ORGANIC CHEMISTRY FRONTIERS

RESEARCH ARTICLE

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Org. Chem. Front.*, 2021, **8**, 6704

Alkoxycarbonyl radicals from alkyloxalyl chlorides: photoinduced synthesis of isoquinolinediones under visible light irradiation†

Mingjuan Ji,‡[a] Liang Xu,‡[a] Xiangxiang Luo,[a] Minghui Jiang,[a] Siyu Wang,[a] Jian-Qiang Chen*[a] and Jie Wu *[a,b,c]

Received 13th September 2021,
Accepted 20th October 2021

DOI: 10.1039/d1qo01368h

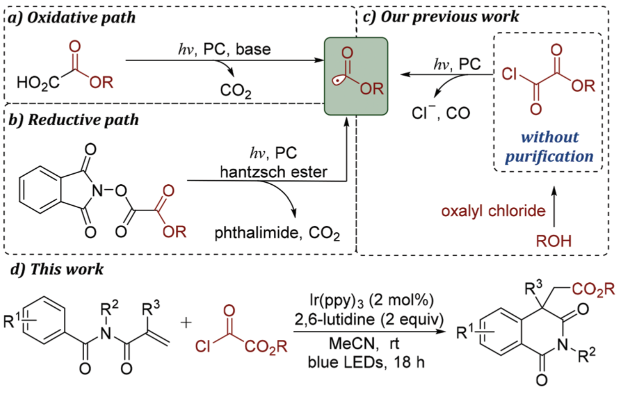
rsc.li/frontiers-organic

Alkyloxalyl chlorides, generated from alcohols and oxalyl chlorides, are used as alkoxycarbonyl radicals in the reaction of *N*-acryloyl benzamides under photocatalysis at room temperature. In this report, we demonstrate that this approach can be compatible with a variety of alcohol-containing pharmaceutically active compounds under visible light irradiation. A variety of isoquinoline-1,3(2*H*,4*H*)-diones are prepared in moderate to good yields.

Carbonylation reactions are of crucial importance in the field of modern organic synthesis since they provide access to carbonyl-containing derivatives, such as ketones, amides and carboxylic esters, which play an important role in fields ranging from organic chemistry to medical and pharmaceutical sciences.[1] In these fields, acyl/carbamoyl/alkoxycarbonyl radicals are useful reactive intermediates which can be combined with carbon fragments to obtain unique carbonyl-containing derivatives.[2] So far, many methods for the generation and application of acyl/carbamoyl radicals have been reported.[3–12] For example, acyl radicals can be obtained either by single-electron reduction of acyl chlorides,[4] anhydrides,[5] and hypervalent iodine reagents,[6] or upon oxidation of α-ketoacids[7] and acyl silanes.[8] Carbamoyl radicals can also be generated from the corresponding 4-carbamoyl dihydropyridines,[9] *N*-hydroxyphthalimido oxamides,[10] oxalate monoamides[11] and carbamoyl chlorides[12] in the presence of a photocatalyst under visible light irradiation.

However, compared with acyl/carbamoyl radicals, alkoxycarbonyl radicals have remained largely unexplored.[13] Although alkoxycarbonyl radicals can attack unsaturated C–C bonds leading to carboxylic esters, the concurrent decarboxylation step to form stable tertiary carbon radicals often plays a dominant role in synthesis. Thus, much effort has been devoted to alkoxycarbonyl radical decarboxylation through photocatalysis in recent years.[14]

Traditionally, alkoxycarbonyl radicals can be generated most commonly from the corresponding xanthates and selenides.[15] Additionally, these radicals can also be formed from carbazates by treatment with metal catalysts and stoichiometric quantities of oxidants.[16] Recently, it was reported that alkoxycarbonyl radicals could be produced by photoredox-catalyzed fragmentation of alkyl oxalates and methyl *N*-phthalimidoyl oxalates (Schemes 1a and b).[13,14] The existing approaches for providing alkoxycarbonyl radical precursors often require multistep synthetic processes. Thus, the development of a robust strategy for the rapid generation of alkoxycarbonyl radicals under mild conditions, especially using readily available and inexpensive substrates, is highly desirable.



Scheme 1 Generation of alkoxycarbonyl radicals under photoredox catalysis.

---

[a] School of Pharmaceutical and Materials Engineering & Institute for Advanced Studies, Taizhou University, Taizhou 318000, China. E-mail: chenjq@tzc.edu.cn, jie_wu@fudan.edu.cn

[b] State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, Shanghai 200032, China

[c] School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China

† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1qo01368h

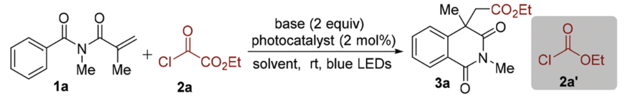
‡ These authors contributed equally.

