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Visible light mediated organocatalytic dehydrogenative aza-coupling of 1,3-diones using aryldiazonium salts†

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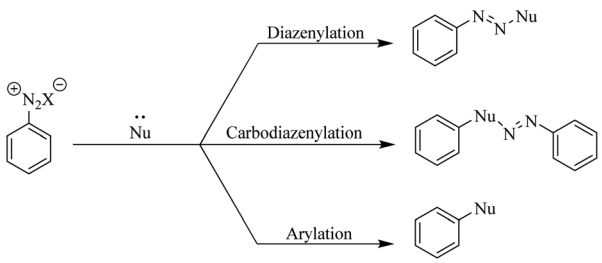
An efficient protocol for diazenylation of 1,3-diones under photoredox conditions is presented herein. C–N bond forming C_{sp^3}–H functionalization of cyclic and alkyl diones by unstable aryl diazenyl radicals is achieved through reaction with aryldiazonium tetrafluoroborates by organocatalysts under visible light irradiation. The reaction has wide substrate scope, gives excellent yields, and is also efficient in water as a green solvent. This method provides an easy access to aryldiazenyl derivatives that are useful key starting materials for the synthesis of aza heterocycles as well as potential pharmacophores.

Introduction

Finding newer methods for a carbon–heteroatom bond, in particular, C–N bond formation reactions is pivotal in organic synthesis because of the rich abundance of C–N functionalization in a vast number of natural products, drugs, and other important molecules.[1] Among the huge number of nitrogenous molecules, azo compounds are of great importance due to their rich abundance in naturally occurring bioactive compounds, drug molecules containing nitrogenous heterocycles, their applications in dye industry, and others.[2] Many azo compounds are known to mediate site-specific drug delivery.[3] Therefore, the development of various synthetic routes to azo compounds has attracted the attention of synthetic organic chemists at large.[4] But till now only a limited number of synthetic routes to such azo compounds could be devised.[5] Among them diazenylazation is considered to be a convenient and efficient method. Diazenylazation is the incorporation of diazo alkyl or aryl group into an active methylene compound[6] or any C-nucleophile.[7] These diazenylated products can be obtained from aryl diazonium salts, triazenes[8] and hydrazine salts,[9] which often require the use of heavy metal catalysis, difficult reaction conditions, and other complicated techniques. However, the generation of unstable diazenyl radical is very less known because of its short half-life period in solution,[10] which loses a nitrogen molecule to produce a more stable phenyl radical.[11] Therefore, mainly three types of reactions, *viz.* diazenylation, carbodiazenylation,[12] and most widely arylation[13] reactions are observed (Scheme 1).

Aryl diazonium salts are easily accessed and synthesized in one-step by diazotization of readily available corresponding anilines,[14] of which are mostly useful for arylation[15] or less frequently for diazenylation[16] depending upon the condition used. In the last few years, resourceful researches have been carried out using aryl diazonium salts as substrates under organophotocatalysed, visible light irradiation for arylation or diazenylation of different substituted heteroaryl moieties which resulted in the synthesis of drug scaffolds.[17] But only a handful of diazenylazation type of reactions are being reported, where Fagnoni *et al.* (Fig. 1) method provides one-pot diazenyl compounds. However, the method requires stable arylazo sulfones and excess silyl enol ether, and maintaining the pH of the solution.[6c] Recently, Brahmachari *et al.* reported one-step diazenylation of 4-hydroxycoumarins with *in situ* generated aryl diazonium cation in ball milling process. However, this method is limited to the diazenylation of 4-hydroxycoumarin derivatives.[18] In this regard, the advancement of the synthesis of diazenyl compound is still a challenging area for chemists which demand cheap and efficient synthetic techniques. Compared to aryl diazenyl compounds, the alkyl diazenyl



Scheme 1 Different types of reaction with aryldiazonium salts.

