ORIGINAL PAPERS



Visible-light-promoted nitrone synthesis from nitrosoarenes under catalyst- and additive-free conditions

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Received: 15 April 2021 / Accepted: 27 May 2021

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Abstract

A green and sustainable nitrone formation reaction via visible-light-promoted reaction of aryl diazoacetates with nitrosoarenes is described. This protocol exhibits good functional group tolerance and broad substrate scope for both aryl diazoacetates with nitrosoarenes. Comparing the reported methods for the synthesis of nitrones from nitrosoarenes, the reaction described herein occurs under sole visible-light irradiation without the need of any catalysts and additives.

Graphic abstract



Keywords Nitrones \cdot Visible light \cdot Carbene \cdot Nitrosoarenes

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1 Introduction

Nitrones are important synthetic building blocks in synthetic organic chemistry [1–4]. Generally, nitrones always used 1,3-dipoles to participate cycloaddition reactions to construct biologically important heterocyclic compounds [5–9]. In addition, nitrones can act as electrophiles to react with various nucleophiles to form N,N-disubstituted hydroxy-lamines [10–12] or as radical acceptors to undergo radical addition to create new chemical bonds [13, 14]. Under transition metal catalytic conditions, they can also be used as directing groups to realize sp² C–H activation reactions [15, 16]. In addition, many others useful reaction types of nitrones are developed in the past several years [17–21].

Due to their wide synthetic applications, many methods towards the facile synthesis of nitrones have been developed (Scheme 1). Condensation of *N*-monosubstituted hydroxy-lamines with aldehydes or ketones is an effective method for the preparation of nitrones [1–4, 22–24]. However, those



Scheme 1 Methods for the synthesis of nitrones

processes always require dehydrating reagents or perform at high temperature in a microwave apparatus (Scheme 1a, path A). Oxidation of secondary amines, imines or N,Ndisubstituted hydroxylamines is another elegant route to form nitrones which often needs the consumption of stoichiometric oxidants (Scheme 1a, path B) [25-27]. In addition, the reaction to oximes with various electrophiles in the presence of metal catalysts to obtain nitrones has also attracted much attention (Scheme 1a, path C) [28]. Compared with those well-developed methods, nitrones synthesis from commercially available raw material nitrosobenzene is relatively undeveloped [29, 30]. In 2014, Ashfeld and their co-workers reported a hexamethylphosphorous $(P(NMe_2)_3)$ triamide-mediated addition of 1,2-dicarbonyls to nitroso compounds to construct arylnitrones. Using this umpolung strategy, the corresponding arylnitrones can be obtained in moderate to good yield. However, stoichiometric amounts of P(NMe₂)₃ are needed (Scheme 1b) [29]. Recently, Lattanzi and Mazzanti et al. developed the constructed arylnitrones from aryl acetates and nitrosoarenes in the presence of catalytic amount of 2-tert-butylimino-2-diethylamino-1,3-dimethylperhydro-,3,2-diazaphosphorine (BEMP) as catalyst (Scheme 1b) [30]. Moreover, other types of nitrone construction from nitrosoarenes using transition metal- and dienamine catalytic strategy have also be realized [31–38]. Despite these elegant progresses, to the best of our knowledge, catalyst and additive-free synthesis of nitrones from nitrosoarenes has not yet been discovered. Our group recently found that photo-generated carbene species from diazoalkanes can be efficiently trapped by nitrosoarenes under sole blue LED irradiation [39], thus providing a novel and efficient route to amides under benign reaction conditions [40–68]. Control experiments revealed that nitrones were generated as the key intermediates which rapidly rearranged to the corresponding amides under blue LED irradiation. Based on these findings and our ongoing research interests on the development of visible-light-promoted fine chemical transformations [69–75], we hypothesized whether the nitrone intermediates can be isolated through optimizing the reaction paraments. Comparing the reported methods for the construction of nitrones from nitrosoarenes, the reaction described herein occurred using visible light as green energy source without the need of any catalysts and additives (Scheme 1b).