Xu and co-workers disclosed that single-electron reduction of aroyl chlorides with a photocatalyst would provide aroyl radicals.[4] Inspired by this result, we expected that it might be possible to find a novel strategy for the generation of alkoxycarbonyl radicals from the corresponding acyl chloride under photocatalysis. Recently, we have reported that alkyloxalyl chlorides, generated *in situ* from the corresponding oxalyl chloride and alcohols, can be used as alkoxycarbonyl radical fragments under photoredox catalysis (Scheme 1c).[17] To further demonstrate the advantage of this conversion, a variety of isoquinoline-1,3(2*H*,4*H*)-diones are prepared in moderate to good yields (Scheme 1d). An important feature of this alkoxycarbonylation/cyclization reaction is the capacity of alkyloxalyl chlorides to produce alkoxycarbonyl radicals through single-electron reduction/CO extrusion.

To verify the practicability of the above hypothesis, commercially available ethyl chlorooxoacetate (**2a**)[18] as the alkoxycarbonyl radical precursor and *N*-methacryloyl-*N*-methylbenzamide (**1a**) as the radical trapper were selected as substrates for reaction development (Table 1). The reactions were performed at room temperature under visible light irradiation with a blue LED strip in the presence of Ir(ppy)$_3$ as the photocatalyst. Since HCl would be released during the reaction process, 2,6-lutidine was added as the base. Gratifyingly, the desired alkoxycarbonylation/cyclization product (**3a**) was obtained in good yield (70%) (Table 1, entry 1). This result demonstrated that our design was feasible and promising. The yield of compound **3a** was decreased to 37% when Ir(ppy)$_2$(dtbbpy)PF$_6$ was used as the photocatalyst (Table 1, entry 2). The donor–acceptor-type photocatalyst 3DPA2FBN, which is a strongly reducing organic photocatalyst,[19] provided a lower yield (Table 1, entry 3). Next, the solvent effect was evaluated (Table 1, entries 4–7) and it was found that acetonitrile was the optimal reaction medium, giving rise to the corresponding product **3a** in 76% yield (Table 1, entry 6). Subsequently, other bases were screened, and the result showed that inorganic bases were less efficient, while 2,6-di-*tert*-butylpyridine was comparably effective. Additionally, blank experiments demonstrated that both a photocatalyst and visible light were necessary for this alkoxycarbonylation/cyclization reaction (Table 1, entries 12 and 13). Meanwhile, the reaction could not occur when ethyl chloroformate (**2a′**) was used as the alkoxycarbonyl radical source (Table 1, entry 14). This result might be rationalized by the more negative reduction potential of alkyl chloroformates than the excited-state photocatalyst. With the optimized conditions in hand, we then investigated the scope of *N*-acryloyl benzamides in this reaction. As shown in Table 2, it was found that a wide range of *N*-methacryloyl benzamide derivatives bearing electron-donating (methyl, methoxy, *tert*-butyl and dimethyl) and electron-withdrawing (F, Cl and Br) substituents in the aromatic ring were suitable substrates for this transformation. Notably, reactions of *para*-^{t}butyl- and 3,5-dimethyl-substituted substrates afforded the acyl migration products **3e′** and **3f′**, respectively. Substrates bearing different alkyl groups at the *N*-position of amides could readily convert into the isoquinoline-1,3(2*H*,4*H*)-diones (**3i**–**3t**). The excellent functional group tolerance of –Bn (**3o**), –CN (**3p**), and –CO$_2$Et (**3q**), and a terminal unsaturated bond (**3r**) supported the practicality of this reaction. Additionally, chiral *N*-methacryloyl benzamides served as radical trappers in this alkoxycarbonylation/cyclization reaction, leading to the chiral isoquinoline-1,3(2*H*,4*H*)-diones (**3s** and **3t**) in moderate yields. Acrylamides with a benzyl and phenyl group at the α-position converted into the target products **3u** and **3v** as well. To demonstrate the practicability of this alkoxycarbonylation/cyclization reaction, a gram-scale experiment was carried out, which provided the corresponding product **3a** in 62% yield.

Subsequently, various alkyloxalyl chlorides were examined, giving rise to the results shown in Table 3. It was found that alkyloxalyl chlorides generated directly from the corresponding alcohols could smoothly provide the alkoxycarbonyl radicals. The yield of the alkoxycarbonylation/cyclization product decreased to 85% (**4a** *vs.* **3p**) when methyl oxalyl chloride was used as the radical precursor in the reaction with *N*-(2-cyanoethyl)-*N*-methacryloyl benzamide **1p**. Further underscoring the compatibility of this transformation, some alkyloxalyl chlorides were obtained by treatment of alcohols with a slight excess of oxalyl chloride in DCM, which were employed in this radical cascade reaction after the removal of the solvent and the excess oxalyl chloride.[20] The alkyloxalyl chloride derived from long-chain aliphatic alcohols was found to be successful in this transformation (**4b**). To further demonstrate the synthetic robustness of this conversion, we applied this approach for the construction of a series of diversely functionalized isoquinoline-1,3(2*H*,4*H*)-diones. Chlorooxoacetates derived from natural products including menthol (product **4c**, 80% yield), (−)-borneol (product **4d**, 58% yield), β-cholestanol (product **4e**,

