Photoredox Catalysis

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Visible-Light-Induced Photoredox Catalysis of Dye-Sensitized Titanium Dioxide: Selective Aerobic Oxidation of Organic Sulfides

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Abstract: *TiO_2 photoredox catalysis has recently attracted much interest for use in performing challenging organic transformations under mild reaction conditions. However, the reaction scheme is hampered by the fact that TiO_2 can only be excited by UV light of wavelengths λ shorter than 385 nm. One promising strategy to overcome this issue is to anchor an organic, preferably metal-free dye onto the surface of TiO_2. Importantly, we observed that the introduction of a catalytic amount of the redox mediator TEMPO [(2,2,6,6-tetramethylpiperidin-1-yl)oxyl] ensured the stability of the anchored dye, alizarin red S, thereby resulting in the selective oxidation of organic sulfides with O_2. This result affirms the essential role of the redox mediator in enabling the organic transformations by visible-light photoredox catalysis.*

Visible light or sunlight has been foreseen as a potential driving force for organic reactions for more than one hundred years and has recently attracted renewed interest.[1] Most of the commonly used organic substrates are colorless; such substances cannot be directly excited by visible light. Thus, efficient photoredox catalysts, such as Ru or Ir complexes and some metal-free organic dyes, have been widely adopted to drive selective redox reactions under very mild conditions.[2] However, such catalysts are seldom exploited under oxidative conditions with O_2 as the terminal oxidant[3] because doing so requires that they can activate O_2 under visible-light irradiation, which, in turn, might result in the degradation of the more fragile chromophore of the photoredox catalyst rather than the aerobic oxidative transformation of the substrate. Thus, much more stable metal-oxide semiconductors, with TiO_2 as a notable example, are better suited to performing aerobic oxidation reactions.[4]

Indeed, TiO_2 has been widely adopted in a wide range of oxidation reactions with O_2, including both non-selective and selective reactions under UV irradiation.[5] Because TiO_2 can only be excited by UV light of wavelengths λ shorter than 385 nm, this reaction scheme is severely limited because of the harvesting of only a small portion of sunlight. Furthermore, the absorption edge of the substrates or the formed products lies in the near-UV region, which could cause undesired photochemical side reactions, leading to low selectivity of the oxidation products. To avoid these drawbacks, visible-light photoredox catalysis based on TiO_2 should be developed. We previously achieved the visible-light-induced selective oxidation of an organic sulfide with O_2 on TiO_2, prompted by synergistic oxidation with benzyl amines[6] or the presence of a catalytic amount of tertiary amines.[7] We concluded that adding a redox mediator is important in bestowing the smooth formation of the sulfoxide product by TiO_2 photoredox catalysis.[6,7] In these reaction schemes, the visible-light absorption was caused by the surface complex of the Lewis base–acid interaction between an amine and the surface Ti sites of TiO_2; only a very narrow band of visible light at approximately 400 nm was harvested.[8] Even further improvement is required to capture more abundant visible light.

Consequently, we propose to anchor an organic dye onto TiO_2 to extend its visible-light absorption range. If this design is used directly for the oxidation of organic molecules, then the same challenge of the instability of the chromophore must be overcome. Some organic dyes, which are otherwise stable in the presence of sunlight and O_2, could be degraded easily on TiO_2 under visible-light irradiation.[9] However, a constant redox mediator can expedite hole transfer from the excited dye to the target molecule, preventing the accumulation of oxidative pressure on the anchored dyes and accordingly preserving their stability under aerobic conditions. In fact, this strategy allows for the success of dye-sensitized solar cells (DSSCs) and natural photosynthesis, in which I_3^-/I_2 or a Mn-Ca cluster act as the redox mediator for photogenerated oxidative processes to release electric current or O_2.[10] TEMPO [(2,2,6,6-tetramethylpiperidin-1-yl)oxyl] has been applied as the redox mediator in some DSSCs.[11] Meanwhile, its application in organic oxidative transformations has increased substantially in recent years.[12]

Therefore, TEMPO is adopted as the redox mediator for the selective oxidation of organic sulfides with O_2 under dye-sensitized TiO_2 visible-light photoredox catalysis. TEMPO is a commercially available stable free radical with particular application in the selective oxidation of alcohols.[13] To the best of our knowledge, only one example of the oxidation of sulfides with TEMPO as a co-catalyst has been reported, and the reaction was conducted under relative harsh conditions of acetic acid solvent and Mn^{II}–Co^{II} dual metal catalysts.[14] Herein, we report the visible-light-induced aerobic oxidation of sulfides to sulfoxides with TEMPO that can ensure the stability of the organic dye anchored on TiO_2 and mediate the selective oxidation of sulfide. Moreover, the role of TEMPO

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for the oxidation of alcohols is still debated, even after intensive research.[15] Hence, this system might have implications for the elucidation of TEMPO in mediating oxidation of different organic molecules.