2 Experimental

2.1 General information

All reactions involving air- or moisture-sensitive reagents or intermediates were carried out in pre-heated glassware under an argon atmosphere using standard Schlenk techniques. All solvents and reagents were purified according to standard procedures or were used as received from chemical suppliers. The starting materials were synthesized according to literature procedures. The light employed in this work was bought from GeAo Chemical: model H106062, 24 W blue LEDs. Analytical thin layer chromatography was performed using Qingdao Puke Parting Materials Co. silica gel plates (Silica gel 60 F254). Visualization was by ultraviolet fluorescence ($\lambda = 254$ nm) and/or staining with phosphomolybdic acid or potassium permanganate (KMnO₄). Flash column chromatography was performed using 200-300 mesh silica gel. ¹H NMR and ¹³C NMR spectra were recorded on a JEOL JNM ECZ400R at 300 K. Spectra were calibrated relative to solvent's residual proton and carbon chemical shift: CHCl₃ (δ = 7.26 for ¹H NMR and δ = 77.0 for ¹³C NMR). Data are reported as follows: chemical shift δ /ppm, integration (¹H only), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, m = multiplet or combinations thereof; ¹³C signals are singlets unless otherwise stated), coupling constants J in Hz, assignment. Mass spectra were recorded on a Finnigan MAT 4200S, a Bruker Daltonics Micro Tof, a Waters-Micromass Quatro LCZ (ESI); peaks are given in m/z (% of basis peak). Melting points were determined by Stuart SMP10 and are uncorrected.

2.2 General procedure for the synthesis of 3

To a 10 mL Schlenk flask equipped with a magnetic stir bar was added **1** (0.2 mmol), **2** (0.1 mmol), dry THF (1.0 mL).

The resulting mixture was degassed via 'freeze–pump–thaw' procedure (3 times). After the solution was stirred at a distance of \sim 3 cm from a 24 W blue LED at room temperature for 4 h. The solvent was removed by vacuum and the crude product was purified by flash chromatography on silica gel silica: 200–300; eluant: petroleum ether/ethyl acetate (20:1–5:1) to provide pure product.

3 Results and discussion

At the beginning, 2-diazo-2-phenylacetate 1a with nitrosobenzene 2a was selected as model substrates to optimize the reaction conditions (Table 1). It was found that the reaction time had significant influence on the product ratio. Using DCM as solvent, the corresponding nitrone 3aa can be isolated in 46% yield under blue light irradiation in 4 h (Table 1, entry 1). Note that, **3aa** will rearrange to amide by prolonging the reaction time [39]. To further improve the reaction efficiency, other reaction paraments were systematically screened (Table 1, entries 2-5). It was found that most of the solvents were suitable for the formation of desired nitrone 3aa, and THF was determined as the best reaction medium (Table 1, entry 3). Control experiments were also performed, and no reaction occurred in the absence of the light irradiation (Table 1, entry 6). It should be pointed out that 23% yield of the desired nitrone can be obtained when the reaction temperature raised to 50 °C in dark conditions (Table 1, entry 7).

Under the optimized reaction conditions, we first investigated the substrate scope for the aryldiazoacetate components (Table 2). In general, most of the reactions proceeded smoothly to afford the desired nitrones in moderate

Table 1 Reaction optimization between 1 and 2a

N₂ + Ph └ CO₂Me + 1a	Ph ^{_N} _{\O} 2a	blue LEDs solvent, rt, 4 h
Entry	Solvent	Yield (%) ^a
1	DCM	46
2	DCE	37
3	THF	91
4	CH ₃ CN	86
5	DMF	Trace
6	THF	Trace
7	THF	23

Reaction conditions: **1a** (0.2 mmol), **2a** (0.1 mmol) in dry solvent (1.0 mL) at rt under irradiation with 24 W blue LEDs for 4 h ^aIsolated yield. ^{*c*} in dark, at 50 °C





^{*a*} Reaction performed with **1** (0.2 mmol), **2a** (0.1 mmol) in dry THF (1.0 mL) at rt under irradiation with 24 W blue LEDs for 4 h. ^{*b*} isolated yield.

