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Green-light-driven thioxanthylium-based organophotoredox catalysts: Organophotoredox promoted radical cation Diels-Alder reaction

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ABSTRACT

Thioxanthylium-based organophotoredox catalysts that operate under irradiation with green light have been developed. These catalysts present high excited-state reduction potentials (E_0 ' (C*/C⁻) = +1.79–1.94 V vs SCE). They are able to efficiently activate dienophiles under green or blue light irradiation afforded the targeted radical cation Diels-Alder cycloadducts in good yields. The present thioxanthylium-based catalysts provide a new green-light-driven photoredox catalysis system.

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1. Introduction

Chemical transformations mediated by visible light have attracted much attention due to their potential in sustainable energy-conversion systems. The current global situation with regard to the balance between the demand and supply of energy and its associated environmental implications could be ameliorated by developing clean systems for the chemical conversion of solar energy.¹ In organic synthesis, photoredox catalysts can be used to carry out a wide variety of organic transformations (Figure 1).² Polypyridyl complexes of ruthenium and iridium are among the most widely used photoredox catalysts, as they usually exhibit high activity and versatility.³ However, such iridium and ruthenium catalysts are usually toxic and expensive. In light of the disadvantages associated with noble-metal-based catalysts, the recent focus of interest has shifted toward the development of metal-free photoredox catalysts, which represent a more cost-effective and sustainable approach.⁴ Despite the promising properties of recently reported catalysts, including metal-based and metal-free photoredox catalysts, these normally suffer from narrow absorption windows and require the use of high-energy light sources. On the other hand, green light is of lower energy (500-600 nm) than blue and ultraviolet, thus efficiently reducing the risk of retinal damage and stress.⁵ Eosin Y is the most widely used organic photoredox catalyst using green light as the irradiation source, and it can be employed in a wide variety of organic transformations.⁶ However, despite its utility, it suffers from a low excited-state reduction potential, which narrows the scope of substrates, and from poor solubility in common organic solvents. Moreover, to the best our knowledge, only a few green-light-activated photoredox catalysts have been reported, despite the desirability of this approach.⁷



Figure 1. Absorption and excited-state reduction potential of representative photoredox catalysts

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Photocatalyst	$E_0'(C^*/C^-)^a(V)$	$E_0'(C/C^{-})^b(V)$	Absorption	Absorption	Excitation	Emission
			$\lambda_{\rm max} ({\rm nm}) / \varepsilon imes 10^{-3}$	$\lambda \text{ (nm)}/\varepsilon \times 10^{-3}$	λ_{\max} (nm)	λ_{\max} (nm)
			$(mol^{-1} dm^3 cm^{-1})$	$(mol^{-1} dm^3 cm^{-1})$		
TXT1	+1.83	-0.31	468/31.7	520/5.5	468	636
TXT2	+1.94	-0.27	461/28.3	520/6.7	461	659
TXT3	+1.86	-0.35	463/42.3	520/7.4	463	620
TXT4	+1.79	-0.35	478/32.8	520/6.9	478	666
-						

^a Excited-state reduction potentials were estimated from ground-state redox potentials and the intersection of the absorption and emission bands.^{4a}

^b Determined by cyclic voltammetry in acetonitrile vs SCE. See the Supporting Information.

Thioxanthylium is a useful compound in the material and biological fields.⁸ It is known that thioxanthylium has absorption in green region.⁹ However, 1-, 3-, 6- and 8-positions of thioxanthylium are amenable to be attacked by nucleophiles, and benzene group at the 9-position is a key substituent group for stabilizing thioxanthylium core.¹⁰ Then, in order to expand the utility of photoredox catalysts, we report herein thioxanthylium-based organophotoredox catalysts that operate under irradiation with green or blue light. These organophotoredox catalysts afford radical cation Diels–Alder cycloadducts in high yields.

