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Thiophenol-Catalyzed Visible-Light Photoredox Decarboxylative Couplings of *N*-(Acetoxy)phthalimides

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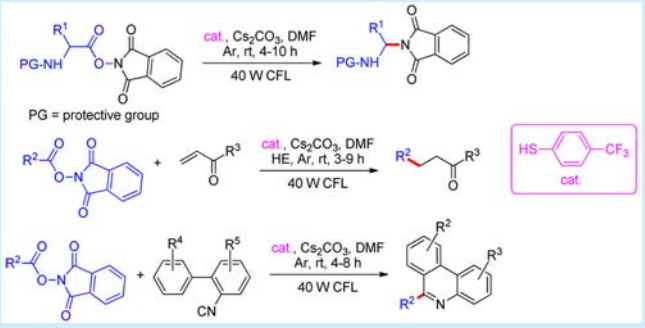
Supporting Information

ABSTRACT: We have developed visible-light photoredox decarboxylative couplings of *N*-(acetoxy)phthalimides without an added photocatalyst in which simple and commercially available thiophenols are used as the effective organocatalysts, and 4-(trifluoromethyl)thiophenol shows optimal catalytic activity. Three representative decarboxylative examples were chosen including one amination and two C−C bond couplings to confirm efficacy of the visible-light photoredox reactions, and the results exhibited that they performed very well at room temperature. The interesting discovery should provide a novel and environmentally friendly strategy for visible-light photoredox transformation of organic molecules.



The acquirement of energy from visible light is a highly economical and environmentally friendly strategy of promoting chemical transformations. A century ago, Ciamician had already realized organic reactions irradiated with visible light.[1] However, the fact that most common organic molecules can not absorb light of visible wavelengths seriously limits the development of photochemical processes. Fortunately, various sensitizers including photocatalysts can absorb photons in the visible range to form excited species capable of activating organic substrates, and the efficiency of reactions usually depends on the photocatalyst systems.[2] In 2008 and 2009, the seminal works by MacMillan,[3] Yoon,[4] and Stephenson[5] demonstrated the tremendous potential of photoredox catalysis in organic synthesis. Since then, the visible-light photoredox catalysis has become a powerful methodology with development of diverse and efficient photocatalysts, and various novel and useful reactions were disclosed under very mild conditions.[2−5] The previous photocatalysts mainly include both transition-metal complexes[6] such as ruthenium or iridium polypyridyl complexes and organic dyes.[7] Aside from classical visible-light-mediated photoredox catalysis, some novel transformations have recently been reported with dual catalytic systems[8] merging photoredox catalysis with other catalyses including organocatalysis[9] and transition-metal catalysis,[10] but the reactions do not proceed using either catalyst in isolation. However, it is a great challenge to develop visible-light photoredox reactions without an added photocatalyst thus far. On the other hand, carboxylic acids are abundant and inexpensive biomass-derived platform molecules, and their conversion into high-value products such as medicinally related molecules and biofuels represents an important goal.[11] Recently, some efficient decarboxylative couplings have been developed under photoredox catalysis.[12] We have also reported some interesting visible-light photoredox organic reactions.[13] More importantly, a visible-light photoredox decarboxylative arylthiation of *N*-(acetoxy)phthalimides has been well established in the absence of an added photocatalyst.[14] As our continuing study on the visible-light photoredox catalysis, we report thiophenol-catalyzed visible-light photoredox decarboxylative couplings of *N*-(acetoxy)phthalimides at rt, in which three representative decarboxylative examples including an intramolecular amination and two intermolecular C−C bond couplings are described without an added photocatalyst.