Reaction performed with 1 (0.2 mmol), 2a (0.1 mmol) in dry THF (1.0 mL) at rt under irradiation with 24 W blue LEDs for 4 h. Isolated yield

to good yields and high E/Z ratio. Both electron-rich (-Me) and electron-deficient substituents (-F, -Cl, -Br, -CF₃) at para or meta-positions of the aromatic ring turned out to be suitable, providing the corresponding nitrones 3aa-3ga in excellent yields (71-95%) and good diastereoselectivity. To our delight, reaction with aryldiazoacetates bearing benzo[d][1,3]dioxole (1h), naphthyl (1i) also proceeded well. Note that nitrone containing adamantane formic acid (3ja) and replacement of the methyl group with other alkyl propargyl (3ka) attached to the aryl group can be obtained in 54% and 60%, respectively. In addition, groups (11-n), cyclic alkyl groups (1q and 1r) or the substituents containing sensitive functional groups, e.g., ether (10), alkene (1p), all successfully yielded the corresponding nitrones in good to excellent yields (63-96%) and high *E/Z* ratio. We also introduced some natural products or drug molecules into the nitrone skeletons and applied them under the optimal reaction conditions. Pleasingly, natural isolates *L*-(-)-*Borneol* (**1** s), *L*-*Menthol* (**1t**), *Citronellol* (**1u**) were successfully converted into nitrones in moderate to high yields (51–83%) and with E/Z>19:1. Metronidazole also smoothly gave the drug-modified nitrone **3va** with 79% yields.

Next, we examined the compatibility of different nitrosoarenes and the results is summarized in Table 3. Under the optimized reaction conditions, various halogen (2b, 2c, 2g, 2i), alkyl (2e, 2h), alkoxyl (2k) and aryl (2f) substituted nitrosoarenes were all suitable for this reaction, providing the corresponding products in 52-95% yields with 10:1 E/Z ratio. To our delight, nitrosoarenes bearing ester (2d) and ketone (2j) fragments were well tolerated and afforded desired nitrones in 75% and 66% yields, respectively. Apart from phenylnitrosoarene, substrate 2l bearing 2-nitrosopyridine was amenable substrate, giving nitrone **3al** in 80% yields with high diastereoselectivity. Note that, 2-methyl-2-nitrosopropane 2 failed to give the final product, this might due to the steric of the 'Bu group. The successful introduction of *Pterostilbene* (2n) and *Vitamin E* (2o) fragment into final nitrone also revealed the advantage of this visible-lightinduced nitrone formation strategy.

With the aim at showing the utility of current methodology, we implemented a gram-scale synthesis under continuous flow reaction conditions (Scheme 2a). To our delight, nitrone **3aa** can be obtained in 89% yield using phenyldiazoacetate **1a** and nitrosobenzene **2a** as substrates. Moreover, treatment of **3aa** under reductive conditions with zinc powder and NH_4Cl provided amino ester derivative **4** in 91% yields (Scheme 2b) [76].

Some preliminary control experiments were conducted to gain some insight into the mechanism. When 1.0 equivalent of radical scavenger TEMPO was added under standard conditions, **3aa** still could be isolated in 92% yield. The result indicated that a radical pathway might be not involved in current reaction (Scheme 3a). It was reported that ethyl diazoacetate is an efficient carbene-trapping reagent under photochemical conditions [65]. When 1.0 equivalent of ethyl diazoacetate was added as a trapping reagent, the reaction provided nitrone **3aa** in 74% yield, together with 11% yield of alkene **6**, which suggested the carbene species formed during the reaction (Scheme 3b).

On the basis of above experimental results and literature report [51–68], a plausible reaction mechanism was proposed in Scheme 3. Initially, visible-light irradiation of aryldiazoacetate resulted in N_2 gas extrusion and generated the reactive carbene species. The carbene intermediate reacts



^{*a*} Reaction performed with **1** (0.2 mmol), **2a** (0.1 mmol) in dry THF (1.0 mL) at rt under irradiation with 24 W blue LEDs for 4 h. ^{*b*} isolated yield.

Reaction performed with **1** (0.2 mmol), **2a** (0.1 mmol) in dry THF (1.0 mL) at rt under irradiation with 24 W blue LEDs for 4 h. Isolated yield



Scheme 2 Synthetic applications



Scheme 3 Mechanism studies

with a nitrosoarene via its nucleophilic N-center to give the zwitterion intermediate 7, which converts the more stable nitrone **3aa** as the predominant resonance form.