We initially synthesized a series of thioxanthylium salts to probe the relationship between the structure and physical properties of these novel catalysts (Table 1). Their synthesis was accomplished through the reaction of a thioether that was treated in chlorobenzene at 120 °C for 1 h with benzoyl chloride in the presence of TfOH. These catalysts exhibit high excited-state reduction potentials (E_0 '(C*/C⁻) = +1.79–1.94 V vs SCE). The substrate scope of such catalysts should therefore be larger than that of eosin Y ($E_{1/2}$ (C*/C⁻) = +0.83 V vs SCE).⁶ Importantly, these thioxanthylium salts exhibit an absorption band in the blue/green region of the visible spectrum (~400–600 nm), which indicates that these catalysts may be activated by visible light. As shown in Table 1, almost the same physical properties were observed in spite of having different substituent groups on benzene ring at the 9-position. In addition, when the solvent effects were examined using MeCN, CH₃NO₂, DMSO and MeOH, no substantial shifts in both UV-vis and emission spectra were observed (see Supporting Information), which exhibit these catalysts would have π - π * transition state. Importantly, it is expected that 9-aromatic substituent on thioxanthylium would a key important group for stabilizing catalysts.^{10,11}

Recently, visible-light-driven radical cation Diels-Alder reactions catalyzed by metal-based photoredox catalysts have been developed that employ ruthenium complexes under irradiation with visible light or chromium complexes under irradiation with NUV light.¹² From a fundamental perspective, as well as with respect to practical applications, the relatively low cost and the fact that these photocatalytic systems operate with visible light are highly desirable. Subsequently, the radical cation Diels-Alder reaction of *trans*-anethole (1) with 2,3-dimethylbutadiene (2) was screened in the presence of an organophotoredox catalyst (Table 2). First, all blank experiments, i.e., in the absence of a catalyst, light source, and air (degassed CH_3NO_2 was used under N_2), afforded trace amounts of the product 3a (entries 1 and 2), and 4% yield of the product (entry 3). When the reaction was carried out with 1 (0.5 mmol), 2 (1.5 mmol), and TXT1 (1.0 mol%) in CH₃NO₂ (0.0625 M) at room temperature under air and irradiation with blue light, excellent yield was obtained within 15 minutes (entries 4). This should partly be due to the protective nature of the otrifluoromethyl group, which minimize any undesirable reactivity of the thioxanthylium chromophore with exogenous nucleophiles and transient radicals.¹¹ On the other hand, it was assumed that such p-methoxy substituted salts (**TXT2**) are easily attacked by nucleophiles.^{11c} Indeed, good yield of the product was obtained after 15 h (entry 5). The parent phenyl group (TXT3) and halogen groups on benzene ring (TXT4) were also suitable in the reaction, giving the corresponding product in high yields (entries 6 and 7). Next, other representative organic photoredox catalysts, such as eosin Y, Acr⁺-Mes, and TPT were screened. The use of eosin Y, whose excited-state reduction potential ($E_{1/2}(C^*/C^-) = +0.83$ V vs SCE) is lower than that of *trans*-anethole **1** ($E_{p/2} = +1.24$ V vs SCE),¹³ did not result in a reaction (entry 8). Acr⁺-Mes and TPT, which have high excited-state reduction potentials and can be used under irradiation with blue light, afforded the product in low yields for 15 min. But when the reaction time was changed to 1.5 h, starting material 1 was consumed and high yields were observed (entries 9 and 10). Surprisingly, when green light was used as the light source, all of thioxanthylium catalysts led to the formation of the desired product in excellent yields (entries 11-14). As expected, eosin Y did not afford any product owing to its low excited-state reduction potential (entry 15). Moreover, Acr⁺-Mes and TPT did not efficiently afford the product for 0.25 h or 15 h, given their inefficient absorption of green light (entries 16 and 17).