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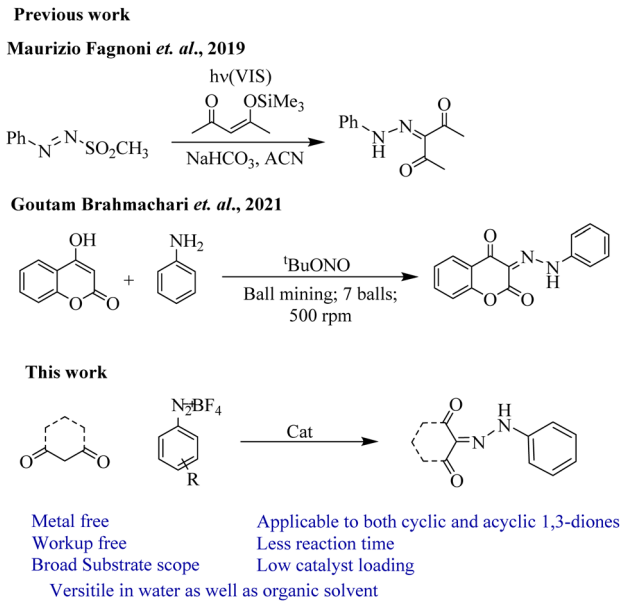


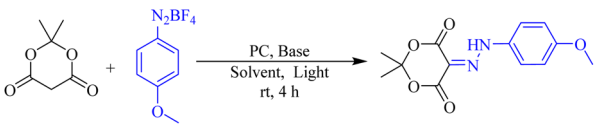
Fig. 1 Dehydrogenative diazenylation of diones.

compounds are least tolerant and unstable towards functional groups.[19] But they are found to possess anti-inflammatory and antibiotic drug like properties. Over the last two decades, visible light photocatalysis has emerged as a greener approach in organic synthesis.[20] Also, the replacement of volatile organic compounds (VOCs) as solvents with greener media[21] like water[22] has become a need of the day. In line with our current research interest in green chemistry and photoredox catalysis, herein we report an efficient and inexpensive visible light-mediated organocatalysed synthesis of diazenyl compounds using 1,3-diones and aryl diazonium salts without the use of any metal activator or ligand. Also, we have carried out the reactions in water obtaining equally excellent yields.

Results and discussion

Considering our current interest in the synthesis of diazenyl compounds, we started our investigation using Meldrum's acid (**1a**, 0.2 mmol) and *p*-methoxy aryldiazonium salt (**2a**, 0.24 mmol) as model substrates. Taking into account the solubility of aryldiazonium tetrafluoroborate salts, we chose acetonitrile (ACN) as the preferred solvent.[23] We then irradiated the reaction mixture with a 40 W Kessil Blue LED bulb in the presence of 5 mol% Eosin Y[24] as a photocatalyst and 2 equivalent of diisopropyl ethyl amine (DIPEA). The reaction was carried out at room temperature in acetonitrile (0.1 M, 2 mL). Air cooling was maintained to dissipate the little heat generated in such visible light-catalysed reactions. We were delighted to isolate the

Table 1 Optimization of reaction condition for 1,3 diones and aryl diazonium salts[a]