4 Conclusions

In summary, we have developed a green and sustainable nitrone formation protocol via visible-light-promoted reaction of aryl diazoacetates with nitrosoarenes. Comparing the reported methods for the construction of nitrones from nitrosoarenes, the reaction described herein occurred under sole visible-light irradiation without the need of any catalysts and additives. The reaction showed good substrate scope, excellent functional group tolerance for both aryl diazoacetate and nitrosoarene components. Moreover, the success synthesis of natural product- or drug moleculemodified nitrones, large-scale preparation in continuous flow conditions further render the method attractive and valuable.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43630-021-00062-6.

Acknowledgements We are grateful to the National Natural Science Foundation of China (Nos. 21971001, 21702001), the Natural Science Founda-tion of Anhui Province (No. 1808085MB47) and the Start-up Grant from Anhui University for financial support of this work.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Jones, R. C. F., & Martin, J. N. (2003). Synthetic applications of 1,3-dipolar cycloadditions. In A. Padwa & W. H. Pearson (Eds.), *Chemistry toward heterocycles and natural products*. Hoboken: Wiley.
- 2. Torssell, K. B. G. (1988). In H. Feuer (Ed.), *Nitrile oxides nitrones* and ntronates in organic synthesis. Weinheim: Wiley VCH.
- Tufariello, J. J. (1984). In A. Padwa (Ed.), 1,3-Dipolar cycloaddition chemistry. (Vol. 2). New York: Wiley.
- Murahashi, S.-I., & Imada, Y. (2019). Synthesis and transformations of nitrones for organic synthesis. *Chemical Reviews*. https:// doi.org/10.1021/acs.chemrev.8b00476
- Gothelf, K. V., & Jørgensen, K. A. (1998). Asymmetric 1,3-dipolar cycloaddition reactions. *Chemical Reviews*. https://doi.org/10. 1021/cr970324e
- Stanley, L. M., & Sibi, M. P. (2008). Enantioselective coppercatalyzed 1,3-dipolar cycloadditions. *Chemical Reviews*. https:// doi.org/10.1021/cr078371m
- Hashimoto, T., & Maruoka, K. (2015). Recent advances of catalytic asymmetric 1,3-dipolar cycloadditions. *Chemical Reviews*. https://doi.org/10.1021/cr5007182
- Brandi, A., Cardona, F., Cicchi, S., Cordero, F. M., & Goti, A. (2017). [3 + 2] dipolar cycloadditions of cyclic nitrones with