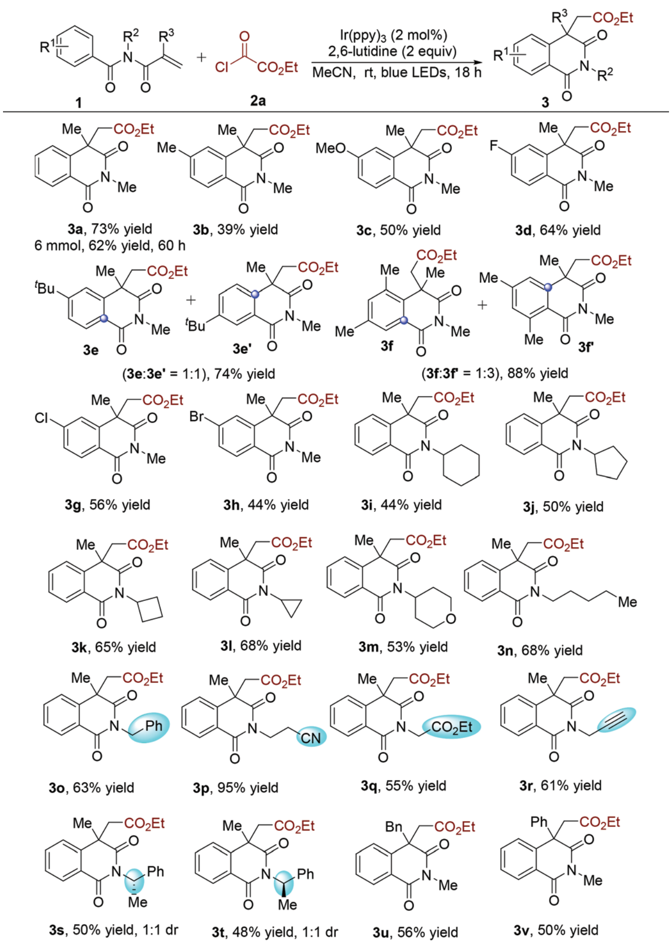
Table 1 Optimization of reaction parameters[a,b]



Entry	PC	Solvent	Base	Time	**3a** (%)
1	Ir(ppy)$_3$	DMF	2,6-Lutidine	12 h	70
2	Ir(ppy)$_2$(dtbbpy)PF$_6$	DMF	2,6-Lutidine	12 h	37
3	3DPA2FBN	DMF	2,6-Lutidine	12 h	47
4	Ir(ppy)$_3$	MeCN	2,6-Lutidine	18 h	76
5	Ir(ppy)$_3$	THF	2,6-Lutidine	36 h	14
6	Ir(ppy)$_3$	DCM	2,6-Lutidine	48 h	30
7	Ir(ppy)$_3$	EA	2,6-Lutidine	48 h	17
8	Ir(ppy)$_3$	MeCN	2,6-di^{t}Bu-Py	18 h	70
9	Ir(ppy)$_3$	MeCN	K$_2$HPO$_4$	18 h	51
10	Ir(ppy)$_3$	MeCN	Na$_2$HPO$_4$	18 h	19
11	Ir(ppy)$_3$	MeCN	KHCO$_3$	18 h	16
12	—	MeCN	2,6-Lutidine	18 h	0
13[c]	Ir(ppy)$_3$	MeCN	2,6-Lutidine	18 h	0
14[d]	Ir(ppy)$_3$	MeCN	2,6-Lutidine	18 h	0

[a] Unless otherwise noted, reaction conditions are as follows: **1a** (0.2 mmol), **2a** (0.6 mmol), photocatalyst (0.004 mmol), base (0.4 mmol), solvent (4 mL), and 36 W blue LEDs under a N$_2$ atmosphere. [b] Yield determined by ^{1}H NMR analysis using 1,3,5-trimethoxybenzene as an internal standard. [c] In the dark. [d] Compound **2a′** was used instead of ethyl chlorooxoacetate **2a**.

Table 2 Photoinduced synthesis of isoquinolinediones under visible light irradiation from *N*-acryloyl benzamides and ethyl chlorooxoacetates[a]



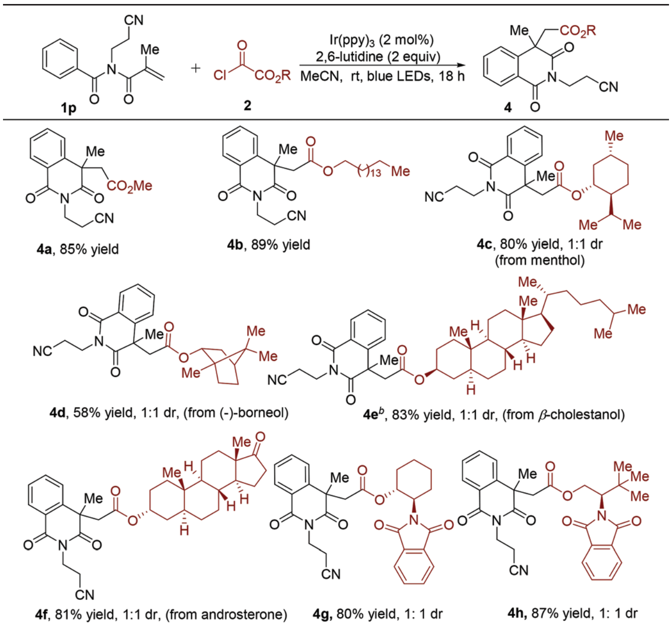
3a, 73% yield
6 mmol, 62% yield, 60 h
3b, 39% yield
3c, 50% yield
3d, 64% yield
(**3e**:**3e'** = 1:1), 74% yield
(**3f**:**3f'** = 1:3), 88% yield
3g, 56% yield
3h, 44% yield
3i, 44% yield
3j, 50% yield
3k, 65% yield
3l, 68% yield
3m, 53% yield
3n, 68% yield
3o, 63% yield
3p, 95% yield
3q, 55% yield
3r, 61% yield
3s, 50% yield, 1:1 dr
3t, 48% yield, 1:1 dr
3u, 56% yield
3v, 50% yield

