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Photoinduced 1,2-dicarbofunctionalization of alkenes with organotrifluoroborate nucleophiles via radical/polar crossover†

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Alkene 1,2-dicarbofunctionalizations are highly sought-after transformations as they enable a rapid increase of molecular complexity in one synthetic step. Traditionally, these conjunctive couplings proceed through the intermediacy of alkylmetal species susceptible to deleterious pathways including β -hydride elimination and protodemetalation. Herein, an intermolecular 1,2-dicarbofunctionalization using alkyl *N*-(acyloxy) phthalimide redox-active esters as radical progenitors and organotrifluoroborates as carbon-centered nucleophiles is reported. This redox-neutral, multicomponent reaction is postulated to proceed through photochemical radical/polar crossover to afford a key carbocation species that undergoes subsequent trapping with organoboron nucleophiles to accomplish the carboallylation, carboalkenylation, carboalkynylation, and carboarylation of alkenes with regio- and chemoselective control. The mechanistic intricacies of this difunctionalization were elucidated through Stern–Volmer quenching studies, photochemical quantum yield measurements, and trapping experiments of radical and ionic intermediates.

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Introduction

The vicinal difunctionalization of alkenes has emerged as an enabling technology in organic synthesis to access diverse structural skeletons from readily available building blocks.^{1,2} In particular, intermolecular 1,2-dicarbofunctionalization (DCF) reactions represent a powerful method to install two carbon subunits across an unsaturated system in one step with an accompanying increase in molecular complexity.³ Traditionally, DCF efforts have been largely limited to transition-metal-mediated processes, with⁴ or without² the aid of a photocatalyst (Fig. 1A). Palladium,⁴ nickel,⁵ copper,⁶ and other metals⁷ have all been utilized to afford 1,2-substituted products. Although these DCF advancements represented milestones in their own right, the necessity of a metal catalyst can lead to numerous deleterious pathways, such as β -hydride elimination, homocoupling, isomerization, or proto-demetalation.¹

Radical/polar crossover (RPC) has recently been enlisted to assemble challenging structural motifs under mild reaction conditions (Fig. 1B).^{8,9} Under RPC paradigms, odd-electron

intermediates are generated through single-electron transfer (SET) and then engage in further transformations. The resulting radical species can subsequently undergo single-electron



Fig. 1 Strategies for olefin 1,2-difunctionalization. (A) Transition-metal-catalyzed difunctionalizations. (B) Overview of photochemical radical/polar crossover. (C) Developed vicinal dicarbofunctionalization using organotrifluoroborate nucleophiles.

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reduction^{10,11} or oxidation^{12,13} to enter the two-electron reaction domain for further diversification. Although photo- and electrochemical RPC-mediated intermolecular 1,2-DCFs that proceed with *in situ* formed carbanions have been reported, these efforts are largely limited to carbonyl alkylation^{8d,10} or carbocarboxylation.^{8d,11}

Methods to incorporate carbon-centered nucleophiles typically rely on the use of electrophilic radicals including perfluoroalkyl feedstocks as well as strongly nucleophilic, electron-rich systems in conjunction with Lewis acids or peroxides as additives.¹³ In this vein, the development of a general RPC route employing two carbon-based coupling partners for DCF remains elusive. Importantly, the implementation of a unified approach toward the carboallylation, carboalkenylation, carboalkynylation, and carboarylation of alkenes presents a formidable, yet highly powerful scenario to rapidly assemble molecular complexity from commodity chemicals.