alkenes. Organic Reactions. https://doi.org/10.1002/0471264180. or094.01

- Xuan, J., Cheng, X., & Cao, X. (2017). [3+3] Cycloaddition of in situ formed azaoxyallyl cations with nitrones: Synthesis of 1,2,4-oxadiazinan-5-one derivatives. *ChemistrySelect*. https:// doi.org/10.1002/slct.201700826
- Merino, P., Franco, S., Merchan, F. L., & Tejero, T. (2000). Nucleophilic additions to chiral nitrones: New approaches to nitrogenated compounds. *Synlett*. https://doi.org/10.1055/s-2000-6555
- Lombardo, M., & Trombini, C. (2000). Nucleophilic additions to nitrones. *Synthesis*. https://doi.org/10.1055/s-2000-6269
- Revuelta, J., Cicchi, S., Goti, A., & Brandi, A. (2007). Enantiopure cyclic nitrones: A useful class of building blocks for asymmetric syntheses. *Synthesis*. https://doi.org/10.1055/s-2007-965914
- Ueda, M., Miyabe, H., Teramachi, M., Miyata, O., & Naito, T. (2003). Novel intermolecular carbon radical addition to a nitrone: Asymmetric synthesis of α-amino acids. *Chemical Communications*. https://doi.org/10.1039/B211570K
- Ueda, M., Miyabe, H., Teramachi, M., Miyata, O., & Naito, T. (2005). Diastereoselective intermolecular radical addition to nitrones. *The Journal of Organic Chemistry*. https://doi.org/10. 1021/jo050603z
- Xie, F., Qi, Z., Yu, S., & Li, X. (2014). Rh(III)- and Ir(III)-Catalyzed C-H alkynylation of arenes under chelation assistance. *Journal of the American Chemical Society*. https://doi.org/10.1021/ ja501910e
- Deng, H., Li, H., Zhang, W., & Wang, L. (2017). Rh^{III}-Catalyzed site-selective amidation with nitrone as a traceless directing group: An approach to functionalized arylaldehydes. *Chemical Communications*. https://doi.org/10.1039/C7CC05297A
- Bøgevig, A., Gothelf, K. V., & Jørgensen, K. A. (2002). Nucleophilic addition of nitrones to ketones: Development of a new catalytic asymmetric nitrone-aldol reaction. *Chemistry A European Journal*. https://doi.org/10.1002/1521-3765(20021216)8:24% 3c5652::AID-CHEM5652%3e3.0.CO;2-J
- Berini, C., Minassian, F., Pelloux-Léon, N., Denis, J.-N., Vallée, Y., & Philouze, C. (2008). Efficient stereoselective nucleophilic addition of pyrroles to chiral nitrones. *Organic & Biomolecular Chemistry*. https://doi.org/10.1039/B802997K
- Richmond, E., Duguet, N., Slawin, A. M. Z., Lébl, T., & Smith, A. D. (2012). Asymmetric pericyclic cascade approach to spirocyclic oxindoles. *Organic Letters*. https://doi.org/10.1021/ol300982f
- Pace, W. H., Mo, D.-L., Reidl, T. W., Wink, D. J., & Anderson, L. L. (2016). Catalytic asymmetric synthesis of dihydropyrido[1,2-a] indoles from nitrones and allenoates. *Angewandte International Edition Chemie*. https://doi.org/10.1002/anie.201602568
- Son, J., Kim, K. H., Mo, D. L., Wink, D. J., & Anderson, L. L. (2017). Single-step modular synthesis of unsaturated morpholine N-oxides and their cycloaddition reactions. *Angewandte Chemie International Edition*. https://doi.org/10.1002/anie.201611791
- LeBel, N. A., & Banucci, E. G. (1971). Intramolecular nitroneolefin cycloadditions. Stereochemistry of hexahydro-2,1-benzisoxazoline formation. *The Journal of Organic Chemistry*. https://doi.org/10.1021/jo00816a013
- Andrade, M. M., Barros, M. T., & Pinto, R. C. (2008). Exploiting microwave-assisted neat procedures: Synthesis of N-aryl and N-alkylnitrones and their cycloaddition en route for isoxazolidines. *Tetrahedron*. https://doi.org/10.1016/j.tet.2008.08.101
- Pfeiffer, J. Y., & Beauchemin, A. M. (2009). Simple reaction conditions for the formation of ketonitrones from ketones and hydroxylamines. *The Journal of Organic Chemistry*. https://doi. org/10.1021/jo901653d
- Soldaini, G., Cardona, F., & Goti, A. (2007). Catalytic oxidation of imines based on methyltrioxorhenium/urea hydrogen peroxide: A mild and easy chemo- and regioselective entry to nitrones. *Organic Letters*. https://doi.org/10.1021/ol062862w