[a] Unless otherwise noted, reaction conditions are as follows: **1** (0.2 mmol), **2a** (0.6 mmol), Ir(ppy)$_3$ (0.004 mmol), 2,6-lutidine (0.4 mmol), MeCN (4 mL), and 36 W blue LEDs under a N$_2$ atmosphere.

83% yield) and androsterone (product **4f**, 81% yield) were workable as well. Chiral amino alcohol derivatives were satisfactory starting materials and could uniformly produce the synthetically valuable isoquinoline-1,3(2*H*,4*H*)-diones with good yields (**4g** and **4h**).

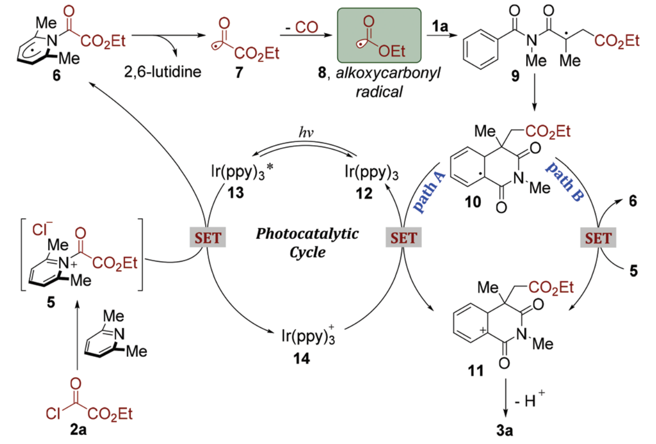
As mentioned above, the control experiments demonstrated that both visible light and photocatalyst were crucial for this alkoxycarbonylation/cyclization reaction. On the basis of these results and previous reports,[17,21] we proposed a plausible mechanism as depicted in Scheme 2. Ethyl chlorooxoacetate (**2a**) could react with 2,6-lutidine to afford the corresponding acyl pyridinium salt (**5**).[22] On the other hand, this photocatalytic cycle was initiated by the excitation of the photocatalyst Ir(ppy)$_3$ (**12**) to the excited-state photocatalyst Ir(ppy)$_3$* (**13**),[22] which subsequently transferred a single electron to acyl pyridinium salt (**5**) to generate radical **6**. Homolysis of the C–N bond would liberate 2,6-lutidine and produce acyl radical **7**.[22] The highly activated acyl radical **7** could rapidly go through CO extrusion and provide a stabilized alkoxycarbonyl radical **8**. Radical **8** would then react with *N*-methacryloyl-*N*-methylbenzamide (**1a**), giving rise to a tertiary carbon radical intermediate **9**. Subsequently, a radical-arene cyclization would occur leading to radical intermediate **10**, which was readily oxidized by Ir(ppy)$_3$$^+$ to generate a cation intermediate **11** (path A). Alternatively, the species **10** could also be oxidized by acyl pyridinium salt (**5**) to providecation **11**, along with the generated radical **6**. After deprotonation, the desired product **3a** would be produced.

Table 3 Photoinduced synthesis of isoquinolinediones under visible light irradiation from *N*-acryloyl benzamide **1p** and alkyloxalyl chlorides[a]



4a, 85% yield
4b, 89% yield
4c, 80% yield, 1:1 dr
(from menthol)
4d, 58% yield, 1:1 dr, (from (-)-borneol)
4e[b], 83% yield, 1:1 dr, (from *β*-cholestanol)
4f, 81% yield, 1:1 dr, (from androsterone)
4g, 80% yield, 1: 1 dr
4h, 87% yield, 1: 1 dr

[a] Unless otherwise noted, reaction conditions are as follows: **1p** (0.2 mmol), **2** (0.6 mmol), Ir(ppy)$_3$ (0.004 mmol), 2,6-lutidine (0.4 mmol), MeCN (4 mL), and 36 W blue LEDs under a N$_2$ atmosphere. [b] DMF was used instead of MeCN.



Scheme 2 Proposed mechanism.

