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Aerobic Visible-Light Photoredox Radical C–H Functionalization: Catalytic Synthesis of 2-Substituted Benzothiazoles

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ABSTRACT

An aerobic visible-light driven photoredox catalytic formation of 2-substituted benzothiazoles through radical cyclization of thioanilides has been accomplished. The reaction features C–H functionalization and C–S bond formation with no direct metal involvement except the sensitizer. The reaction highlights the following: (1) visible-light is the reaction driving force; (2) molecular oxygen is the terminal oxidant, and (3) water is the only byproduct.

Visible-light driven organic chemical reactions are considered to be a sustainable approach, as sunlight is a clean and unlimited energy source.[1] The study of $Ru(bpy)_3^{2+}$ as the sensitizer in photoredox organic reactions began ~30 years ago.[2] In 2008, the reports of seminal work on the direct asymmetric alkylation of aldehyde by MacMillan et al.[3] and the [2 + 2] enone cycloaddition reaction by Yoon et al.[4] revealed the power of visible-light catalysis in radical-involving organic synthesis[5] and drew the attention of many researchers.[6] However, the precursors that form radical intermediates under visible-light photoredox reaction conditions are still very limited. Currently, most of the reports are on the reactions of activated C–X bonds and the C–H bond next to a N-atom. Although organosulfur compounds form radicals easily and have been widely used in radical reactions, the only $Ru(bpy)_3^{2+}$ photocatalytic reaction involving a sulfur radical to date is the oxidation of sulfides to sulfoxides reported by Zen et al.[2d] Dioxygen is the ultimate environmentally benign oxidant, as it is green and readily accessible. Visible-light induced oxidation by molecular oxygen is an attractive but very challenging goal to chemists.[2d,6k,6n,6p,7] Here, we report a novel

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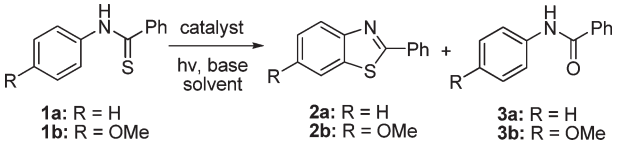
visible-light photoredox catalytic synthesis of benzothiazoles via a radical C−H functionalization/C−S bond formation using dioxygen as the terminal oxidant.

2-Arylbenzothiazoles are an important class of compounds with broad biological and pharmaceutical properties.[8,9] Typically, benzothiazoles are prepared via oxidative intramolecular cyclization of thiobenzanilides.[10−12] The use of a stoichiometric or excess amount of oxidants limits the functionality tolerance and is environmentally unfriendly. Transition-metal (Pd and Cu) catalyzed direct C−H functionalization/cyclizaiton of thiobenzanilides is very attractive as prefunctionalization is unnecessary.[11e,l,m] However, the reported methods involved more than one type of metal and a high reaction temperature, which limit their synthetic applications.

Believing that the sulfur in a thioamide could be oxidized in a $Ru(bpy)_3^{2+}$ photoredox cycle to form a radical intermediate, we started our investigation of visible-light driven synthesis of benzothiazoles using thioamides **1a** and **1b**. $Ru(bpy)_3Cl_2{\bullet}6H_2O$ was used as the catalyst, and the reaction was placed under a household 14 W fluorescent light. It was found that without base all the reactions afforded **3a** and **3b**. No desired product **2a** or **2b** was observed in various solvents (Table 1, entries 1−6).[11e,13]

Bases were added to promote the formation of a more oxidizable imidothiolate anion. To our delight, with 1,8-diazabicycloundec-7-ene (DBU), benzothiazole **2b** formed in 86% HPLC yield (Table 1, entry 7). Switching the catalyst to $Ru(bpy)_3(PF_6)_2$ afforded a similar result (Table 1, entry 8). 4-Dimethylaminopyridine (DMAP) did not effectively promote the reaction (Table 1, entry 9). Addition of 1,8-bis(dimethylamino)naphthalene (proton sponge) gave **3b** as the only product (Table 1, entry 10). With 2,2,6,6-tetramethylpiperidine (TMP), **2b** was isolated in 21% yield (Table 1, entry 11). The use of 1,5-diazabicyclo(4.3.0)non-5-ene (DBN), a base similar to DBU, afforded **2b** in 81% HPLC yield.