- Colladon, M., Scarso, A., & Strukul, G. (2008). Mild catalytic oxidation of secondary and tertiary amines to nitrones and N-oxides with H₂O₂ mediated by Pt(II) catalysts. *Green Chemistry*. https://doi.org/10.1039/B805404E
- Matassini, C., Parmeggiani, C., Cardona, F. & Goti, A. (2015). Oxidation of N,N-disubstituted hydroxylamines to nitrones with hypervalent iodine reagents. *Organic Letters*. https://doi.org/10. 1021/acs.orglett.5b02029.
- Reidl, T. W., Son, J., Wink, D. J., & Anderson, L. L. (2017). Facile synthesis of azetidine nitrones and diastereoselective conversion into densely substituted azetidines. *Angewandte Chemie International Edition*. https://doi.org/10.1002/anie. 201705681
- Chavannavar, A. P., Oliver, A. G., & Ashfeld, B. L. (2014). An umpolung approach toward N-aryl nitrone construction: A phosphine-mediated addition of 1,2-dicarbonyls to nitroso electrophiles. *Chemical Communications*. https://doi.org/10.1039/ C4CC05044D
- Volpe, C., Meninno, S., Roselli, A., Mancinelli, M., Mazzanti, A., & Lattanzi, A. (2020). Nitrone/imine selectivity switch in basecatalysed reaction of aryl acetic acid esters with nitrosoarenes: Joint experimental and computational study. *Advanced Synthesis* & *Catalysis*. https://doi.org/10.1002/adsc.202000855
- Reddy, A. R., Guo, Z., Siu, F.-M., Lok, C.-N., Liu, F., Yeung, K.-C., Zhou, C.-Y., & Che, C.-M. (2012). Diastereoselective ruthenium porphyrin-catalyzed tandem nitrone formation/1,3dipolar cycloaddition for isoxazolidines. Synthesis, in silico docking study and in vitro biological activities. Organic & Biomolecular Chemistry. https://doi.org/10.1039/C2OB26518D
- Reddy, A. R., Zhou, C.-Y., & Che, C.-M. (2014). Ruthenium porphyrin catalyzed three-component reaction of diazo compounds, nitrosoarenes, and alkynes: An efficient approach to multifunctionalized aziridines. *Organic Letters*. https://doi.org/10.1021/ ol4035098
- Singh, R. R., & Liu, R.-S. (2014). Gold-catalyzed 1,2-iminonitronation of electron-deficient alkynes with nitrosoarenes to afford α-imidoyl nitrones. *Chemical Communications*. https://doi.org/ 10.1039/C4CC06962E
- Pagar, V. V., & Liu, R.-S. (2015). Gold-catalyzed cycloaddition reactions of ethyl diazoacetate, nitrosoarenes, and vinyldiazo carbonyl compounds: Synthesis of isoxazolidine and benzo[b] azepine derivatives. *Angewandte Chemie International Edition*. https://doi.org/10.1002/anie.201500340
- Wu, M.-Y., He, W.-W., Liu, X.-Y., & Tan, B. (2015). Asymmetric construction of spirooxindoles by organocatalytic multicomponent reactions using diazooxindoles. *Angewandte Chemie International Edition*. https://doi.org/10.1002/anie.201504640
- Fraboni, A. J., & Brenner-Moyer, S. E. (2016). Dienaminecatalyzed nitrone formation via redox reaction. *Organic Letters*. https://doi.org/10.1021/acs.orglett.6b00770
- Li, X., Feng, T., Li, D., Chang, H., Gao, W., & Wei, W. (2019). KOAc-Catalyzed one-pot three-component 1,3-dipolar cycloaddition of α-diazo compounds, nitrosoarenes, and alkenes: An approach to functionalized isoxazolidines. *The Journal of Organic Chemistry*. https://doi.org/10.1021/acs.joc.9b00299
- Wróbel, Z., & Kwasr, A. (2007). 2-Nitroso-N-arylanilines: Products of acid-promoted transformation of ^σH adducts of arylamines and nitroarenes. *Synlett*. https://doi.org/10.1055/s-2007-982534
- Cai, B.-G., Luo, S.-S., Li, L., Li, L., Xuan, J., & Xiao, W.-J. (2020). Visible light-promoted amide bond formation via one-pot nitrone in situ formation/rearrangement cascade. *CCS Chemistry*. https://doi.org/10.31635/ccschem.020.202000588
- Narayanam, J. M. R., & Stephenson, C. R. J. (2011). Visible light photoredox catalysis: Applications in organic synthesis. *Chemical Society Reviews*. https://doi.org/10.1039/B913880N