In conclusion, we have developed an alkoxycarbonylation/cyclization reaction of *N*-acryloyl benzamides and alkyloxalyl chlorides under photocatalysis at room temperature. The application of alkoxycarbonyl radicals in the intermolecular conjugate addition to electron-deficient alkenes has also been demonstrated. The key finding is the use of alkyloxalyl chlorides as alkoxycarbonyl radical precursors, which are generated from the corresponding alcohols and oxalyl chloride. With this approach, a variety of isoquinoline-1,3(2*H*,4*H*)-diones are prepared in moderate to good yields. Additionally, this strategy is compatible with a variety of alcohol-containing pharmaceutically active compounds.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Financial support from the National Natural Science Foundation of China (No. 21871053), the Leading Innovative and Entrepreneur Team Introduction Program of Zhejiang (No. 2019R01005), and the Open Research Fund of the School of Chemistry and Chemical Engineering, Henan Normal University (2020ZD04) is gratefully acknowledged.

Notes and references

1 For selected reviews, see: (*a*) M. C. Willis, Transition Metal Catalyzed Alkene and Alkyne Hydroacylation, *Chem. Rev.*, 2010, **110**, 725; (*b*) J. Ruan and J. Xiao, From α-Arylation of Olefins to Acylation with Aldehydes: A Journey in Regiocontrol of the Heck Reaction, *Acc. Chem. Res.*, 2011, **44**, 614; (*c*) J. Liu, Z. Wei, H. Jiao, R. Jackstell and M. Beller, Toward Green Acylation of (Hetero)arenes: Palladium-Catalyzed Carbonylation of Olefins to Ketones, *ACS Cent. Sci.*, 2018, **4**, 30; (*d*) I. Ryu and N. Sonoda, Free-Radical Carbonylations: Then and Now, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 1050; (*e*) I. Ryu, Radical Carboxylations of Iodoalkanes and Saturated Alcohols Using Carbon Monoxide, *Chem. Soc. Rev.*, 2001, **30**, 16; (*f*) A. Brennführer, H. Neumann and M. Beller, Palladium-Catalyzed Carbonylation Reactions of Aryl Halides and Related Compounds, *Angew. Chem., Int. Ed.*, 2009, **48**, 4114; (*g*) Z. Chen, L.-C. Wang and X.-F. Wu, Carbonylative synthesis of heterocycles involving diverse CO surrogates, *Chem. Commun.*, 2020, **56**, 6016; (*h*) L.-J. Cheng and N. P. Mankad, Copper-Catalyzed Carbonylative Coupling of Alkyl Halides, *Acc. Chem. Res.*, 2021, **54**, 2261.

2 For selected reviews, see: (*a*) C. Raviola, S. Protti, D. Ravelli and M. Fagnoni, Photogenerated Acyl/Alkoxycarbonyl/Carbamoyl Radicals for Sustainable Synthesis, *Green Chem.*, 2019, **21**, 748; (*b*) C. Chatgilialoglu, D. Crich, M. Komatsu and I. Ryu, Chemistry of Acyl Radicals, *Chem. Rev.*, 1999, **99**, 1991; (*c*) N. Chalotra, S. Sultan and B. A. Shah, Recent Advances in Photoredox Methods for Ketone Synthesis, *Asian J. Org. Chem.*, 2020, **9**, 863.

3 (*a*) M. Zhang, J. Xie and C. Zhu, A General Deoxygenation Approach for Synthesis of Ketones from Aromatic Carboxylic Acids and Alkenes, *Nat. Commun.*, 2018, **9**, 3517; (*b*) M. Zhang, X.-A. Yuan, C. Zhu and J. Xie, Deoxygenative Deuteration of Carboxylic Acids with D_2O, *Angew. Chem., Int. Ed.*, 2019, **58**, 312; (*c*) R. Ruzi, J. Ma, X.-A. Yuan, W. Wang, S. Wang, M. Zhang, J. Dai, J. Xie and C. Zhu, Deoxygenative Arylation of Carboxylic Acids by Aryl Migration, *Chem. – Eur. J.*, 2019, **25**, 12724; (*d*) R. Ruzi, K. Liu, C. Zhu and J. Xie, Upgrading Ketone Synthesis Direct from Carboxylic Acids and Organohalides, *Nat. Commun.*, 2020, **11**, 3312; (*e*) X. Zhang and D. W. C. MacMillan, Direct Aldehyde C–H Arylation and Alkylation *via* the Combination of Nickel, Hydrogen Atom Transfer, and Photoredox Catalysis, *J. Am. Chem. Soc.*, 2017, **139**, 11353; (*f*) R. Sakamoto, N. Hirama and K. Maruoka, The Radical Acylarylation of *N*-Arylacrylamides with Aliphatic Aldehydes using the Photolysis of Hypervalent Iodine(III) Reagents, *Org. Biomol. Chem.*, 2018, **16**, 5412; (*g*) B. Schweitzer-Chaput, M. A. Horwitz, E. de Pedro Beato and P. Melchiorre, Photochemical Generation of Radicals from Alkyl Electrophiles Using a Nucleophilic Organic Catalyst, *Nat. Chem.*, 2019, **11**, 129.