Discussion

As part of a program centered on the development of catalytic tools for alkene functionalization, a photochemical intermolecular 1,2-dicarbonylation of olefins with alkyl *N*-(acyloxy)phthalimide redox-active esters (RAEs) as radical progenitors has been developed (Fig. 1C). RAEs are bench-stable solids readily accessible from carboxylic acids with an

established propensity to undergo decarboxylative fragmentation upon single-electron reduction.¹⁴ We envisioned that radical addition to vinyl arenes would generate key radical and carbocation intermediates that could be harnessed in sequential bond formation through RPC. With these goals in mind, the interrogation of potassium organotrifluoroborates as nucleophiles to construct C–C linkages under photoredox catalysis was considered, as they have been shown to engage in addition reactions under Brønsted and Lewis acid catalysis.¹⁵ Furthermore, alkynyltrifluoroborates have been enlisted as alternative nucleophilic partners in Suzuki–Miyaura cross-couplings, with the Bsp³–Csp bond being adequately polarized to engender a direct transmetalation event.¹⁶ From a synthetic standpoint and through the same RPC reactivity mode, the proposed strategy would facilitate carboallylation, carboalkenylation, carboalkynylation, and carboarylation from commodity chemicals with regio- and chemoselective control. Notably, this net-neutral photochemical RPC process is driven by SET events that occur predominantly between the photocatalyst and substrates/intermediates, bypassing the requirement for stoichiometric external reductants or oxidants.

To examine the feasibility of the proposed reaction design, 4-acetoxystyrene **1a**, aliphatic RAE **2a**, and potassium (2-phenylethynyl)trifluoroborate **3a** were employed (Table 1). A more detailed optimization of the equivalences of reaction components, catalyst loading, solvent, and reaction concentration is

Table 1 Optimization of reaction conditions^a

Photocatalysts

- PC1: R¹ = R² = H; Ir(ppy)₃
- PC2: R¹ = R² = F; Ir(dFppy)₃
- PC3: R¹ = H, R² = Me; Ir(ρ-Me-ppy)₃
- PC4: R¹ = H, R² = CF₃; Ir(ρ-CF₃-ppy)₃
- PC5: R¹ = H, R² = F; Ir(ρ-F-ppy)₃
- PC6: R³ = R⁴ = R⁵ = R⁶ = H; [Ir(bpy)(ppy)₂](PF₆)
- PC7: R³ = *t*-Bu, R⁴ = R⁵ = R⁶ = H; [Ir(dtbbpy)(ppy)₂](PF₆)
- PC8: R³ = *t*-Bu, R⁴ = R⁵ = Me, R⁶ = H; [Ir(dtbbpy)(dMeppy)₂](PF₆)
- PC9: R³ = R⁵ = R⁶ = *t*-Bu, R⁴ = H; [Ir(dtbbpy)(dtbbpy)₂](PF₆)
- PC10: [Ir(dF(CF₃)₂ppy)₂(dtbbpy)](PF₆)
- PC11: 4CzIPN
- PC12: [Fe(bpy)₃](BF₄)₂
- PC13: naphthyl phenothiazine

Entry	Deviation from std. conditions	% Yield ^b	Entry	Deviation from std. conditions	% Yield ^b
1	None	89	10	PC10 instead PC1	nr
2	PC2 instead PC1	81	11	PC11 instead PC1	Trace
3	PC3 instead PC1	67	12	PC12 instead PC1	nr
4	PC4 instead PC1	91	13	PC13 instead PC1	nr
5	PC5 instead PC1	89	14	20 mol% Cu(OTf) ₂	32
6	PC6 instead PC1	52	15	20 mol% Yb(OTf) ₃	36
7	PC7 instead PC1	58	16	No PC	nr
8	PC8 instead PC1	68	17	No light	nr
9	PC9 instead PC1	81			

^a Reaction conditions: styrene **1a** (0.1 or 0.2 mmol), RAE **2a** (1.5 equiv.), potassium organotrifluoroborate salt **3a** (2 equiv.), Ir(ppy)₃ (3 mol%) in MeCN (0.1 M), 24 h irradiation with blue LEDs (λ_{\max} = 456 nm). ^b Yields were determined by ¹H NMR analysis using trimethoxybenzene as internal standard. Abbreviations: std, standard; nr, no reaction.



provided in the ESI.† Here, the most relevant findings are highlighted, namely the critical performance of photoredox catalysts on the DCF outcome.

