Metal-Free Epoxidation of Alkenes with Molecular Oxygen and Benzaldehyde under Visible Light Irradiation

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Abstract: A new convenient metal-free oxidation protocol of a wide variety of alkenes with molecular oxygen and benzaldehyde under visible light irradiation of fluorescent lamp afforded their corresponding epoxides in 49–99% yields

Key words: aerobic, epoxidation, visible light, benzaldehyde

Since epoxides are versatile intermediates for a variety of chemicals, epoxidation of alkenes is a most important functional-group transformation in organic synthesis.¹ Generally epoxidations of alkenes have been carried out with peracids; however, caution is necessary due to their explosivility. As such development of new safe and effective oxidants for epoxidation has been studied. Molecular oxygen is thought to be the most desirable oxidant with respect to environmental and economic consideration, and much effort has been made to develop direct epoxidation of alkenes with molecular oxygen as an oxygen donor. Although there have been many reports on the metal-catalyzed epoxidation of alkenes with molecular oxygen as a terminal oxidant,² only a limited number of metal-free methods have been reported.³ Among them, epoxidation of alkenes using peracids, prepared by oxidation of aldehyde with molecular oxygen in situ, under photoirradiation conditions is an important and a promising method;⁴ however, the previous methods were carried out under UV irradiation or applicable to the limited alkenes.^{3a,d} An effective use of visible light appears optimal development of novel energy conversion and energy-using technology. Towards this goal, we have previously reported photooxidation using visible light from a general purpose fluorescent lamp;⁵ in this letter, we report a general and convenient synthetic method for metal-free epoxidation of alkenes using molecular oxygen and benzaldehyde under visible light irradiation.

Table 1 shows the results of study of reaction conditions for the epoxidation. The conditions were examined with benzaldehyde under the molecular oxygen atmosphere (O_2 balloon) and visible light irradiation at room temperature, followed by the reaction with *trans*-stilbene (1) under nitrogen atmosphere at room temperature, and acetonitrile was found to be most suitable solvent among our examination (entries 1–6).⁶ A better result was observed in the reaction with 2 equivalents of benzaldehyde and initial exposure for 3 hours to afford stereospecifically *trans*-stilbene oxide (**2**) in 93% yield without the formation of the *cis*-isomer (entries 7–11). It is worth noting that the epoxidation proceeds in good yield under air atmosphere instead of O₂ balloon (entry 12). Both molecular oxygen and visible light irradiation are necessary for this epoxidation since **2** cannot be satisfactorily obtained without them (entries 13 and 14).

Table 1 Study of Reaction Conditions

~) <i>hv</i> (fluorescent lamp), C benzaldehyde (equiv) solvent, r.t., time	D ₂	
		e) 1 , r.t., 10 h, N ₂		
~	1 (0.3 mmol)		~	2
Entry	Solvent	Benzaldehyde (equiv)	Time (h)	Yield (%) ^a
1	CH_2Cl_2	2.0	5	0
2	THF	2.0	5	0
3	EtOAc	2.0	5	73
4	acetone	2.0	5	67
5	MeOH	2.0	5	0
6	MeCN	2.0	5	92
7	MeCN	1.5	5	69
8	MeCN	2.0	3	93
9 ^b	MeCN	2.0	3	82
10 ^c	MeCN	2.0	3	0
11	MeCN	2.0	1	65
12 ^d	MeCN	2.0	3	83
13 ^e	MeCN	2.0	5	24
14 ^f	MeCN	2.0	5	0

^a The yields were determined by integration of ¹H NMR with internal standard.

^b 4-Methoxybenzaldehyde was used instead of benzaldehyde.

^c 4-Nitrobenzaldehyde was used instead of benzaldehyde.

^d The reaction was carried out under air.

^e The reaction was carried out in the dark.

^f The reaction was carried out under N₂.

