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Protonated Pteridine and Flavin Analogues acting as Efficient and Substrate-selective Photocatalysts in the Oxidation of Benzyl Alcohol Derivatives by Oxygen

Shunichi Fukuzumi,* Kumiko Tanii, and Toshio Tanaka

Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan

Protonated aminopterin, lumazine, and riboflavin-tetra-acetate efficiently catalyse the substrate-selective photo-oxidation of benzyl alcohol derivatives by oxygen in the presence of perchloric acid in acetonitrile at 298 K.

Flavin coenzymes which contain a tricylic isoalloxazine ring as well as pterin coenzymes such as folic acid (pteroylglutamic acid) and biopterin which contain a dicyclic pteridine ring (a part of the skeleton of flavins) are known to play versatile roles in biological redox reactions.¹ Both flavins and pteridine analogues can absorb visible light and thus, flavin photochemistry has been the subject of intense research for a long time.² In contrast with flavin photochemistry, little is known

of the excited-state chemistry of pteridine analogues.³ In addition, pteridine analogues as well as flavins are known to undergo photo-degradation and thus, cannot be used as efficient photocatalysts by themselves.^{4.5} We have previously reported that flavin analogues can be used as photocatalysts for the oxidation of *p*-methylbenzyl alcohol when they are complexed with metal ions.⁶ In this study, we report that protonated pteridine derivatives, aminopterin (4-aminofolic

acid) and lumazine (pteridine-2,4-diol), as well as a protonated flavin analogue (riboflavin-tetra-acetate) can be used as much more efficient and more stable photocatalysts for the substrate-selective oxidation of benzyl alcohol derivatives with oxygen than the flavin-metal ion complex. Thus, the present study provides a unique opportunity to compare the photo-catalytic activity of pteridine analogues of biologically important redox coenzymes, folic acid and biopterin, with that of a structurally related flavin coenzyme analogue.

No appreciable photo-oxidation of benzyl alcohol by oxygen occurred when aminopterin (AP), lumazine (Lu), or riboflavin-tetra-acetate (RFl) was used as a photocatalyst in the absence of acid in acetonitrile (MeCN). When perchloric acid was added to this system, the flavin and pteridine derivatives were protonated ($\lambda_{max.}$ 334, 350, and 392 nm for APH+, LuH+, and RF1H+, respectively).7-9 Each protonated species (catH+) acted as an efficient photocatalyst for the oxidation of benzyl alcohol derivatives (X-C₆H₄CH₂OH) with oxygen [equation (1)] when the photochemical reactions were carried out using a xenon lamp with a filter transmitting light of 220 nm $< \lambda < 440$ nm. The formation of X-C₆H₄CHO was identified by 1H n.m.r. and electronic spectra, and that of hydrogen peroxide was confirmed by titration with iodide ion as described elsewhere.⁶ No appreciable photo-degradation of the catalysts was observed during the photocatalytic oxidation in the presence of HClO₄ in MeCN.

$$X-C_6H_4CH_2OH + O_2 \xrightarrow{hv} X-C_6H_4CHO + H_2O_2 (1)$$

The quantum yields (ϕ) of the photocatalytic oxidation were determined using a ferrioxalate actinometer with the difference in light absorption between the catalyst and the actinometer appropriately accounted for according to the literature.¹⁰ The ϕ value increased with increase in the HClO₄ concentration to reach a constant value (>1.0 × 10⁻² mol dm⁻³) when all photocatalyst molecules are protonated. The ϕ values at a constant X-C₆H₄CH₂OH concentration (2.9 × 10⁻² mol dm⁻³) as well as the limiting quantum yields ϕ_{∞} in the presence of HClO₄ (1.4 × 10⁻² mol dm⁻³) are listed in Table 1. The ϕ value (0.30) for RF1H⁺ at 2.9 × 10⁻² mol dm⁻³ *p*-MeC₅H₄CH₂CH₂OH is 13-fold larger than the reported ϕ value for a flavin-Mg²⁺ complex.⁶ Such large ϕ values are obtained for each photocatalyst when the substituents (X)