- Xuan, J., & Xiao, W.-J. (2012). Visible-light photoredox catalysis. Angewandte Chemie International Edition. https://doi.org/10. 1002/anie.201200223
- Xi, Y., Yi, H., & Lei, A. (2013). Synthetic applications of photoredox catalysis with visible light. *Organic & Biomolecular Chemistry*. https://doi.org/10.1039/C3OB40137E
- Prier, C. K., Rankic, D. A., & MacMillan, D. W. C. (2013). Visible light photoredox catalysis with transition metal complexes: Applications in organic synthesis. *Chemical Reviews*. https://doi. org/10.1021/cr300503r
- Hopkinson, M. N., Sahoo, B., Li, J.-L., & Glorius, F. (2014). Dual catalysis sees the light: Combining photoredox with organo-, acid, and transition-metal catalysis. *Chemistry A European Journal*. https://doi.org/10.1002/chem.201304823
- Marzo, L., Pagire, S., Reiser, O., & König, B. (2018). Visible-light photocatalysis: Does it make a difference in organic synthesis? *Angewandte Chemie International Edition*. https://doi.org/10. 1002/anie.201709766
- 46. Chen, Y., Lu, L.-Q., Yu, D.-G., Zhu, C.-J., & Xiao, W.-J. (2019). Visible light-driven organic photochemical synthesis in china. *Science China Chemistry*. https://doi.org/10.1007/ s11426-018-9399-2
- Cai, B.-G., Xuan, J., & Xiao, W.-J. (2019). Visible light-mediated C-P bond formation reactions. *Science Bulletin*. https://doi.org/10. 1016/j.scib.2019.02.002
- Yu, X.-Y., Zhao, Q.-Q., Chen, J., Xiao, W.-J., & Chen, J.-R. (2020). When light meets nitrogen-centered radicals: From reagents to catalysts. *Accounts of Chemical Research*. https://doi.org/ 10.1021/acs.accounts.0c00090
- Sun, K., Lv, Q.-Y., Chen, X.-L., Qu, L.-B., & Yu, B. (2021). Recent advances in visible-light-mediated organic transformations in water. *Green Chemistry*. https://doi.org/10.1039/D0GC03447A
- Sun, K., Lv, Q.-Y., Lin, Y.-W., Yu, B., & He, W.-M. (2021). Nitriles as radical acceptors in radical cascade reactions. *Organic Chemistry Frontiers*. https://doi.org/10.1039/D0Q001058H
- Ciszewski, L. W., Rybicka-Jasinska, K., & Gryko, D. (2019). Recent developments in photochemical reactions of diazo compounds. Organic & Biomolecular Chemistry. https://doi.org/10. 1039/C80B02703J
- Yang, Z., Stivanin, M. L., Jurberg, I. D., & Koenigs, R. M. (2020). Visible light-promoted reactions with diazo compounds: A mild and practical strategy towards free carbene intermediates. *Chemical Society Reviews*. https://doi.org/10.1039/D0CS00224K
- Empel, C., & Koenigs, R. M. (2019). Sustainable carbene transfer reactions with iron and light. *Synlett*. https://doi.org/10.1055/s-0037-1611874
- Jana, S., Guo, Y., & Koenigs, R. M. (2021). Recent perspectives on rearrangement reactions of ylides via carbene transfer reactions. *Chemistry A European Journal*. https://doi.org/10.1002/ chem.202002556
- Jurberg, I., & Davies, H. M. L. (2018). Blue light-promoted photolysis of aryldiazoacetates. *Chemical Science*. https://doi.org/10. 1039/C8SC01165F
- Hommelsheim, R., Guo, Y., Yang, Z., Empel, C., & Koenigs, R. M. (2019). Blue-light-induced carbene-transfer reactions of diazoalkanes. *Angewandte Chemie International Edition*. https:// doi.org/10.1002/anie.201811991
- Jana, S., Yang, Z., Li, F., Empel, C., Ho, J., & Koenigs, R. M. (2020). Photoinduced proton-transfer reactions for mild O-H functionalization of unreactive alcohols. *Angewandte Chemie International Edition*. https://doi.org/10.1002/anie.201915161
- Jana, S., Yang, Z., Pei, C., Xu, X., & Koenigs, R. M. (2019). Photochemical ring expansion reactions: Synthesis of tetrahydrofuran derivatives and mechanism studies. *Chemical Science*. https://doi. org/10.1039/C9SC04069B