Table 1. Optimization of Reaction Conditions



1a: R = H
1b: R = OMe

2a: R = H
2b: R = OMe

3a: R = H
3b: R = OMe

entry	substrate	catalyst (1 mol %)	solvent	base	product (yield)
1	**1a**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	DMF	–	**3a**
2	**1a**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	CH_3CN	–	**3a**
3	**1a**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	CH_2Cl_2	–	**3a**
4	**1a**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	DMSO	–	**3a**
5	**1b**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	CH_3CN	–	**3b**
6	**1b**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	DMF	–	**3b**
7	**1b**	$Ru(bpy)_3Cl_2{\bullet}6H_2O$	DMF	DBU	**2b** (86%)[a]
8	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	DBU	**2b** (87%)[a]
9	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	DMAP	N.R.
10	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	Proton sponge	**3b**
11	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	TMP	**2b** (21%)[b]
12	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	DBN	**2b** (81%)[a]
13	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	DBU	**2b** (85%)[b,c]
14	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	K_2CO_3	**2b** (71%)[a,c]
15	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	DBU[d]	**2b** (80%)[a,c]
16	**1b**	–	DMF	DBU	N.R.[c]
17	**1b**	$Ru(bpy)_3(PF_6)_2$	DMF	DBU	N.R.[c,e]

[a] HPLC yield. [b] Isolated yield. [c] Under 5% O_2 balloon. [d] 0.5 equiv of DBU was used. [e] Reaction was carried out in the dark.

We then questioned what was the terminal oxidant in this oxidative cyclization reaction, as the reaction was done under a N_2 atmosphere. The net reaction would generate two hydrogen atoms without an oxidant. A reaction was carried out in an apparatus to measure the gas volume change. To our surprise, it was observed that a stoichiometric amount of gas was consumed. Further investigation revealed that dioxygen from the residual air in the apparatus participated in the reaction. Interestingly, the reaction is very sensitive to the level of the dioxygen concentration. The reaction works very well under a low level of dioxygen. Introduction of less than a stoichiometric amount of dioxygen caused a partial reaction with complete consumption of dioxygen. However, when the reaction was carried out under an air atmosphere (~21% oxygen), 74% of the benzothiazole (**2b**) was formed along with some undesired side product **3b**. When 100% oxygen

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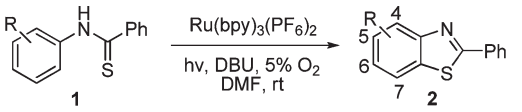
in a balloon was used, the intramolecular cyclization reaction was almost completely stopped. 40% of **3b** was formed along with 60% unreacted starting material **1b**. At the end, a balloon with 5% oxygen was used in the optimized reaction conditions (Table 1, entry 13). The reaction worked with an inorganic base, K_2CO_3, at lower yield (Table 1, enty 14). More importantly, a reaction with 0.5 equiv of DBU afforded 80% of **2b** indicating the base was a catalyst in the reaction as well (Table 1, entry 15). To make sure $Ru(bpy)_3^{2+}$ and light did participate in the reaction, two control reactions, one without $Ru(bpy)_3(PF_6)_2$ (Table 1, entry 16) and one in the dark (Table 1, entry 17), were carried out. No reaction occurred under either condition. The results showed that both light and sensitizer were essential to the reaction.

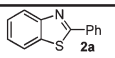
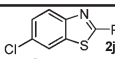
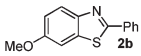
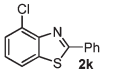
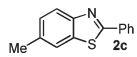
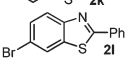
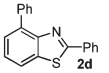
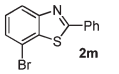
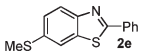
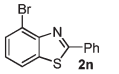
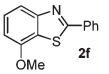
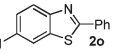
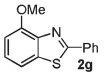
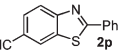
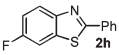
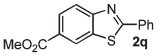
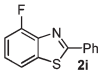
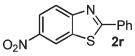
With the standard protocol in hand, we started to investigate the scope and functional group compatibility of the new visible-light photocatalytic reaction. The reaction is very mild and tolerates many functional groups (Table 2). The reaction works very well with electron-donating groups and weak electron-withdrawing groups (Table 2, entries 1−13). For halogen substituted compounds, mixtures of the desired product and dehalogenated benzothiozole (**2a**) were obtained with *o*-Br and *p*-I substitutions (Table 2, entries 14−15). *o*-I substitution afforded 76% of the dehalogenated product (**2a**) as the only isolated product, while other halogen substituted compounds afforded the C−H functionalized product (Table 2, entries 8−13). The trend seemed to be parallel to the C−X bond dissociation energies. Moderate yields were obtained with strong electron-withdrawing substitutions on the aromatic ring (Table 2, entries 16−17). The nitro group completely inhibited the reaction (Table 2, entry 18) probably because the electron transfer occurred on the benzene ring.[14]