Notably, the crux of this net-neutral RPC approach is a series of well-orchestrated, single-electron oxidation and reduction steps. To achieve chemo- and regio-selectivity, the following criteria must be considered: (i) the aliphatic RAE should be more susceptible to reduction than the alkene or the resulting benzylic radical formed upon addition to the olefin. (ii) The alkyl radical should react with alkene **1** at a rate faster than its single-electron oxidation to a carbocation intermediate or radical dimerization. (iii) The rate of benzylic radical oxidation must be competitive with its addition to another equivalent of the styrene. (iv) The rate of single-electron oxidation of the benzylic radical must be faster than that of the radical intermediate generated from RAE reduction. (v) The rate of nucleophilic addition of the potassium organotrifluoroborate to the benzylic carbocation should take place preferentially over single-electron oxidation of the organoboron reagent under photoredox conditions. (vi) This rate must also be competitive with the nucleophilic addition of phthalimide anions generated upon decarboxylative fragmentation of the RAE. In this vein, the choice of photocatalyst significantly impacts product distributions. Given the propensity of RAEs to undergo SET ($E_{1/2}^{\text{red}} = -1.26 \text{ V vs. SCE}$ for 1-methylcyclohexyl-*N*-hydroxyphthalimide-ester¹⁷), a palette of catalysts in acetonitrile (MeCN) was surveyed (entries 1–13). Reducing iridium-based (Ir) photocatalysts in combination with 2-phenylpyridine (ppy) derived-ligands (entries 1–9) exhibited optimal reactivity, affording **4a** in excellent yield. Importantly, in the absence of a highly oxidizing photocatalyst, the corresponding organotrifluoroborates would not undergo SET.¹⁸ As expected, weaker reductants, **PC10** ($\text{Ir}^{\text{IV}}/\text{Ir}^{\text{III}} E_{1/2} = -1.00 \text{ V vs. SCE}^{19}$) and organic dye **PC11** ($\text{PC}^{\cdot+}/\text{PC}^* E_{1/2} = -1.12 \text{ V vs. SCE}^{19}$), showed little (entry 11) to no conversion (entry 10). Notably, iron-based catalyst **PC12** ($\text{Fe}^{\text{III}}/\text{Fe}^{\text{II}} E_{1/2} = -1.65 \text{ V vs. SCE}^{19}$) and organic sensitizer **PC13** ($\text{PC}^{\cdot+}/\text{PC}^* E_{1/2} = -2.1 \text{ V vs. SCE}^{19}$) resulted in full recovery of the styrene derivative (entries 12–13), presumably because they possess a short excited-state lifetime (for **PC13**, $\tau = \sim 0.8\text{--}2.3 \text{ ns}$ (ref. 19)). Inspired by precedents on the activation of RAEs with Lewis acids,²⁰ the influence of these additives on the outcome of the three-component photochemical paradigm was studied. Surprisingly, the addition of $\text{Cu}(\text{OTf})_2$ or $\text{Yb}(\text{OTf})_3$ led to a decrease in yield (entries 14–15). Control experiments omitting light as well as photocatalyst validated the necessity of all reaction components to facilitate sequential bond formation (entries 16–17).

With suitable conditions established, the scope of RAEs with nucleophile **3a** was evaluated (Scheme 1). In general, the reaction is amenable to an array of unactivated secondary and tertiary radical architectures. The method further benefits from broad substrate tolerance, facilitating the incorporation of a strained cyclobutane subunit (**4b**), a Boc-protected amine (**4d**), a bridged bicycle (**4e**), acyclic moieties, as well as biologically relevant scaffolds including lipid-lowering agent gemfibrozil (**4h**). In addition, efficient product formation occurs in the presence of an internal olefin (**4c**), showcasing the

chemoselectivity of this protocol toward styrenyl-type systems. Notably, RAE bearing a chloride handle (**4g**, **4k**, **4y**, **4ah**, **4ai**) can be introduced without compromising yields, delivering linchpins that can drive molecular complexity through subsequent transition metal-mediated functionalization.