Initially, intramolecular visible-light photoredox decarboxylative amination of Boc-Val-OPht (Pht = phthalimide) (**1d**) leading to **2d** was used as the model to optimize conditions including catalysts, bases, and solvents (Table S1, Supporting Information (SI)). The results showed that the optimal photoredox conditions are as follows: 10 mol % 4-(trifluoromethyl)thiophenol (TFTP) (**G**) as the organocatalyst, Cs_2CO_3 as the base, and DMF as the solvent under an Ar atmosphere and irradiation of visible light with 40 W compact fluorescent light (CFL). Subsequently, we investigated the substrate scope on the decarboxylative amination of various *N*-protected amino acid active esters (**1**). As shown in Table 1, active esters of eight neutral amino acids (Boc-AA-OPht, AA = amino acid) including natural and unnatural amino acids provided satisfactory yields (see **2a−h**). *N,O*-Protected amino acid active esters (Boc-Ser(O^{t}Bu)-OPht and Boc-Thr(O^{t}Bu)-OPht) with hydroxyl on the side chains were tested, and the corresponding products **2i** and **2j** were obtained in 83% and 95% yields, respectively. Boc-Met-OPht afforded target product **2k** in 71% yield. Boc-

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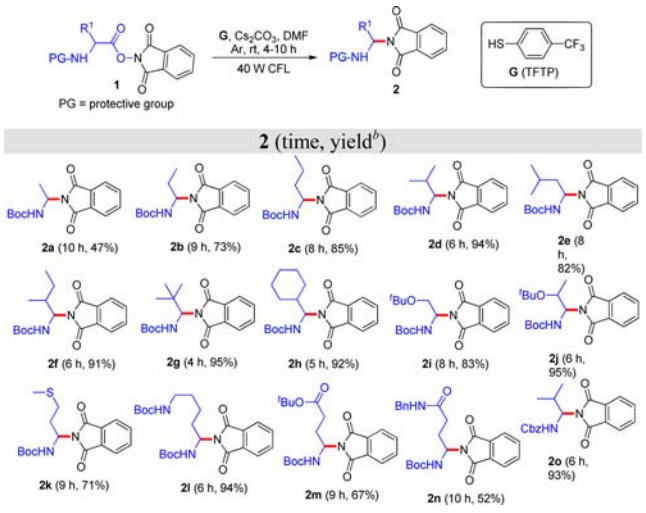
Table 1. Intramolecular Visible-Light Photoredox Decarboxylative Amination of *N*-Protected-AA-OPht (1) under Catalysis of TFTP (G)[a]

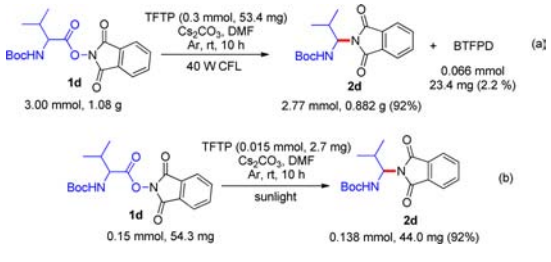


[a]Reaction conditions: Ar atmosphere and irradiation of visible light, *N*-protected AA-OPht (**1**) (0.15 mmol), TFTP (**G**) (15 μmol), Cs_2CO_3 (0.075 mmol), DMF (1.5 mL), temperature (rt, ~25 °C), time (4−10 h) in a sealed Schlenk tube. [b]Isolated yield. CFL = compact fluorescent light. Boc = *tert*-butyloxycarbonyl. ^{t}Bu = *tert*-butyl. Cbz = benzyloxycarbonyl.

Lys(Boc)-OPht displayed high reactivity (**2l**). Boc-glutamic acid and glutamine active esters afforded **2m** and **2n** in 67% and 52% yields, respectively. Another *N*-protective group, benzyloxycarbonyl (Cbz), was attempted, and Cbz-Val-OPht showed similar reactivity to Boc-Val-OPht (**2d** and **2o**). The decarboxylicative amination exhibited tolerance of some functional groups including amides, ethers (**2i** and **2j**), thioether (**2k**), and ester (**2m**). In previous research, arylthiolation of *N*-(acetoxy)phthalimides without NH at the β-position of ester was found.[14] Here, we attempted the reaction of Boc-Ala-OPht (**1a**) with 4-(trifluoromethyl)thiophenol (TFTP) (1.2 equiv) under standard conditions, but no arylthiolation product was observed. One key reason is that the present substrate (**1a**) contains β-NH, and its arylthiolation product can further react with phthalimide to form **2a**.