4 (*a*) S.-M. Xu, J.-Q. Chen, D. Liu, Y. Bao, Y.-M. Liang and P.-F. Xu, Aroyl Chlorides as Novel Acyl Radical Precursors *via* Visible-Light Photoredox Catalysis, *Org. Chem. Front.*, 2017, **4**, 1331; (*b*) C.-G. Li, G.-Q. Xu and P.-F. Xu, Synthesis of Fused Pyran Derivatives *via* Visible-Light-Induced Cascade Cyclization of 1,7-Enynes with Acyl Chlorides, *Org. Lett.*, 2017, **19**, 512; (*c*) Y. Liu, Q.-L. Wang, C.-S. Zhou, B.-Q. Xiong, P.-L. Zhang, C.-A. Yang and K.-W. Tang, Visible-Light-Mediated *Ipso*-Carboacylation of Alkynes: Synthesis of 3-Acylspiro[4,5]trienones from *N*-(*p*-Methoxyaryl)propiolamides and Acyl Chlorides, *J. Org. Chem.*, 2018, **83**, 2210; (*d*) Q.-S. Zhao, G.-Q. Xu, H. Liang, Z.-Y. Wang and P.-F. Xu, Aroylchlorination of 1,6-Dienes *via* a Photoredox Catalytic Atom-Transfer Radical Cyclization Process, *Org. Lett.*, 2019, **21**, 8615; (*e*) Y.-L. Wei, J.-Q. Chen, B. Sun and P.-F. Xu, Synthesis of Indolo[2,1-a]isoquinoline Derivatives *via* Visible-Light-Induced Radical Cascade Cyclization Reactions, *Chem. Commun.*, 2019, **55**, 5922; (*f*) D. V. Patil, H. Y. Kim and K. Oh, Visible Light-Promoted Friedel–Crafts-Type Chloroacylation of Alkenes to β-Chloroketones, *Org. Lett.*, 2020, **22**, 3018; (*g*) Z. Lei, A. Banerjee, E. Kusevska, E. Rizzo, P. Liu and M.-Y. Ngai, β-Selective Aroylation of Activated Alkenes by Photoredox Catalysis, *Angew. Chem., Int. Ed.*, 2019, **58**, 7318.

5 (*a*) F. Pettersson, G. Bergonzini, C. Cassani and C.-J. Wallentin, Redox-Neutral Dual Functionalization of Electron-Deficient Alkenes, *Chem. – Eur. J.*, 2017, **23**, 7444; (*b*) S. Dong, G. Wu, X. Yuan, C. Zou and J. Ye, Visible-light Photoredox Catalyzed Hydroacylation of Electron-Deficient

Alkenes: Carboxylic Anhydride as an Acyl Radical Source, *Org. Chem. Front.*, 2017, **4**, 2230; (*c*) M. Zhang, R. Ruzi, J. Xi, N. Li, Z. Wu, W. Li, S. Yu and C. Zhu, Photoredox-Catalyzed Hydroacylation of Olefins Employing Carboxylic Acids and Hydrosilanes, *Org. Lett.*, 2017, **19**, 3430; (*d*) G. Bergonzini, C. Cassani and C. Wallentin, Acyl Radicals from Aromatic Carboxylic Acids by Means of Visible-Light Photoredox Catalysis, *Angew. Chem., Int. Ed.*, 2015, **54**, 14066; (*e*) G. Bergonzini, C. Cassani, H. L. Olsson, J. Hçrberg and C. J. Wallentin, Visible-Light-Mediated Photocatalytic Difunctionalization of Olefins by Radical Acylarylation and Tandem Acylation/Semipinacol Rearrangement, *Chem. – Eur. J.*, 2016, **22**, 3292.

6 (*a*) W. Ji, H. Tan, M. Wang, P. Li and L. Wang, Photocatalyst-Free Hypervalent Iodine Reagent Catalyzed Decarboxylative Acylarylation of Acrylamides with α-Oxocarboxylic Acids Driven by Visible-Light Irradiation, *Chem. Commun.*, 2016, **52**, 1462; (*b*) H. Huang, G. Zhang and Y. Chen, Dual Hypervalent Iodine(III) Reagents and Photoredox Catalysis Enable Decarboxylative Ynonylation under Mild Conditions, *Angew. Chem., Int. Ed.*, 2015, **54**, 7872; (*c*) H. Tan, H. Li, W. Ji and L. Wang, Sunlight-Driven Decarboxylative Alkynylation of α-Keto Acids with Bromoacetylenes by Hypervalent Iodine Reagent Catalysis: A Facile Approach to Ynones, *Angew. Chem., Int. Ed.*, 2015, **54**, 8374.