Next, the reactivity of various potassium organotrifluoroborates using 4-acetoxystyrene **1a** was evaluated (Scheme 1). Carboallylation proved feasible, affording the difunctionalized product (**4j**) in good yield, while simultaneously incorporating an olefinic moiety that can engage in diverse downstream alkene transformations. Although progress has been made in conjunctive cross-couplings employing transition-metal catalysts with alkynyl, alkenyl, alkyl, and aryl electrophiles, the use of allyl counterparts remains scarce.^{21,22} In addition to β -hydride elimination associated with alkylmetal species, these processes are further complicated by the generation of undesired two-component allylation products. Importantly, the allyl handle might be susceptible to additional insertion events resulting in oligomerization.^{21,22} In this vein, the utility of the developed three-component allylation is partially driven by its ability to deliver two $\text{C}(\text{sp}^3)\text{--}\text{C}(\text{sp}^3)$ linkages selectively from readily available building blocks. Similarly, potassium aryloxytrifluoroborates bearing electron-donating (*para*-methoxy, **4k**) or electron-neutral (naphthyl, **4l**) substituents serve as effective nucleophiles. The phenyl moiety was successfully replaced by primary short- (**4m**) and long-chain (**4o**) alkyl groups as well as more sterically hindered carbocycles (**4n**). The scope was further extended to alkenyltrifluoroborates (**4p–4s**), with aryl-substituted derivatives performing slightly better under the reaction conditions. Notably, both the (*E*-) and (*Z*-) isomers of 1-propenyltrifluoroborate resulted in product formation with retention of stereochemistry about the olefin (**4p**, **4q**).

Remarkably, aryltrifluoroborates function as competent nucleophiles, facilitating intermolecular 1,2-alkylarylation (Scheme 1). Substitution at the *para*- and *meta*-positions of the aryl scaffolds was explored, whereby efficient photocoupling took place. Specifically, alkoxy derivatives, a methyl thioether, and a Boc-protected amine were successfully harnessed to afford difunctionalized synthetic frameworks (**4t–4aa**). The amenability of aryltrifluoroborates provides a facile, unique approach toward the synthesis of 1,1-diaryl compounds of significance in drug discovery efforts.²³ Furthermore, medicinally relevant heterocycles such as furan (**4ab**, **4ad**) and thiophene (**4ac**) moieties exhibited good reactivity. Notably, this photoredox-mediated RPC proceeds exceptionally well with electron-rich aryl systems that suffer from lower coupling efficiency in certain transition-metal-catalyzed cross-couplings. The mild reaction conditions (room temperature, additive-free, and near-neutral pH) serve to suppress side reactivity stemming from an otherwise competitive hydrodeboration of the trifluoroborate starting material.

Finally, the scope of olefins was investigated (Scheme 1). In general, styrenes bearing no substitution, electron-donating, and electron-withdrawing groups at the *ortho*-, *meta*-, and *para*-positions exhibited comparable reactivity (**4ae–4ai**). Of note, aryl bromide **4ag** proved to be a suitable substrate with





Scheme 1 Evaluation of substrate scope. Reaction conditions: styrene **1** (0.3 mmol), RAE **2** (0.45 mmol, 1.5 equiv.), potassium organotrifluoroborate salt **3** (0.6 mmol, 2 equiv.), Ir(ppy)₃ (3 mol%) in MeCN (3.0 mL, 0.1 M), 24 h irradiation with blue LEDs ($\lambda_{\max} = 456$ nm). ^a[Ir(dtbbpy)(ppy)₂]₂PF₆ (3 mol%) was used instead Ir(ppy)₃. ^bGram scale reaction: styrene **1** (6.2 mmol).

complete retention of the halide handle, providing a clear advantage in terms of scope over traditional transition-metal-catalyzed DCFs. A broad array of functional groups is tolerated, including esters, ketones, Boc-protected amines, and carbamates (**4aj–4ar**). Additionally, a substrate derived from estrone was examined, generating steroid derivative **4an** in excellent yield. Heterocyclic compounds including pyridine, benzofuran, benzothiophene, and indazole systems were readily incorporated under the developed conditions (**4ao–4ar**). In particular, these Lewis basic moieties are traditionally challenging structures in cross-couplings because of their ability to bind and poison the catalyst.