Table 1. Synthesis and physical properties of thioxanthylium-based photocatalysts







Entry	Time (h)	Light	Catalyst	Yield (%)
1	0.25	Blue	No catalyst	0
2	0.25	No light	TXT1	0
3 ^{b,c}	0.25	Blue	TXT1	4
4	0.25	Blue	TXT1	92
5	15	Blue	TXT2	94
6	1.15	Blue	TXT3	89
7	0.75	Blue	TXT4	89
8	0.25	Blue	Eosin Y	0
9	0.25, (1.5)	Blue	Acr ⁺ -Mes	5 ^b , (91)
10	0.25, (1.5)	Blue	TPT	16 ^b , (91)
11	0.25	Green	TXT1	88
12	15	Green	TXT2	92
13	1.15	Green	TXT3	91
14	0.5	Green	TXT4	95
15	0.25, (15)	Green	Eosin Y	0, (0)
16	0.25, (15)	Green	Acr ⁺ -Mes	$0, (11)^{b}$
17	0.25, (15)	Green	TPT	0, (0)

^a All reactions were carried out with **1** (0.5 mmol), **2** (1.5 mmol), and the catalyst (1.0 mol%) in the specified solvent (0.0625 M) at room temperature under air and irradiation with visible light. ^b NMR yield. ^c Under N₂.

With the optimal conditions in hand, a variety of dienes and dienophiles were examined to evaluate the generality of the reaction (Table 3). When isoprene and myrcene were used as a diene, the desired products were obtained in 94% and 84%, respectively (**3b** and **3c**). When benzyloxy group was used instead of methoxy group on benzene ring of dienophile, the reaction afforded the corresponding cycloadduct in high yield (**3d**). In addition, isosafrole also gave good yield in the reaction (**3e**). When 1,2-dimethoxy-4-(1-propenyl)benzene was reacted with isoprene or 2,3-dimethylbutadiene, medium yields were observed (**3f** and **3g**).

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Table 3. Scope and limitation of the reaction

^a NMR yield





Scheme 1. Proposed reaction mechanism

A proposed mechanism for this reaction is shown in Scheme 1. Excitation of the photocatalysts (PC*), whose $E_0'(C^*/C^-)$ values range between +1.79 and +1.94 V (vs SCE), under irradiation with visible light enable the oxidation of *trans*-anethole 1 ($E_{p/2} =$ +1.24 V vs SCE).¹³ In addition, the results of Stern-Volmer experiments suggest that the electron transfer from *trans*-anethole to the photocatalyst should occur smoothly.¹⁴ The reduced photocatalyst (PC⁻⁻) can be regenerated into the original photocatalyst (PC) via single-electron transfer from O₂. The resulting radical cation **A** undergoes a [4+2] cycloaddition to generate the radical cation product **B**. Finally, the transfer of a single electron from the superoxide radical (based on Table 2, entry 3) or *trans*-anethole **1** afforded the desired product **3**.¹⁵ According to the reaction quantum yield experiment shown in supporting information, the reaction would mainly proceed through the radical chain process. The scope and mechanism are currently under investigation and will be reported in due course.

Finally, when the reaction was performed on the gram scale under sunlight irradiation, the reaction furnished the desired product after 5 min in 84% yield (1.5 g, Scheme 2). This means that the present thioxanthylium-based catalytic system provides a sustainable synthetic method using only 1.0 mol% of the organocatalyst and solar energy.



Scheme 2. Reaction carried out under irradiation with sunlight

In conclusion, thioxanthylium-based organophotoredox catalysts that operate under irradiation with green light have been developed. These organophotoredox catalysts absorb light in the visible region (~400–600 nm) and have the high excited-state reduction potentials ($E_0^{\circ}(C^*/C^{-}) = +1.79-1.94$ V vs SCE). Catalytic amounts (1.0 mol%) of the thioxanthylium catalysts are able to efficiently

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promote radical cation Diels-Alder reactions under irradiation with green, which cannot be activated by any of the representative organic photocatalysts. In addition, the utility of this system was demonstrated on the gram scale under irradiation with solar light. The present catalysts provide a new green-light-driven photoredox catalytic system.

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