7 (*a*) T. Xiao, L. Li and L. Zhou, Synthesis of Functionalized gem-Difluoroalkenes *via* a Photocatalytic Decarboxylative/Defluorinative Reaction, *J. Org. Chem.*, 2016, **81**, 7908; (*b*) J.-Q. Chen, R. Chang, Y.-L. Wei, J.-N. Mo, Z.-Y. Wang and P.-F. Xu, Direct Decarboxylative–Decarbonylative Alkylation of α-Oxo Acids with Electrophilic Olefins *via* Visible-Light Photoredox Catalysis, *J. Org. Chem.*, 2018, **83**, 253; (*c*) L. Chu, J. M. Lipshultz and D. W. C. MacMillan, Merging Photoredox and Nickel Catalysis: The Direct Synthesis of Ketones by the Decarboxylative Arylation of α-Oxo Acids, *Angew. Chem., Int. Ed.*, 2015, **54**, 7929; (*d*) G. Z. Wang, R. Shang, W. M. Cheng and Y. Fu, Decarboxylative 1,4-Addition of α-Oxocarboxylic Acids with Michael Acceptors Enabled by Photoredox Catalysis, *Org. Lett.*, 2015, **17**, 4830; (*e*) W. Cheng, R. Shang, H. Yu and Y. Fu, Room-Temperature Decarboxylative Couplings of α-Oxocarboxylates with Aryl Halides by Merging Photoredox with Palladium Catalysis, *Chem. – Eur. J.*, 2015, **21**, 13191; (*f*) T. Morack, C. Mück-Lichtenfeld and R. Gilmour, Bioinspired Radical Stetter Reaction: Radical Umpolung Enabled by Ion-Pair Photocatalysis, *Angew. Chem., Int. Ed.*, 2019, **58**, 1208; (*g*) J.-J. Zhao, H.-H. Zhang, X. Shen and S. Yu, Enantioselective Radical Hydroacylation of Enals with α-Ketoacids Enabled by Photoredox/Amine Cocatalysis, *Org. Lett.*, 2019, **21**, 913.

8 L. Capaldo, R. Riccardi, D. Ravelli and M. Fagnoni, Acyl Radicals from Acylsilanes: Photoredox-Catalyzed Synthesis of Unsymmetrical Ketones, *ACS Catal.*, 2018, **8**, 304.

9 N. Alandini, L. Buzzetti, G. Favi, T. Schulte, L. Candish, K. D. Collins and P. Melchiorre, Amide Synthesis by Nickel/Photoredox-Catalyzed Direct Carbamoylation of (Hetero) Aryl Bromides, *Angew. Chem., Int. Ed.*, 2020, **59**, 5248.

10 W. F. Petersen, R. J. K. Taylor and J. R. Donald, Photoredox-Catalyzed Reductive Carbamoyl Radical Generation: A Redox-Neutral Intermolecular Addition–Cyclization Approach to Functionalized 3,4-Dihydroquinolin-2-ones, *Org. Lett.*, 2017, **19**, 874.

11 Q.-F. Bai, C. Jin, J.-Y. He and G. Feng, Carbamoyl Radicals *via* Photoredox Decarboxylation of Oxamic Acids in Aqueous Media: Access to 3,4-Dihydroquinolin-2(1*H*)-ones, *Org. Lett.*, 2018, **20**, 2172.

12 E. de Pedro Beato, D. Mazzarella, M. Balletti and P. Melchiorre, Photochemical Generation of Acyl and Carbamoyl Radicals using a Nucleophilic Organic Catalyst: Applications and Mechanism Thereof, *Chem. Sci.*, 2020, **11**, 6312.

13 Y. Slutskyy and L. E. Overman, Generation of the Methoxycarbonyl Radical by Visible-Light Photoredox Catalysis and Its Conjugate Addition with Electron-Deficient Olefins, *Org. Lett.*, 2016, **18**, 2564.

14 (*a*) G. L. Lackner, K. W. Quasdorf, G. Pratsch and L. E. Overman, Fragment Coupling and the Construction of Quaternary Carbons Using Tertiary Radicals Generated from *tert*-Alkyl *N*-Phthalimidoyl Oxalates by Visible-Light Photocatalysis., *J. Org. Chem.*, 2015, **80**, 6012; (*b*) C. C. Nawrat, C. R. Jamison, Y. Slutskyy, D. W. C. MacMillan and L. E. Overman, Oxalates as Activating Groups for Alcohols in Visible Light Photoredox Catalysis: Formation of Quaternary Centers by Redox-Neutral Fragment Coupling, *J. Am. Chem. Soc.*, 2015, **137**, 11270; (*c*) N. A. Weires, Y. Slutskyy and L. E. Overman, *Angew. Chem., Int. Ed.*, 2019, **58**, 8561.

15 (*a*) B. M. Trost, J. Waser and A. Meyer, Total Synthesis of (−)-Pseudolaric Acid B, *J. Am. Chem. Soc.*, 2008, **130**, 16424; (*b*) W.-Y. Yu, W. N. Sit, K.-M. Lai, Z. Y. Zhou and A. S. C. Chan, Palladium-Catalyzed Oxidative Ethoxycarbonylation of Aromatic C–H Bond with Diethyl Azodicarboxylate, *J. Am. Chem. Soc.*, 2008, **130**, 3304; (*c*) S. H. Kyne, C. H. Schiesser and H. Matsubarac, Multi-component Orbital Interactions during Oxyacyl Radical Addition Reactions Involving Imines and Electron-Rich Olefins, *Org. Biomol. Chem.*, 2007, **5**, 3938; (*d*) M. D. Bachi and E. Bosch, Synthesis of α-Alkylidene-γ-Lactones by Intramolecular Addition of Alkoxycarbonyl Free-Radicals to Acetylenes, *Tetrahedron Lett.*, 1986, **27**, 641.