As shown in Scheme 1a, intramolecular decarboxylicative coupling of **1d** (1.08 g) on gram scale was performed under the standard conditions. Interestingly, the reaction provided the target product (**2d**) in a high yield (0.882 g, 92%) with a small amount (2.2%) of 1,2-bis(4-(trifluoromethyl)phenyl)disulfane (BTFPD) as the byproduct appearing from the dimerization of TFTP.[15] Therefore, the present method is very effective for

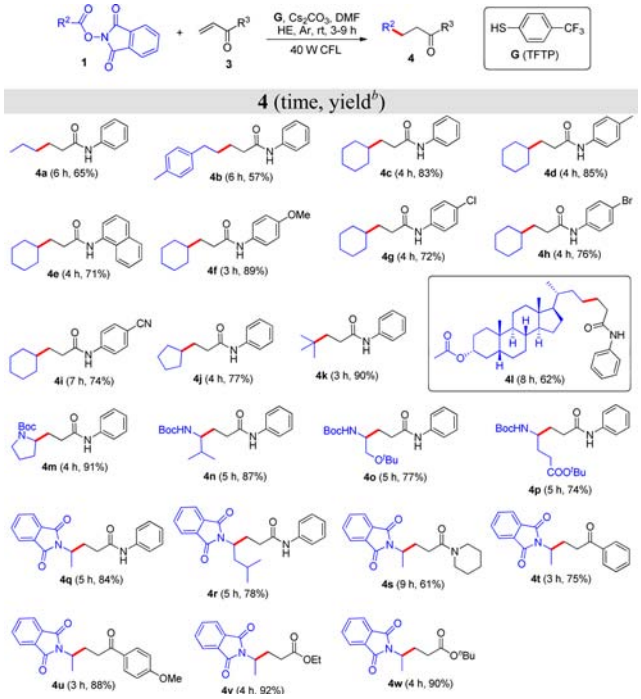
Scheme 1. (a) Gram Scale Preparation of 2d under the Standard Conditions; (b) Decarboxylation of 1d Irradiated with Sunlight



visible-light photoredox decarboxylicative couplings. Sunlight is a nearly inexhaustible source of clean energy, and its use in sustainable organic synthesis has gained considerable attention. We attempted decarboxylicative amination of **1d** irradiated with sunlight, and the result showed that the reactivity was similar to that irradiated with visible light (Scheme 1b).

Next, photoredox decarboxylative coupling of carboxylic acid active esters (R^2COOPht) (**1**) with various olefins (**3**) including α,β-unsaturated amides, ketones, and esters was investigated in the presence of TFTP (**G**) as the organocatalyst (Table 2). For active esters of common organic carboxylic acids,

Table 2. Visible-Light Photoredox Decarboxylative Coupling of Active Esters R^2CO-OPht (1) with Alkenes (3) under Catalysis of TFTP (G)[a]



[a]Reaction conditions: Ar atmosphere and irradiation of visible light, R^2CO−OPht (**1**) (0.225 mmol), alkene (**3**) (0.15 mmol), TFTP (**G**) (15 μmol), Cs_2CO_3 (0.075 mmol), Hantzsch ester (HE) (0.225 mmol), DMF (1.5 mL), temperature (rt, ~ 25 °C), time (3−9 h) in a sealed Schlenk tube. [b]Isolated yield. Boc = *tert*-butyloxycarbonyl. ^{t}Bu = *tert*-butyl. ^{n}Bu = *normal*-butyl.

secondary and tertiary carboxylic acid derivatives showed higher reactivity than primary ones (compare **4a**−**k**). Lithocholic acid derivatives show diverse pharmaceutical activity.[16] However, modification of lithocholic acid through C−C bond formation via a decarboxylative process is difficult by using a classical synthetic method. Herein, photoredox decarboxylative coupling of lithocholic acid active ester with *N*-phenylacrylamide was performed well, and the corresponding product (**4l**) was obtained in 62% yield. For α,β-unsaturated amides with aryl, the substrates containing electron-donating groups on the aryl rings afforded higher yields than those containing electron-withdrawing groups (**4c**−**i**). Various *N*-protected amino acid active esters were also used as the radical sources (**4m**−**r**), and different acceptors, α,β-unsaturated amides (**4c**−**i** and **4s**), ketones (**4t** and **4u**), and esters (see **4v** and **4w**), were suitable.