The new visible-light photoredox catalytic reaction is probably the mildest oxidative formation of 2-substituted benzothiazoles as the oxidation-sensitive thioether survived the reaction (Table 2, entry 5), which is in contrast with what was reported previously under very similar conditions.[2d] Another important fact is that the *meta* substitued thioanilides afforded major products with the substitution on C-7 (*ortho* to the newly formed C−S bond) (Table 2, entries 6 and 13), which is different from the previously reported C-5 (*para* to the C−S bond) substituted products via ionic intermediates.[11e,l,m] The *ortho*-selective arylation results strongly suggest that the reaction goes through a radical-based pathway.[15]

The scope of the substrate investigation was extended to the substitutions on the 2-aryl group. The results are shown in Table 3. Both eletron-donating and -withdrawing groups are tolerated. Good to moderate yields were obtained.

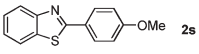
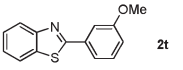
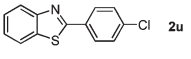
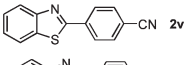
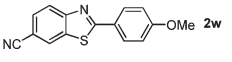
Table 2. Synthesis of 2-Phenylbenzothiazoles[a]



entry	product	yield (%)[b]	entry	product	yield (%)[b]
1	 **2a**	84	10	 **2j**	83
2	 **2b**	85	11	 **2k**	71
3	 **2c**	81	12	 **2l**	78
4	 **2d**	85	13	 **2m**	84[d]
5	 **2e**	89	14	 **2n**	34[e]
6	 **2f**	88[c]	15	 **2o**	10[f]
7	 **2g**	77	16	 **2p**	63
8	 **2h**	91	17	 **2q**	63
9	 **2i**	63	18	 **2r**	N.R.

[a] Reaction conditions: substrate **1** (1 equiv), DBU (1 equiv), $Ru(bpy)_3(PF_6)_2$ (1 mol %), 14 W CFL light, DMF, rt, 5% O_2 balloon, 24 h. [b] Isolated yield. [c] Contained 5% C-5 substituted product. [d] Contained 15% C-5 substituted product. [e] Along with the isolation of 42% dehalogenated product **2a**. [f] Isolated as a mixture of 10% **2o** and 34% dehalogenated product **2a** by ^1H NMR.

Table 3. Substitutions on the 2-Phenyl Group[a]

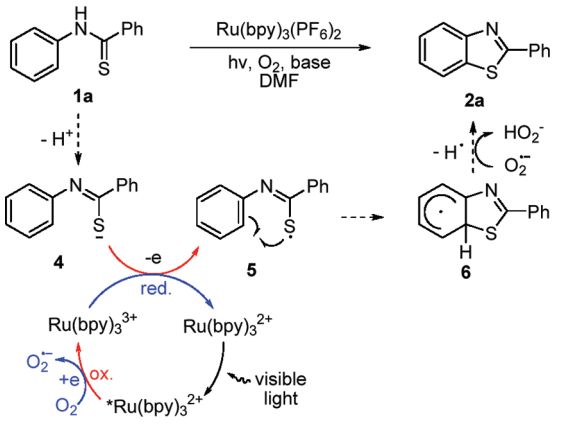
entry	product	yield (%)[b]
1	 **2s**	69
2	 **2t**	86
3	 **2u**	83
4	 **2v**	63
5	 **2w**	85

[a] Same reaction conditions as those in Table 2. [b] Isolated yield.

