the average of lignin C_{α} - C_{β} bond cleavage in the literature; 18,31 yet our photocatalytic system only contained PTH photocatalyst without other HAT or sacrificial agents. It is also noteworthy that when a white light LED source was added in combination with the 390 nm light, the rate of product formation was significantly faster than using 390 nm light irradiation alone (Fig. S8, ESI†). Greater visible light absorption by PTH^{•+} was indeed helpful for the generation of PTH^{•+}*.

When the ambient air environment was replaced by Ar, there was almost no conversion of **1a** and no product was detected (entry 4). The solution dissolved molecular oxygen was

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Table 1 Reaction Optimization for the Steady-State Photolysis of the Lignin Model 1a

Entry	Deviation from standard conditions	Con. (%)	Yield of pro- ducts (%)		
			1b	1c	1d
1	None	96	82	14	23
2	10 mol% PTH	93	66	16	24
3	20 mol% PTH	96	87	16	24
4	Ar instead of air	n.r.	n.d	n.d.	n.d.
5	In the dark	n.r.	n.d	n.d.	n.d.
6	No PTH	33	12	8	12
7	2,6-Lutidine (4 equiv.)	30	5	1	5
8	HCOOH (4 equiv.)	85	43	18	22
9	10% water	76	31	16	28
10	$AgNO_3$	71	27	11	39
11	BQ	66	11	18	36
12	TEOA	24	1	1	1
13	TEMPO	25	1	3	1
14	MeOH instead of CH ₃ CN	36	5	3	12

Standard reaction conditions: 0.1 mmol 1a, 15 mol% PTH, 2 mL CH₃CN, 390 nm LED (15 mW·cm⁻²), air, 48 h, room temperature. Yield of 1b, 1c, 1d = moles of product 1b, 1c, 1d formed/moles of 1a \times 100%. n.r. = no reaction. n.d. = not detected. All yields were determined by HPLC analysis. Electron, hole, or radical scavengers: 200 mM AgNO₃, 200 mM BQ, 200 mM TEOA, 200 mM TEMPO.

the default electron acceptor for PTH*, while PTH* by itself was unable to perform photoredox chemistry towards 1a as suggested by the previous fluorescence quenching experiment. When the reaction was placed in the dark, no conversion of 1a was found, which eliminated the possibility of thermoreactions (entry 5). Conversion of 1a in the absence of PTH was observed but in a much slower rate (entry 6). The observation was not unprecedented though when lignin substrates were exposed to UV light. 32,33 The above variations of reaction conditions confirmed that light, photocatalyst, and O2 were all essential factors to achieve efficient C_{α} - C_{β} bond cleavage for 1a. It is noteworthy that the addition of other environmental factors such as acid, base, or water dramatically suppressed the yields of C_{α} - C_{β} bond cleavage products (entries 7-9). As we emphasized, the PTH photocatalyzed C_{α} - C_{β} bond cleavage for 1a proceeded under mild conditions without the need for additional additives.

The scope of the lignin model substrates that included β -1 and β-O-4 linkages (2a-6a) was also investigated for PTH photocatalyzed C_{α} – C_{β} bond cleavage reactions. The oxidations of 2a–6a were all irreversible with $E_{\rm p/2}$ spanning between 1.59 V and 1.92 V (Fig. S9–S13, ESI†), which were well below $E^{\circ}(PTH^{\bullet^{+}\star^{/0}})$. The photocatalytic reaction conversions were all close to 100% across the substrate scope under the standard reaction conditions (Table S1, ESI†). Substituents to the aromatic rings of 1a resulted in comparatively high yields and selectivity as well (Table S1, entries 2 and 3, ESI†). Similar to the β -1 model, the C_{α} - C_{β} bond of the β -O-4 linkage model was also cleaved with moderate yields under the standard reaction conditions (Table S1, entries 4 and 5, ESI†).