16 (*a*) T. Taniguchi, Y. Sugiura, H. Zaimoku and H. Ishibashi, Iron-Catalyzed Oxidative Addition of Alkoxycarbonyl Radicals to Alkenes with Carbazates and Air, *Angew. Chem., Int. Ed.*, 2010, **49**, 10154; (*b*) X. Xu, Y. Tang, X. Li, G. Hong, M. Fang and X. Du, Iron-Catalyzed Arylalkoxycarbonylation of *N*-Aryl Acrylamides with Carbazates, *J. Org. Chem.*, 2014, **79**, 446; (*c*) G. Wang, S. Wang, J. Wang, S.-Y. Chen and X.-Q. Yu, Synthesis of Oxindole-3-Acetates through Iron-Catalyzed Oxidative Arylalkoxycarbonylation of Activated Alkenes, *Tetrahedron*, 2014, **70**, 3466; (*d*) Z. Zong, S. Lu, W. Wang and Z. Li, Iron-Catalyzed Alkoxycarbonylation–

Peroxidation of Alkenes with Carbazates and T-Hydro, *Tetrahedron Lett.*, 2015, **56**, 6719; (*e*) Y. Tang, M. Zhang, X. Li, X. Xu and X. Du, Tetrabutylammonium Iodide-Catalyzed Radical Alkoxycarbonylation of Activated Alkenes: Synthesis of Isoquinolinedione Derivatives, *Chin. J. Org. Chem.*, 2015, **35**, 875; (*f*) W. Kong, M. Casimiro, N. Fuentes, E. Merino and C. Nevado, Metal-Free Aryltrifluoromethylation of Activated Alkenes, *Angew. Chem., Int. Ed.*, 2013, **52**, 13086.

17 J.-Q. Chen, X. Tu, Q. Tang, K. Li, L. Xu, S. Wang, M. Ji, Z. Li and J. Wu, Efficient Access to Aliphatic Esters by Photocatalyzed Alkoxycarbonylation of Alkenes with Alkyloxalyl Chlorides, *Nat. Commun.*, 2021, **12**, 5328.

18 0.5 kg/$227:supplier:Sigma-Aldrich and 0.5 kg/$202:supplier:TCI.

19 E. Speckmeier, T. G. Fischer and K. Zeitler, A Toolbox Approach to Construct Broadly Applicable Metal-Free Catalysts for Photoredox Chemistry: Deliberate Tuning of Redox Potentials and Importance of Halogens in Donor–Acceptor Cyanoarenes, *J. Am. Chem. Soc.*, 2018, **140**, 15353.

20 Y. Zhao, G. Wang, Y. Li, S. Wang and Z. Li, Design, Synthesis and Insecticidal Activities of Novel *N*–Oxalyl Derivatives of Neonicotinoid Compound, *Chin. J. Chem.*, 2010, **28**, 475.

21 For selected examples, see: (*a*) Y. Li, R. Mao and J. Wu, *N*-Radical Initiated Aminosulfonylation of Unactivated C(sp^3)–H Bond through Insertion of Sulfur Dioxide, *Org. Lett.*, 2017, **19**, 4472; (*b*) T. Liu, Y. Li, L. Lai, J. Cheng, J. Sun and J. Wu, Photocatalytic Reaction of Potassium Alkyltrifluoroborates and Sulfur Dioxide with Alkenes, *Org. Lett.*, 2018, **20**, 3605; (*c*) S. Ye, D. Zheng, J. Wu and G. Qiu, Photoredox-Catalyzed Sulfonylation of Alkyl Iodides, Sulfur Dioxide, and Electron-Deficient Alkenes, *Chem. Commun.*, 2019, **55**, 2214; (*d*) J. Zhang, X. Li, W. Xie, J. Wu and S. Ye, Photoredox-Catalyzed Sulfonylation of O-Acyl Oximes *via* Iminyl Radicals with the Insertion of Sulfur Dioxide, *Org. Lett.*, 2019, **21**, 4950; (*e*) X. Gong, M. Yang, J.-B. Liu, F.-S. He and J. Wu, Photoinduced Synthesis of alkylalkynyl Sulfones through A Reaction of Potassium Alkyltrifluoroborates, Sulfur Dioxide, and Alkynyl Bromides, *Org. Chem. Front.*, 2020, **7**, 938; (*f*) X. Gong, M. Yang, J.-B. Liu, F.-S. He, X. Fan and J. Wu, A Metal-Free Route to Alkynyl Sulfones under Photoinduced Conditions with the Insertion of Sulfur Dioxide, *Green Chem.*, 2020, **22**, 1906.

22 (*a*) J. D. Nguyen, E. M. D'Amato, J. M. R. Narayanam and C. R. J. Stephenson, Engaging Unactivated Alkyl, Alkenyl and Aryl Iodides in Visible-Light-Mediated Free Radical Reactions, *Nat. Chem.*, 2012, **4**, 854; (*b*) J.-Q. Chen, R. Chang, J.-B. Lin, Y.-C. Luo and P.-F. Xu, Photoredox-Induced Intramolecular 1,5-H Transfer Reaction of Aryl Iodides for the Synthesis of Spirocyclic γ-Lactams, *Org. Lett.*, 2018, **20**, 2395.