- Guo, Y., Nguyen, T. V., & Koenigs, R. M. (2019). Norcaradiene synthesis via visible-light-mediated cyclopropanation reactions of arenes. *Organic Letters*. https://doi.org/10.1021/acs.orglett.9b034 53
- He, F., & Koenigs, R. M. (2019). Visible light mediated, metalfree carbene transfer reactions of diazoalkanes with propargylic alcohols. *Chemical Communications*. https://doi.org/10.1039/ C9CC00927B
- He, F., Li, F., & Koenigs, R. M. (2020). Metal-free insertion reactions of silanes with aryldiazoacetates. *The Journal of Organic Chemistry*. https://doi.org/10.1021/acs.joc.9b02605
- Empel, C., Patureau, F. W., & Koenigs, R. M. (2019). Visible light induced metal-free carbene N-carbazolation. *The Journal* of Organic Chemistry. https://doi.org/10.1021/acs.joc.9b01753
- Orlowska, K., Rybicka-Jasinska, K., Krajewski, P., & Gryko, D. (2020). Photochemical doyle–kirmse reaction: A route to allenes. *Organic Letters*. https://doi.org/10.1021/acs.orglett.9b04560
- Yang, J., Wang, J., Huang, H., Qin, G., Jiang, Y., & Xiao, T. (2019). gem-Difluoroallylation of aryl diazoesters via catalystfree, blue-light-mediated formal doyle–kirmse reaction. Organic Letters. https://doi.org/10.1021/acs.orglett.9b00647
- Xiao, T., Mei, M., He, Y., & Zhou, L. (2018). Blue light-promoted cross-coupling of aryldiazoacetates and diazocarbonyl compounds. *Chemical Communications*. https://doi.org/10.1039/ C8CC04609C
- Yang, Z., Guo, Y., & Koenigs, R. M. (2018). Solvent-dependent, rhodium catalysed rearrangement reactions of sulfur ylides. *Chemical Communications*. https://doi.org/10.1039/C9CC03809D
- Rybicka-Jasińska, K., Shan, W., Zawada, K., Kadish, K. M., & Gryko, D. (2020). Porphyrins as photoredox catalysts: Experimental and theoretical studies. *Journal of the American Chemical Society*. https://doi.org/10.1021/jacs.6b09036
- Cheng, R., Qi, C., Wang, L., Xiong, W., Liu, H., & Jiang, H. (2020). Visible light-promoted synthesis of organic carbamates

from carbon dioxide under catalyst- and additive-free conditions. *Green Chemistry*. https://doi.org/10.1039/D0GC00910E

- Cai, B.-G., Chen, Z.-L., Xu, G.-Y., Xuan, J., & Xiao, W.-J. (2019). [3 + 2]-cycloaddition of 2*H*-azirines with nitrosoarenes: Visible-light-promoted synthesis of 2,5-dihydro-1,2,4-oxadiazoles. Organic Letters. https://doi.org/10.1021/acs.orglett.9b01416
- Ge, Q.-Q., Qian, J.-S., & Xuan, J. (2019). Electron donor–acceptor complex enabled eecarboxylative sulfonylation of cinnamic acids under visible-light irradiation. *The Journal of Organic Chemistry*. https://doi.org/10.1021/acs.joc.9b00552
- He, X.-K., Cai, B.-G., Yang, Q.-Q., Wang, L., & Xuan, J. (2019). Visible-light-promoted cascade radical cyclization: Synthesis of 1,4-diketones containing chroman-4-One Skeletons. *Chemistry An Asian Journal*. https://doi.org/10.1002/asia.201901078
- He, X.-K., Lu, J., Zhang, A.-J., Zhang, Q.-Q., Xu, G.-Y., & Xuan, J. (2020). BI-OAc-accelerated C3–H alkylation of quinoxalin-2(1H)-ones under visible-light irradiation. *Organic Letters*. https://doi.org/10.1021/acs.orglett.0c02080
- Lu, J., He, X.-K., Cheng, X., Zhang, A.-J., Xu, G.-Y., & Xuan, J. (2020). Photoredox catalyst free, visible light-promoted C3–H acylation of quinoxalin-2(1H)-ones in water. *Advanced Synthesis* & *Catalysis*. https://doi.org/10.1002/adsc.202000116
- Xuan, J., He, X.-K., & Xiao, W.-J. (2020). Visible light-promoted ring-opening functionalization of three-membered carbo- and heterocycles. *Chemical Society Reviews*. https://doi.org/10.1039/ C9CS00523D
- Ye, C., Cai, B.-G., Lu, J., Cheng, X., Li, L., Pan, Z.-W., & Xuan, J. (2021). Visible-light-promoted polysubstituted olefins synthesis involving sulfur ylides as carbene trapping reagents. *The Journal* of Organic Chemistry. https://doi.org/10.1021/acs.joc.0c02500
- Guo, W., Gu, J., & Gu, Z. (2020). Catalytic asymmetric synthesis of atropisomeric nitrones: Versatile intermediate for axially chiral biaryls. Organic Letters. https://doi.org/10.1021/acs.orglett.0c028 30