Furthermore, we tested decarboxylative coupling of carboxylic acid active esters (**1**) with substituted 2-isocyanobiphenyls

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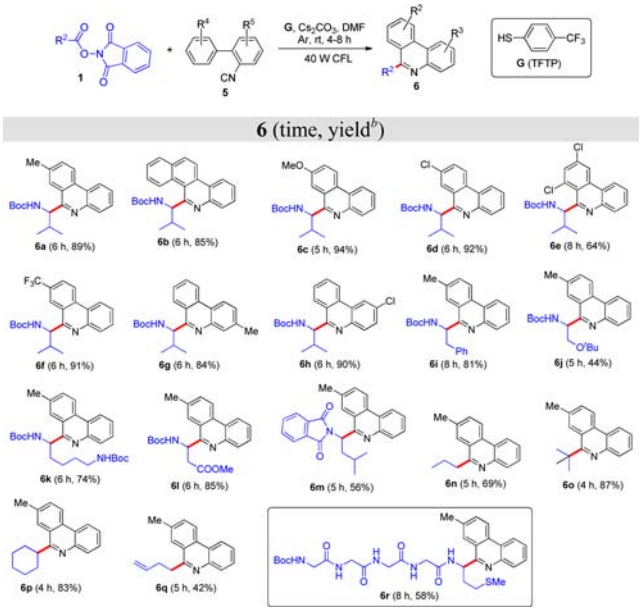
(5) in the presence of organocatalyst TFTP (G). As shown in Table 3, the reactivity of eight different substituted 2-

Table 3. Visible-Light Photoredox Decarboxylative Coupling of Active Esters R^2CO-OPht (1) with Substituted 2-Isocyanobiphenyls (5) under Catalysis of TFTP (G)[a]



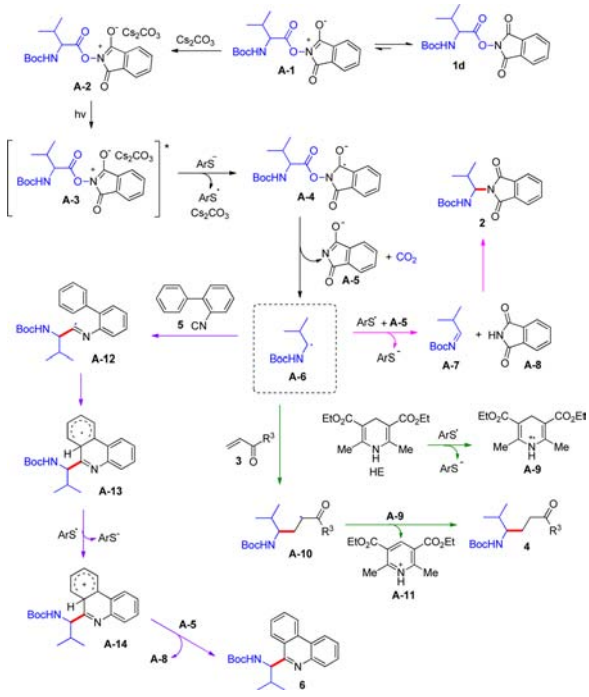
[a]Reaction conditions: Ar atmosphere and irradiation of visible light, R^2CO−OPht (1) (0.375 mmol), substituted 2-isocyanobiphenyl (5) (0.15 mmol), TFTP (G) (15 μmol), Cs_2CO_3 (0.075 mmol), DMF (1.5 mL), temperature (rt, ~25 °C), time (4−8 h) in a sealed Schlenk tube. [b]Isolated yield. Boc = *tert*-butyloxycarbonyl. [t]Bu = *tert*-butyl.

isocyanobiphenyls (5) was first investigated using Boc-Val-Opht (1d) as the partner, and the reactions provided the corresponding phenanthridines in 64−94% yields (6a−h). The tested carboxylic acid active esters include various derivatives of *N*-protected amino acids (6a−m) and common carboxylic acids (see 6n−q). An active ester containing alkene provided a lower yield (6q), and other substrates displayed higher reactivity (6a−p). An active ester of pentapeptide Boc-Gly-Gly-Gly-Gly-Met-OPht was also used in the photoredox reaction. Interestingly, the conjugate (6r) containing peptide and phenanthridine was obtained in 58% yield. The visible-light photoredox decarboxylative coupling exhibited tolerance of some functional groups including amides, ethers (6c and 6j), C−Cl bond (6d, 6e, and 6h), CF_3 (6f), ester (6l), and thioether (6r). Phenanthridines widely occur in a variety of natural alkaloids[17] and show diverse biological and pharmaceutical activities.[18] The present method affords an efficient and practical protocol for synthesis of diverse phenanthridines.