We chose anatase TiO_2 (BET specific surface area of $275\ m^2 g^{-1}$, see Figures S1 and S2 for characterizations in the Supporting Information) and alizarin red S (ARS) to produce a dye-sensitized photoredox catalysis for the selective oxidation of an organic sulfide. The high surface area of TiO_2 is beneficial to the generation of photocurrent in DSSCs that operates on similar principles. The ARS-sensitized TiO_2 was fashioned in a very facile manner. Both TiO_2 and ARS are insoluble in ethanol (see the Supporting Information for more details). However, after ultrasonication in ethanol, a uniform visible-light photoredox catalyst, ARS-TiO_2, was obtained (BET specific surface area of $213\ m^2 g^{-1}$); the sample is stable in air for months in the absence of light irradiation and is suitable for further investigation for photoredox catalytic aerobic oxidation.

The precise adsorption model of the organic dye could substantially influence the eventual visible-light photochemical activity, which should be discerned first. There are two possible models for the adsorption of ARS onto the surface of TiO_2 based on the molecular structure of ARS (Figure 1). In low-pH aqueous solution, the sulfate group has been assigned as the docking site (Figure 1 a). However, this process is quite unlikely for the exchange of sodium cation and the surface hydroxy groups of TiO_2 in ethanol, a condition we designed for the photoredox catalyst. The catechol group of ARS acts as the docking site by binding with the surface hydroxy groups of TiO_2 (Figure 1 b). This notion is further confirmed by the observation that the adsorption spectrum is red-shifted (Figures S3 and S4) after the binding of ARS and TiO_2, suggesting the chromophore group, that is, the catechol group, interacts with the surface of TiO_2.

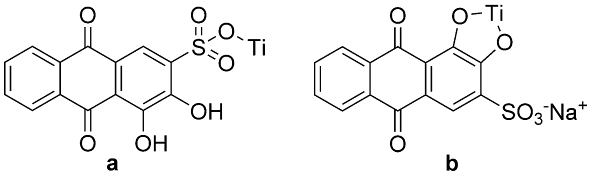


Figure 1. The possible adsorption models of ARS on the surface of anatase TiO_2.

After understanding the key features for the adsorption of ARS onto the surface of anatase TiO_2, we next attempted to deduce the importance of the TEMPO redox mediator in enabling the stability of anchored ARS under visible-light irradiation, a characteristic required before the examination of the photoredox catalytic activity. The comparison results are shown in Figure 2 (diffuse reflectance UV/Vis spectroscopy; Figure S5). In the presence of a substrate of thioanisole and an oxidant of O_2, the decoloration of the dispersed ARS-TiO_2 in CH_3OH occurs only after minutes of visible-light irradiation because of the oxidative pressure it endures, leading to the oxidation of ARS itself rather than to oxidation of thioanisole. This unintended oxidation of anchored dye likely explains why the literature contains so few accounts of systems based on dye-sensitized TiO_2 for selective aerobic oxidation. However, with the addition of a catalytic amount (2 mol %) of TEMPO to the reaction medium, the stability of dispersed ARS-TiO_2 could be substantially increased by the rapid shuttling of the photogenerated holes of the anchored ARS, which releases the oxidative pressure placed upon it.

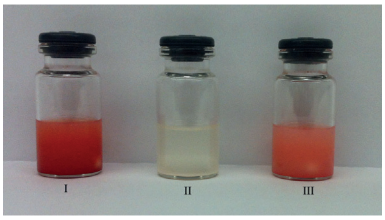
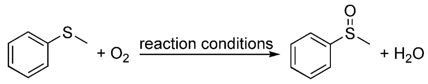


Figure 2. Photograph of the visible-light photoredox catalytic systems based on ARS-TiO_2. I) Before visible-light reaction. II) After visible-light irradiation for 5 minutes without TEMPO. III) After visible-light irradiation for 1.5 h with TEMPO (2 mol %) redox mediator. Reaction conditions: see the footnotes of Table 1.

After confirming that TEMPO can substantially improve the stability of ARS-TiO_2, we next considered the details of the photoredox catalytic activity under different conditions, which is important for understanding the reaction mechanism. In addition, thioanisole is a substrate that can be oxidized by either the electron-transfer or the energy-transfer pathways.[16] These two pathways can also be distinguished by control experiments. The results for these control experiments are listed in Table 1. Under standard reaction conditions, the selective oxidation of thioanisole proceeds smoothly, affording methyl phenyl sulfoxide in high selectivity (entry 1, Table 1). In the absence of TEMPO, ARS-TiO_2 was decolored quickly, delivering only a slight transformation of thioanisole (entry 2, Table 1). Anatase TiO_2 exhibited no activity, suggesting the reaction results were not caused by the interaction between thioanisole and TiO_2 (entry 3, Table 1). This type of interaction cannot be excited by visible light of

Table 1: Control experiment for the selective aerobic oxidation of thioanisole on ARS-sensitized TiO_2 with TEMPO as the redox mediator.