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Table 2 shows scope and limitation of this epoxidation with various alkenes such as aromatic alkenes, aliphatic alkenes, and allylic alcohols under the optimized reaction conditions.⁷ Disubstituted aromatic alkenes, such as *trans*-stilbene, *cis*-stilbene, *trans*- β -methylstyrene, cin-

namyl alcohol, and 1,2-dihydronaphthalene, afforded stereospecifically the corresponding epoxides in good to excellent yield without formation of the geometrical isomers (entries 1–5). Monosubstituted styrenes with *tert*butyl and chloro groups at *para* position afforded the cor-

Table 2	Epoxidation	of Aromatic and	Aliphatic Alkenes
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substrate	 hv (fluorescent lamp), O₂ benzaldehyde (2 equiv) MeCN, r.t., 3 h 	- product			
(0.3 mmol)	2) substrate, r.t., time (h), N ₂				
Entry	Substrate	Product	Time (h)	Yield (%) ^a	
1			10	89°	
2			10	80°	
3		€ C	5	85	
4	ОН	Он	5	82	
5		€	5	66	
6			5	76°	
7	CI	CI CI	10	73°	
8	O ₂ N	O ₂ N O	10	49°	
9	$\checkmark \checkmark \checkmark \land \land$	\sim	24	81	
10		° C	10	70 ^c	
11	$\sim\!\!\sim\!\!\sim\!\!\sim$		10	99	
12	\frown	он он	5	78	
13		ο	5	27 (89) ^b	

^a Isolated yields. Numbers in parentheses are ¹H NMR yields.

^b *cis*-Cyclooctene oxide is unstable under preparative TLC.

^c The substrate recovery was 10%, 13%, 5%, 6%, 50%, and 8% for entries 1, 2, 6–8, and 10.

responding epoxides in good yields; however, electronwithdrawing nitro group retarded this reaction (entries 6– 8). Furthermore, both mono- and disubstituted aliphatic alkenes gave the corresponding epoxides in good to excellent yields (entries 9–13).

A plausible reaction path is shown in Scheme 1. Perbenzoic acid, usual epoxidation reactant, is assumed to be formed in situ, since we could detect perbenzoic acid in 50% yield when benzaldehyde was irradiated with visible light under molecular oxygen atmosphere at room temperature for 3 hours.⁸ This result agrees with the requirement of two equivalents of benzaldehyde to complete this epoxidation. Furthermore, perbenzoic acid was obtained only in 15% yield when the reaction was carried out in the dark, visible light was found to accelerate the generation of perbenzoic acid.



Scheme 1 Plausible path

In conclusion, we have developed the convenient and environmentally benign metal-free epoxidation of various alkenes in the presence of molecular oxygen and benzaldehyde under visible light irradiation of fluorescent lamp. This method is of great value from the view point of using visible light and applicable to a wide variety of alkenes. Further application of this oxidation to other reactions is now in progress in our laboratory.

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- (6) Exposure of benzaldehyde to the molecular oxygen under visible light irradiation in the presence of *trans*-stilbene (1) result in the no reaction, probably because *trans*-stilbene (1) inhibits photooxidation of benzaldehyde. On the other hand, 11% of *trans*-5-decene oxide was produced when using *trans*-5-decene instead of 1.

(7) Typical Procedure of the Epoxidation

A dry MeCN solution (1 mL) of the benzaldehyde (63.7 mg, 0.6 mmol) in a 30 mL round-bottom flask equipped with an O_2 balloon was stirred and irradiated with four 22 W fluorescent lamps, which were set up at a distance of 65 mm, for 3 h. The temperature of the final stage of this reaction was about 50 °C. Then, *trans*-stilbene (1, 54.1 mg, 0.3 mmol) was added to the reaction mixture and stirred without irradiation for 10 h at r.t. The reaction mixture was concentrated under reduced pressure. The residue was purified by preparative TLC to afford the pure product **2** (52.4 mg, 89%).

(8) Yield of perbenzoic acid was determined by integration of ¹H NMR with internal standard (1,1,2,2,-tetrachloroethane).

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