Based on our observations and literature reports, a plausible mechanism is proposed in Scheme 1. $Ru(bpy)_3^{2+}$ readily accepts a photon to generate the excited $*Ru(bpy)_3^{2+}$. It has been reported that $*Ru(bpy)_3^{2+}$ can be

(14) Poupko, R.; Rosenthal, I. *J. Phys. Chem.* **1973**, *77*, 1722.
(15) (a) Tiecco, M.; Testaferri, L. In *Reactive Intermediates*, Vol. 3; Abramovitch, R. A., Ed.; Plenum Press: New York, 1983; p 61. (b) Conrad, J. C.; Kong, J.; Laforteza, B. N.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2009**, *131*, 11640.

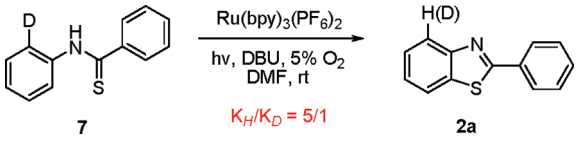
Scheme 1. Proposed Mechanism



oxidized to $Ru(bpy)_3^{3+}$ by molecular oxygen, in which O_2 turned into the $O_2^{\bullet-}$ radical anion after receiving an electron.[16] In some of our experiments, the reaction mixture color turned green at the beginning of the reaction. This is a strong indication of the formation of $Ru(bpy)_3^{3+}$, which is known to be green.[16a] Therefore, we believe that $Ru(bpy)_3^{2+}$ goes through an oxidative catalytic cycle in our system. It is different from the recently reported areobic $Ru(bpy)_3^{2+}$ photoredox reactions.[6k,n,p] On the other hand, thioanilide is deprotonated to form anion **4**. It is then reduced to radical **5** through single eletron transfer (SET) by $Ru(bpy)_3^{3+}$, regenerating $Ru(bpy)_3^{2+}$ to complete the photoredox cycle. The sulfur radical in **5** attacks the benzene ring to form intermediate **6**. Upon giving away a hydrogen to the $O_2^{\bullet-}$ radical anion, radical **6** rearomatizes to provide benzothiazole **2a** and completes the reaction. However, a reductive quenching mechanism, in which $*Ru(bpy)_3^{2+}$ is reduced to $Ru(bpy)_3^{+}$ by anion **4** to form the same radical intermediate **5**, and then molecular oxygen turns $Ru(bpy)_3^{+}$ back to $Ru(bpy)_3^{2+}$ and generates the $O_2^{\bullet-}$ radical anion, could not be ruled out.

To investigate the reaction kinetics, monodeuterated thioanilide **7** was prepared and subjected to the photoredox reaction (Scheme 2). An intramolecular isotope effect (K_H/K_D = 5) was observed suggesting that the C−H bond breaking step was the rate-determining step.

Scheme 2. Intramolecular Kinetic Study



Finally, all the above studies were carried out in a standard laboratory fume hood using household CFL light to mimic visible-light irradiation. To demonstrate the photoredox reaction works under sunlight, a reaction was carried out under sunshine. 2-Phenylbenzothiazole (**2a**) was afforded in 65% yield after 24 h of direct sun light irradiation over 2 days.

In summary, we have developed an aerobic visible-light photoredox synthesis of 2-substituted benzothiazoles via C−H functionalization/C−S bond formation. The methodology expands the scope of substrates for visible-light photoredox chemistry. It does not need any sacrificing of electron donor or acceptor. Moreover, the reaction uses affordable, readily available molecular oxygen as the terminal oxidant. This method is complementary to the existing benzothiozole synthesis with the advantages of high efficiency, unique selectivity, and an environmental-friendly nature. The reaction conditions are very mild and can tolerate many functional groups. Further applications of this method in the construction of other heterocyclic compounds are under investigation.

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Supporting Information Available. Experimental procedures, ^1H and ^{13}C NMR spectra, and IR spectra for all products. This material is available free of charge via the Internet at http://pubs.acs.org.

(16) (a) Das, A.; Joshi, V.; Kotkar, D.; Pathak, V. S.; Swayambunathan, V.; Kamat, P. V.; Ghosh, P. K. *J. Phys. Chem. A* **2001**, *105*, 6945. (b) Zhang, X.; Rodgers, M. A. J. *J. Phys. Chem.* **1995**, *99*, 12797. (c) Kotkar, D.; Joshi, V.; Ghosh, P. K. *Chem. Commun.* **1987**, 4. (d) Ghosh, P. K.; Brunschwig, B. S.; Chou, M.; Creutz, C.; Sutin, N. *J. Am. Chem. Soc.* **1984**, *106*, 4772.