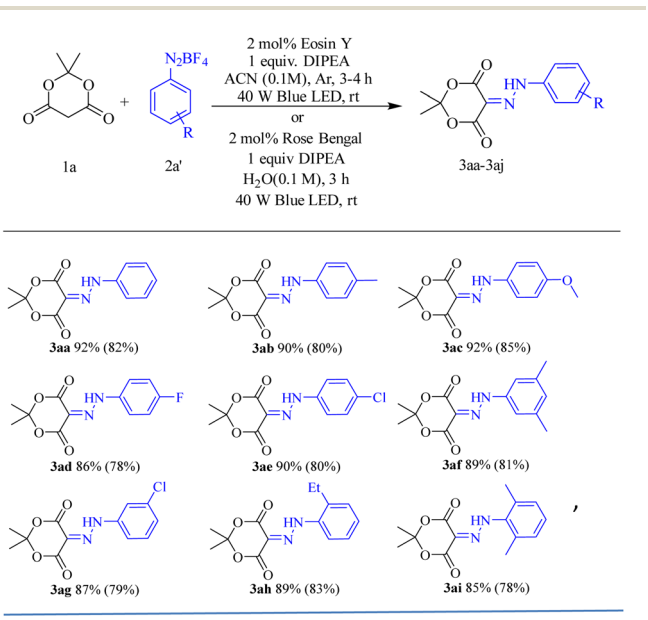
Entry	Catalyst (mol%)	Base (equivalent)	Solvent	Yield[b] (%)
1	Eosin Y (5 mol%)	DIPEA (2)	ACN	80
2	Eosin Y (5 mol%)	DIPEA (2)	DMF	65
3	Eosin Y (5 mol%)	DIPEA (2)	Toluene	ND
4	Eosin Y (5 mol%)	DIPEA (2)	1,4-Dioxane	70
5	Eosin Y (5 mol%)	DIPEA (2)	DCM	ND
6	Eosin Y (2 mol%)	DIPEA (2)	ACN	80
7	**Eosin Y (2 mol%)**	**DIPEA (1)**	**ACN**	**92**
8	—	DIPEA (1)	ACN	20
9[c]	Eosin Y (2 mol%)	—	ACN	25
10	Eosin Y (2 mol%)	K_3PO_4 (1)	ACN	58
11	$Ru(bpy)_3Cl_2$ (2 mol%)	Et_3N (1)	ACN	71
12	Eosin Y (2 mol%)	Et_3N (1)	ACN	25
13[d]	Eosin Y (2 mol%) (in dark, 8 h)	DIPEA (1)	ACN	20
14	Eosin Y (10 mol%)	DIPEA (1)	ACN	84
15	Methylene Blue (2 mol%)	DIPEA (1)	ACN	67
16	Rose Bengal (2 mol%)	DIPEA (1)	ACN	74
17	Methylene Blue (2 mol%)	DIPEA (1)	ACN	NR
18	**Rose Bengal (2 mol%)**	**DIPEA (1)**	**H_2O**	**85**
19	Rose Bengal (2 mol%)	—	H_2O	NR
20	Eosin Y	DIPEA (1)	H_2O	70

[a] Reaction condition: 1,3-dione **1a** (0.2 mmol), aryl diazonium salts (0.24 mmol), solvent (2.0 mL), room temperature, under 40 W Blue LEDs irradiation for 4 h. [b] Isolated yield. [c] Without base. [d] 1,3-Dione **1a** (0.2 mmol), aryl diazonium salts (0.24 mmol), solvent (2.0 mL), room temperature in dark condition.

corresponding diazenyl compound (**3ac**) in 80% yield after 3 hours. Remarkably, the reaction was very clean furnishing **3ac** as a single product, and no significant amount of undesired products was observed. Then we embarked upon finding the optimum reaction condition (Table 1). First, we explored other polar solvents such as DMF, 1,4-dioxane, dichloromethane, and non-polar solvent like toluene were also examined. But we found that the reaction furnished optimum yield in ACN compared to other solvents (entries 1–5, Table 1). Noticeably, the reaction in DCM produced a significant number of undesired products (entry 5, Table 1). Hence, we carried out all the reactions in ACN as our solvent of choice. We then screened various bases such as triethyl amine (Et_3N), diisopropyl ethyl amine (DIPEA), and K_3PO_4, and found that 1 equivalent of DIPEA was optimum for completion of the reaction (entries 7–12, Table 1). When we carried out the reaction in the absence of a base, the desired product was obtained in just 25% yield. Hence, it was inferred that DIPEA was needed for the regeneration of the catalyst in the catalytic cycle. However, increasing the equivalent of aryl diazonium salt from 1.2 to 2 equivalents, no improvement in the yield% was observed. The optimum catalyst loading was determined to be 2 mol% (entry 7, Table 1). Again, the same reaction was carried out in the presence of DIPEA and Eosin Y but in the absence of visible light for 24 h (entry 13, Table 1). Only 20% conversion was observed. But the same when done in the absence of either base or photocatalyst and absence of both, no conversion was observed. It established that both DIPEA and Eosin Y as the photocatalyst are essential for success of the diazenylation. With all the optimized conditions in our hand, we then started reacting different aryl diazonium salts with Meldrum's acid to furnish the corresponding diazenylated products (Scheme 2). The advantage of this reaction is that it does not require any external workups or quenching. The reaction mixture is directly concentrated and purified by column chromatography (CC).