Scheme 1

are moderately electron-donating or electron-withdrawing (X = o-Br, p-Cl, H, p-Me, p-Prⁱ). Thus, protonated flavin and pteridine analogues act as much more efficient and more stable photocatalysts than the flavin-metal ion complex reported previously.6 However, no appreciable photo-oxidation of X-C₆H₄CH₂OH by oxygen was observed with strongly electron-donating (X = p-OH, p-MeO) or -withdrawing $(X = p - NO_2)$ substituents. Such substrate selectivities and the magnitude of quantum yields are similar among the photocatalysts irrespective of them being dicyclic pteridine analogues (APH+ and LuH+) or a tricyclic flavin (RF1H+) as shown in Table 1. The similar photo-catalytic activities may be ascribed to the cancellation of the difference in the ground state oxidizing ability, which is in the order $RF1H^+ > LuH^+ >$ PH⁺,⁸ by that in the excitation energy, which is in the opposite order RF1H⁺ < LuH⁺ < PH⁺.

$$2RF1H^+ + X - C_6H_4CH_2OH \xrightarrow{hv} 2RF1H_2^{+} + X - C_6H_4CHO (2)$$

In the absence of oxygen, RF1H⁺ can be reduced by X-C₆H₄CH₂OH by irradiation of the absorption band due to RF1H⁺ (λ_{max} 392 nm) to yield the dihydroflavin radical cation RF1H₂⁺ (λ_{max} 416 nm) and X-C₆H₄CHO, equation (2).¹¹ The limiting quantum yields ϕ_{∞} for the formation of RF1H₂⁺ were determined and the ϕ_{∞} values are also listed in Table 1. The ϕ_{∞} values in the absence of oxygen agree well with those of the RF1H⁺-catalysed photo-oxidation of X-C₆H₄CH₂OH by oxygen (Table 1). Such an agreement of the ϕ_{∞} values in the absence and in the presence of oxygen was also confirmed in the case of LuH⁺ (Table 1). In addition, the reduced flavin and pteridine analogues are known to be readily oxidized to yield hydrogen peroxide.^{8.12} Thus, the photocatalytic oxidation of X-C₆H₄CH₂OH by oxygen may proceed *via* the photo-reduction of the catalyst (catH₃⁺), followed by the



Table 1. Quantum yields (ϕ) of photocatalytic oxidation of benzyl alcohol derivatives (X-C₆H₄CH₂OH) with oxygen, catalysed by APH⁺, LuH⁺, and RF1H⁺ in the presence of HClO₄ (1.4 × 10⁻² mol dm⁻³) in MeCN at 298 K.

	(APH+)	(LuH+)		(RF1H+)		
X-C ₆ H ₄ CH ₂ OH						
Х	Φ^{a}	φ ^a	φ^{∞_p}	Φ^{a}	$\phi_{\infty}^{b.c}$	
$p-NO_2$	d	d	d	d	e	(0.18)
o-Br	0.084	0.020	0.10	0.089	0.17	(0.17)
p-Cl	0.16	0.088	0.17	0.22	0.28	(0.28)
Н	0.15	0.17	0.38f	0.094	0.23	(0.25)
p-Me	0.13	0.18	0.30	0.21	0.29	(0.30)
<i>p</i> -Pr ⁱ	0.17	0.18	0.23	0.19	0.28	(0.31)
p-MeO	0.020	d	d	d	e	(0.0016)
p-HO	d	d	d	d	d	ď

^a [X-C₆H₄CH₂OH] 2.9 × 10⁻² mol dm⁻³. ^b Limiting quantum yields (ϕ_{∞}) were obtained from the intercepts of the linear plots between ϕ^{-1} and [X-C₆H₄CH₂OH]⁻¹. ^c The values in parentheses are those for the formation of RF1H₂⁺⁺ in the absence of oxygen. ^d Value < 1 × 10⁻³. ^e Value could not be determined accurately. ^f The ϕ_{∞} value in the absence of oxygen is 0.40.

thermal oxidation of the reduced catalyst $(catH_3^+)$ by oxygen to yield H_2O_2 , accompanied by the regeneration of $catH^+$, as shown in Scheme 1.

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