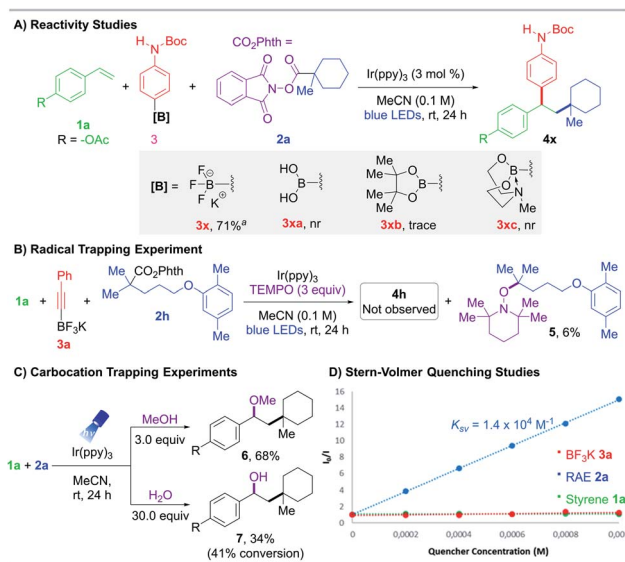
To confirm this RPC protocol was unique to potassium organotrifluoroborates, boronic acid **3xa**, pinacol boronate **3xb**, and MIDA boronate **3xc** were tested as partner nucleophiles but proved ineffectual (Scheme 2A). These results are in accordance with the *N*-parameters reported by Mayr,²⁴ a solvent-dependent nucleophilicity scale, which identified potassium

organotrifluoroborates as one of the most reactive nucleophilic organoboron sources.

To investigate the reaction mechanism, radical and carbocation trapping studies were performed under standard conditions (Scheme 2). Addition of TEMPO (2,2,6,6-tetramethyl-1-piperidinyloxy) inhibited product generation. Specifically, recovery of 4-acetoxystyrene **1a** was observed, and the corresponding TEMPO adduct **5** was isolated and confirmed *via* NMR and HRMS analysis (Scheme 2B). To probe the intermediacy of carbocation species, nucleophilic trapping experiments were conducted using *O*-centered nucleophiles with slight modifications in the loading of these reagents (3.0 equiv. of MeOH or 30.0 equiv. of H₂O). The corresponding ether **6** and alcohol **7** were successfully isolated and characterized, providing further credence to the existence of an ionic pathway (Scheme 2C).

Stern–Volmer luminescence studies of individual reaction components established that the excited state photocatalyst was quenched most effectively by the aliphatic RAE with an observed

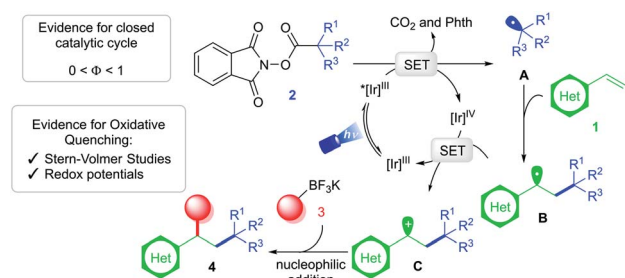




Scheme 2 (A) Reactivity studies of organoboron compounds. (B) Radical trapping experiments. (C) Carbocation trapping experiments. (D) Stern–Volmer quenching. Reaction conditions: styrene **1** (0.2 mmol), RAE **2** (0.3 mmol, 1.5 equiv.), potassium organotrifluoroborate salt **3** (0.4 mmol, 2 equiv.), Ir(ppy)₃ (3 mol%) in MeCN (2.0 mL, 0.1 M), 24 h irradiation with blue LEDs ($\lambda_{\text{max}} = 456 \text{ nm}$). ^aYield was determined by ¹H NMR analysis using trimethoxybenzene as internal standard. Abbreviations: nr, no reaction.