In our previous research, we explored the mechanism on the visible-light photoredox decarboxylative arylthiation of *N*-(acetoxy)phthalimides in the presence of Cs_2CO_3.[14] Similarly, to determine the mechanism in the present decarboxylative couplings, we surveyed UV−visible absorption spectra of cyclohexanecarboxylic acid active ester (AE), Hantzsch ester (HE), 4-(trifluoromethyl)thiophenol (TFTP), and 1,2-bis(4-(trifluoromethyl)phenyl)disulfane (BTFPD) in the absence or presence of Cs_2CO_3 and performed the corresponding Stern−Volmer fluorescence quenching and radical-trapping experiments (Figures S2−S6 and Scheme S1, SI). In addition, some control experiments were performed (Scheme 2S, SI).

Therefore, a plausible mechanism is proposed in Scheme 2 according to the results above and our previuos investigations.[14]

Scheme 2. Possible Mechanism for the Three Visible-Light Photoredox Decarboxylative Couplings



Here, Boc-Val-OPht (1d) was chosen as the example to explain the mechanism. Treatment of arylthiol with a base (Cs_2CO_3) affords ArSCs and $CsHCO_3$. There are two resonance structures of 1d and A-1 in the solution (Note: the charge transfer occurs from N to O in *N*-(acetoxy)phthalimide to form A-1 with assistance of Cs_2CO_3, but no evidence was found for metal to ligand charge transfer between Cs^+ and the *N*-acetoxyphthalimide to date),[19] and complexation of A-1 with Cs_2CO_3 affords A-2. Irradiation of A-2 as a photosensitizer with visible light provides the excited-state A-3,[14] and an electron in the ArS^- anion transfers to the phthalimide group of A-3 to form two radicals $ArS^•$ and A-4 (Note: the control experiment in Scheme S2a(B) showed that the reaction provided a low yield without thiophenol, so the procedure of a single electron transfer from the ArS^- anion to phthalimide in A-3 to form A-4 is a key step). Decarboxylation of A-4 provides A-5 and radical A-6 freeing CO_2, and reaction of A-5, radicals A-6 and $ArS^•$ yields imine A-7 and phthalimide A-8 regenerating catalyst anion ArS^-. Finally, nucleophilic addition of A-7 to A-8 affords the target product (2) (demonstrated by Scheme S2b). For the formation of product 4, reaction of $ArS^•$ with Hantzsch ester (HE) donates A-9 regenerating catalyst anion ArS^-. Meanwhile, Michael addition of A-6 to α,β-unsaturated alkene (3) leads to radical A-10, and treatment of A-10 with A-9 affords the target product (4) leaving a pyridine derivative A-11. For the formation of product 6, addition of A-6 to substituted 2-isocyanobiphenyl (5) forms radical A-12, and intramolecular cyclization of A-12 gives A-13. Treatment of radical $ArS^•$ with A-13 produces cation A-14 regenerating catalyst anion ArS^-. Finally, reaction of A-14 with A-5 donates the target product (6) freeing phthalimide (A-8).

In summary, we have developed thiophenol-catalyzed visible-light photoredox decarboxylative couplings of *N*-(acetoxy)-

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phthalimides in which simple and commercially available thiophenols are used as the effective organocatalysts, and 4-(trifluoromethyl)thiophenol shows optimal catalytic activity. Three representative decarboxylative examples including one intramolecular amination and two intermolecular C−C bond couplings performed well at room temperature with excellent tolerance of functional groups.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b03300.

Reaction optimization, synthetic procedures, characterization data, and ^{1}H, ^{13}C NMR spectra (PDF)

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Notes

The authors declare no competing financial interest.

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