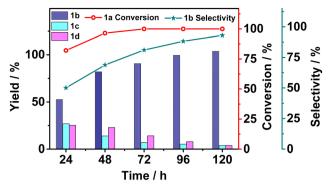


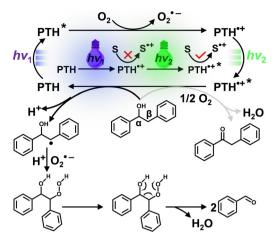
Fig. 2 The product yields from photocatalytic C_{α} – C_{β} bond cleavage of **1a** over the elapsed time. 1b selectivity = moles of product 1b/moles of product (1b + 1c + 1d) \times 100%.

Although 1a conversion approached unity after 48 hours of photocatalysis, the uncleaved product 1d was still present in a significant amount. Therefore, we set out to monitor the product yields by sampling the reaction solution every 24 hours (Fig. 2). The conversion of 1a climbed close to unity within 48 hours and stayed almost invariant in the next 120 hours, but the ratio of the product yields kept changing over time. Initially, all three products were present but the yields of 1c and the uncleaved product 1d gradually decreased to almost 0 while that of 1b increased to almost the only product. The yields of products over time suggested that 1d might be the kinetically competitive product but was subject to further photoredox induced cleavage to the final thermodynamically stable 1b. The long-time photolysis result was encouraging in terms of selectively obtaining high purity of the C_α-C_β-bond-cleaved photoproduct.

Electron, hole, and radical scavengers including AgNO₃, 1, 4-benzoquinone (BQ), triethanolamine (TEOA), and 2,2,6, 6-tetramethylpiperidine-1-oxyl (TEMPO) were used to test possible reactive intermediates for elucidation of the reaction mechanism (Table 1, entries 10-13). The addition of TEOA significantly decreased the product yields, suggesting that PTH^{•+}* was a necessity. The formation of O₂• was also critical to the reaction conversion because BQ as a superoxide scavenger and AgNO₃ as a competitive electron acceptor to O₂ could both significantly decrease the product yields. The addition of TEMPO dramatically reduced the efficiency of the reaction, indicating that the catalytic process involved free radical intermediates.

Based on the above control tests and transient spectroscopic data, the following photocatalytic mechanism was proposed for lignin C_{α} – C_{β} bond cleavage (Scheme 2). Under the first photon irradiation, the photoexcited PTH was oxidatively quenched by O_2 with PTH $^{\bullet^+}$ and $O_2{}^{\bullet^-}$ as the primary photoproducts. PTH $^{\bullet^+}$ was insufficient to oxidize 1a, but with its absorption of the second photon, the doublet excited state PTH*+* was a superoxidant $(E^{\circ}(PTH^{\bullet^{+}*/0}) > 2.3 \text{ V})$ that abstracted an electron to generate a C_{β} -centered radical and released a proton (H^{+}) . Subsequently, the C₆-centered radical of 1a reacted with O₂•and H⁺ to produce a peroxide intermediate. Next, the unstable

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Scheme 2 Proposed mechanism for $C_{\alpha}-C_{\beta}$ bond cleavage of **1a** via consecutive photo-excitation of the PTH photocatalyst.

peroxide intermediate induced cleavage of the C_{α} - C_{β} bond to form benzaldehyde and water. 34 Control experiments showed that benzaldehyde was further oxidized to produce benzoic acid.

In summary, we proposed a new photocatalytic strategy where a commercially available, metal-free small organic photocatalyst, PTH, can be used to valorize lignin under ambient air conditions through photocatalysis. The doublet excited state PTH*+* formed from consecutive two-photon excitation was a potent oxidant to activate the $C(sp^3)$ -H bond of lignin models possibly through ground state association with the substrate and subsequently induced C_{α} - C_{β} bond cleavage. The conversion of a variety of major lignin models was close to unity with a benzoic acid moiety as the major photocleaved product. The reaction conditions were mild without any additional HAT agents and sacrificial electron/hole donors. Therefore, the photocatalytic strategy is a green approach to value-added carbon sources from lignin waste.

This work is supported by the National Natural Science Foundation of China (22173022) and the Natural Science Foundation of Shanghai (21ZR1404400, 19DZ2270100).

Conflicts of interest

There are no conflicts to declare.

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