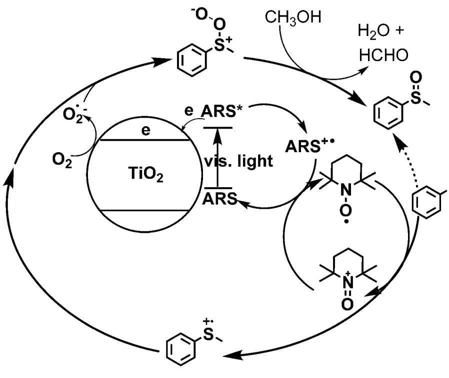


Entry	Conditions	Conv. [mol %][b]	Select. [mol %][b]
1[c]	Standard	42	96
2	No TEMPO	9	99
3	TiO_2	0	–
4	TEMPO	0	–
5	ARS	2	99
6	0.1 MPa air	33	97
7	No O_2	0	–
8	$\lambda > 400$ nm	50	95
9	$\lambda > 490$ nm	35	96
10	$\lambda > 510$ nm	31	97

[a] Reaction conditions: 0.3 mmol of thioanisole, 0.006 mmol of TEMPO, 9.6 mg of ARS-TiO_2 (0.002 mmol of ARS), 300 W Xe lamp, 5 mL of CH_3OH, $\lambda > 450$ nm, 0.1 MPa of O_2, 1.5 h. [b] Determined by GC-FID using chlorobenzene as the internal standard, conversion of thioanisole, selectivity of methyl phenyl sulfoxide. [c] Errors for the conversion numbers are ±3 mol %.

wavelengths longer than 450 nm. TEMPO, a red-orange solid, possesses slight solvatochromism, appearing colorless in CH_3OH solution, thus triggering no reaction under visible-light irradiation (entry 4, Table 1). If the reaction was initiated by the energy transfer from the excited dye to O_2, then only ARS could perform the reaction. However, almost no reaction occurs with ARS as the sensitizer (entry 5, Table 1), indicating that the reaction proceeds through the electron-transfer pathway. The reaction can also be performed with oxygen in 0.1 MPa of air as the oxidant (entry 6, Table 1). In the absence of O_2, the reaction completely stopped (entry 7, Table 1). Moreover, the reaction shows light-wavelength-dependent behavior (entries 8–10, Table 1). Thus, a wide arrange of visible-light spectra can be used for this reaction, representing a giant step forward compared to the system investigated in our previous reports, where only visible light of approximately 400 nm could be used.[6,7]

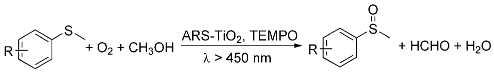
With the results of the control experiment in hand, in conjunction with our and others' previous findings, the tentative mechanism of visible-light photoredox catalysis by ARS-sensitized TiO_2 with TEMPO as a redox mediator is rationalized in Scheme 1. ARS can be anchored on TiO_2 with a catechol group to form a stable complex, ARS-TiO_2, which absorbs a wide range of visible light. Under visible-light irradiation, ARS is excited to ARS*. Then charge transfer from ARS* to TiO_2 occurs, leading to the injection of electron to the conduction band of TiO_2 and the formation of $ARS^{\bullet+}$. Next, the electron travels through the conduction band of TiO_2 to react with O_2, thereby forming $O_2^{\bullet-}$. $ARS^{\bullet+}$ drives the oxidation of the redox mediator, TEMPO, to afford $TEMPO^+$, thereby quickly restoring the ground state of ARS to maintain its stability in the presence of different oxidative species. $TEMPO^+$ interacts with thioanisole by single-electron transfer to form an S-centered free-radical cation. Simultaneously, TEMPO is regenerated from $TEMPO^+$. The S-centered free-radical cation prefers to react with $O_2^{\bullet-}$ formed at the conduction band of TiO_2, allowing for the evolution of sulfide peroxide. In the protic solvent CH_3OH, the final methyl phenyl sulfoxide is formed, accompanied by the side product of HCHO and H_2O. At this stage, this proposed mechanism lacks direct evidence because of the elusive transition states in the photoinduced radical process. Further experimental and theoretical work will be done in the future to present a clearer mechanistic insight.