constant K_{SV} of $1.4 \times 10^4 \text{ M}^{-1}$ (Scheme 2D, see the ESI[†]). Furthermore, the photochemical quantum yield Φ of this reaction is 0.26, indicating that a radical chain mechanism is unlikely or inefficient (see the ESI[†]).²⁵

Based on these findings, a mechanistic scenario is postulated (Scheme 3) whereby excitation of Ir(ppy)₃ under blue light irradiation generates a potent excited state $^*[\text{Ir}^{\text{III}}]$ complex ($E_{1/2}[\text{Ir}^{\text{IV}}/\text{Ir}^{\text{III}}] = -1.88 \text{ V vs. SCE}^{19}$). Single-electron transfer (SET) to RAE **2** ($E_{1/2}^{\text{red}} = -1.26 \text{ V vs. SCE}$ for 1-methylcyclohexyl-*N*-hydroxyphthalimide ester¹⁷) induces formation of C(sp³)-hybridized radical **A** followed by extrusion of carbon dioxide. Subsequent addition of this reactive intermediate to vinyl arene **1** furnishes a relatively stabilized 2° benzylic radical **B** ($E_{1/2}^{\text{ox}} = 0.37 \text{ V vs. SCE}^{26}$). Single-electron oxidation of this species by $[\text{Ir}^{\text{IV}}]$ ($E_{1/2}[\text{Ir}^{\text{IV}}/\text{Ir}^{\text{III}}] = 0.77 \text{ V vs. SCE}^{19}$) yields the corresponding carbocation **C**, restoring the



Scheme 3 Proposed mechanism of photoinduced olefin dicarbofunctionalization via RPC.

ground-state photocatalyst. At this critical juncture, ionic intermediate **C** is intercepted by the organotrifluoroborate nucleophile **3** to furnish the desired 1,2-dicarbofunctionalized product **4**.

Conclusions

In summary, a unified protocol to achieve the carboallylation, carboalkenylation, carboalkynylation, and carboarylation of olefins with regio- and chemoselective control has been developed. Through an oxidative quenching pathway, the photoreduction of aliphatic RAEs has been enlisted to generate reactive alkyl radical intermediates that react with alkene feedstocks in a regulated fashion. The resulting C-centered radical undergoes single-electron oxidation to afford a key carbocation intermediate that is intercepted by organotrifluoroborate nucleophiles to facilitate sequential C–C bond formation under mild reaction conditions. Mechanistic studies, including Stern–Volmer quenching studies, photochemical quantum yield measurements, and trapping experiments of radical and ionic intermediates, emphasize that a RPC-mediated mechanism is likely operational. Most importantly, this report provides a general blueprint toward 1,2-dicarbofunctionalizations in the absence of organometal species.

Author contributions

The project was conceived by Shorouk O. Badir. Dr María Jesús Cabrera-Afonso and Shorouk O. Badir performed Stern–Volmer quenching studies. Dr Mirna El Khatib conducted quantum yield experiments. Dr María Jesús Cabrera-Afonso and Anasheh Sookezian contributed equally. Dr María Jesús Cabrera-Afonso, Anasheh Sookezian, and Shorouk O. Badir performed experiments with input from Professor Gary A. Molander. Shorouk O. Badir, Dr María Jesús Cabrera-Afonso, and Anasheh Sookezian wrote the manuscript with input from Professor Gary A. Molander.

Conflicts of interest

There are no conflicts to declare.

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