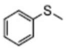
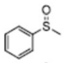
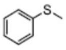
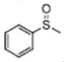
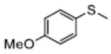
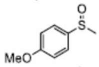
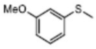
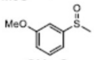
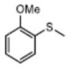
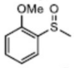
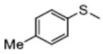
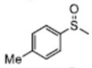
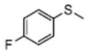
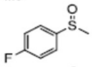
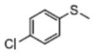
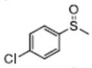
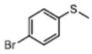
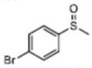
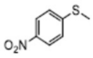
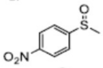
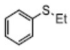
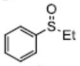
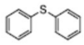
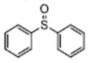


Scheme 1. Proposed mechanism for the visible-light-induced oxidation of thioanisole with O_2 on ARS-sensitized TiO_2 with TEMPO as a redox mediator.

After the formulation of the tentative reaction mechanism, we finally seek to establish the scope of the substrates for this visible-light photoredox catalysis, which is important for demonstrating the generality for this reaction scheme. The reaction results are summarized in Table 2. The stability of the anchored ARS remains a concern. Thus, with the increase of the amount of thioanisole to 5 times the standard conditions, comparable conversion was achieved with only 3.33 times the reaction time (entry 1, Table 2). A turnover number (TON) of 607 in terms of ARS for the aerobic oxidation of thioanisole was achieved, demonstrating the stability of the anchored ARS. This result also categorically reveals heterogeneous photoredox catalysis can be performed under the condition of a very high concentration of substrate. An amount of 0.155 g of methyl phenyl sulfoxide was obtained as the product, suggestive of its usefulness in preparative organic synthesis.

Table 2: Visible-light-induced selective oxidation of sulfides into sulfoxides with O_2 on ARS-sensitized TiO_2 with TEMPO as a redox mediator.[a]



Entry	Substrate	Product	T(h)	Conv. (mol%)[b]	Select. (mol%)[b]
1[c]			10	81	91
2[d]			3	84	90
3			2.5	81	94
4			3	75	93
5			3	81	98
6			2.5	81	93
7			3.5	81	88
8			4	84	84
9			4.5	82	86
10			12	57	83
11			4	82	85
12			10	58	79

[a] Reaction conditions: 0.3 mmol of sulfide, 0.006 mmol of TEMPO, 9.6 mg of ARS-TiO_2 (0.002 mmol of ARS), 300 W Xe lamp, 5 mL of CH_3OH, $\lambda > 450$ nm, 0.1 MPa of O_2. [b] Determined by GC-FID using chlorobenzene as the internal standard, conversion of sulfide, and selectivity of the corresponding sulfoxide. [c] 1.5 mmol of thioanisole, 0.03 mmol of TEMPO. [d] Errors for the conversion numbers are ±3 mol%.

Thioanisole and its derivatives were all good substrates subjected to the standard reaction conditions (entries 2–9, Table 2). Some general patterns can be observed for the oxidation of this type of substrate. With comparable conversion of the sulfide substrate, thioanisoles with an electron-donating group (entries 3 and 6, Table 2) typically require shorter reaction times than thioanisole; conversely, thioanisoles with electron-withdrawing groups (entries 7–9, Table 2) commonly require longer reaction times than thioanisole (entry 2, Table 2).

The thioanisole substituted with an *m*-methoxy group (entry 4, Table 2) with a negligible electronic effect, has a similar reaction time as thioanisole. Nevertheless, thioanisole with the *o*-methoxy group possessing the strongest electron-donating effect requires a longer time (entry 5, Table 2). This result might be due to the steric hindrance effect of the *o*-methoxy group during the reaction with TEMPO. The combined electronic and steric effects of the substituted group are responsible for the final results. A strong electron-withdrawing group such as NO_2 demands a much longer reaction time (entry 10, Table 2). When an ethyl group was substituted for the methyl group of thioanisole, the corresponding sulfoxide was produced in high selectivity, with only a slightly longer reaction time (entry 11, Table 2). When a phenyl group was substituted for the methyl group of thioanisole, a substantially longer time and lower selectivity for the corresponding sulfoxide were obtained. Together, these results assert that aliphatic sulfides are more suitable substrates than aromatic sulfides.

In summary, we designed a system for the visible-light-induced selective aerobic oxidation of organic sulfides, with the core principles being similar to that of the DSSCs. TEMPO, a redox mediator, plays a pivotal role in facilitating the reaction to ensure the stability of the anchored dye and the selectivity of the desired oxidation product. Adding a redox mediator might be especially useful for photoredox catalysts that exhibit excellent photochemical activity but are not stable under aerobic oxidation conditions. Accounting for the fact that the oxidation chemistry of TEMPO is ever-expanding and interesting catalytic systems based on metal oxides and intermetallic materials are rapidly developing,[17] we are seeking better examples similar to the current dye-sensitized TiO_2 photoredox catalysis setup in due course.

Acknowledgements

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Keywords: aerobic oxidation · photoredox catalysis · redox meditor · sulfoxides · visible light

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