Use of volatile organic compounds (VOCs) significantly impacts our environment. Avoidance of such VOCs is one of the major goals of modern green chemistry. In this regard, water has evolved into a preferable solvent for green chemistry approach. Increasingly, visible light catalyzed reactions are being performed in water.[25] Major reason behind it is that many of the dyes used as organophotocatalysts are soluble in water, like Rose Bengal, Eosin Y, Eosin B, Rhodamine B, Methylene Blue, various Flavonoids, *etc.* Therefore, we repeated the reaction of **1a** and **2a** in the presence of 2 mol% of Eosin Y and 1 equivalent of DIPEA in water (2 mL) and irradiated with a 40 W Blue LED bulb resulting in a little lower yield of **3ac** (70%, entry 21, Table 1). Then we tried the same reaction with 2 mol% of different water soluble photocatalysts such as $Ru(bpy)_3Cl_2$, Methylene Blue, and Rose Bengal (Table 1). Gratifyingly, Rose Bengal in water gave **3ac** in excellent yield (85%, entry 18, Table 1). Though the yield was slightly lower than in ACN using Eosin Y. Encouraged by this success, we decided to repeat each reaction with optimized conditions in both ACN and water. Obtained yields in water are reported in parentheses in each case.

To shed light on the efficiency of the reaction, UV-Vis spectroscopy technique was used. We observed that *p*-methoxy aryldiazonium tetrafluoroborate salt (**2a**) exhibits a UV-vis absorption band at 310 nm whereas catalyst Eosin Y exhibits a notable UV-visible absorption band at 530 nm (Fig. S1, ESI†). The above reported reaction was performed using Meldrum's acid (**1a**), *p*-methoxy aryldiazonium salt (**2a**), Eosin Y, and DIPEA in 2 mL ACN irradiated with 40 W Blue LED light and UV-Vis



Scheme 2 Substrate scope of Meldrum's acid. [a] Isolated yield; reaction condition: **1a** (0.20 mmol), **2** (0.24 mmol), Eosin Y (2 mol%), DIPEA (0.20 mmol), ACN (2 mL), 40 W Kessil Blue LED bulb and stirring at room temperature.

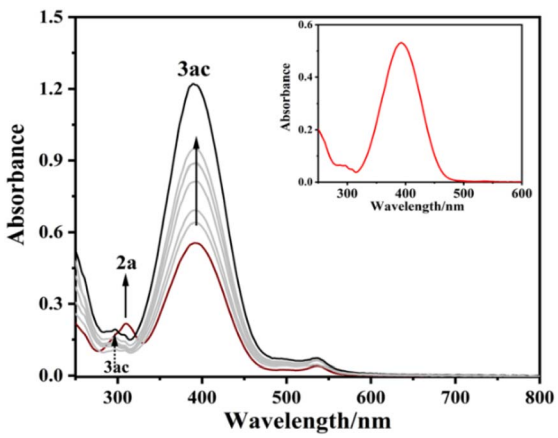
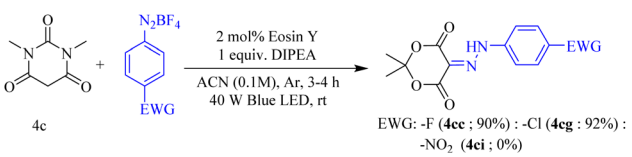
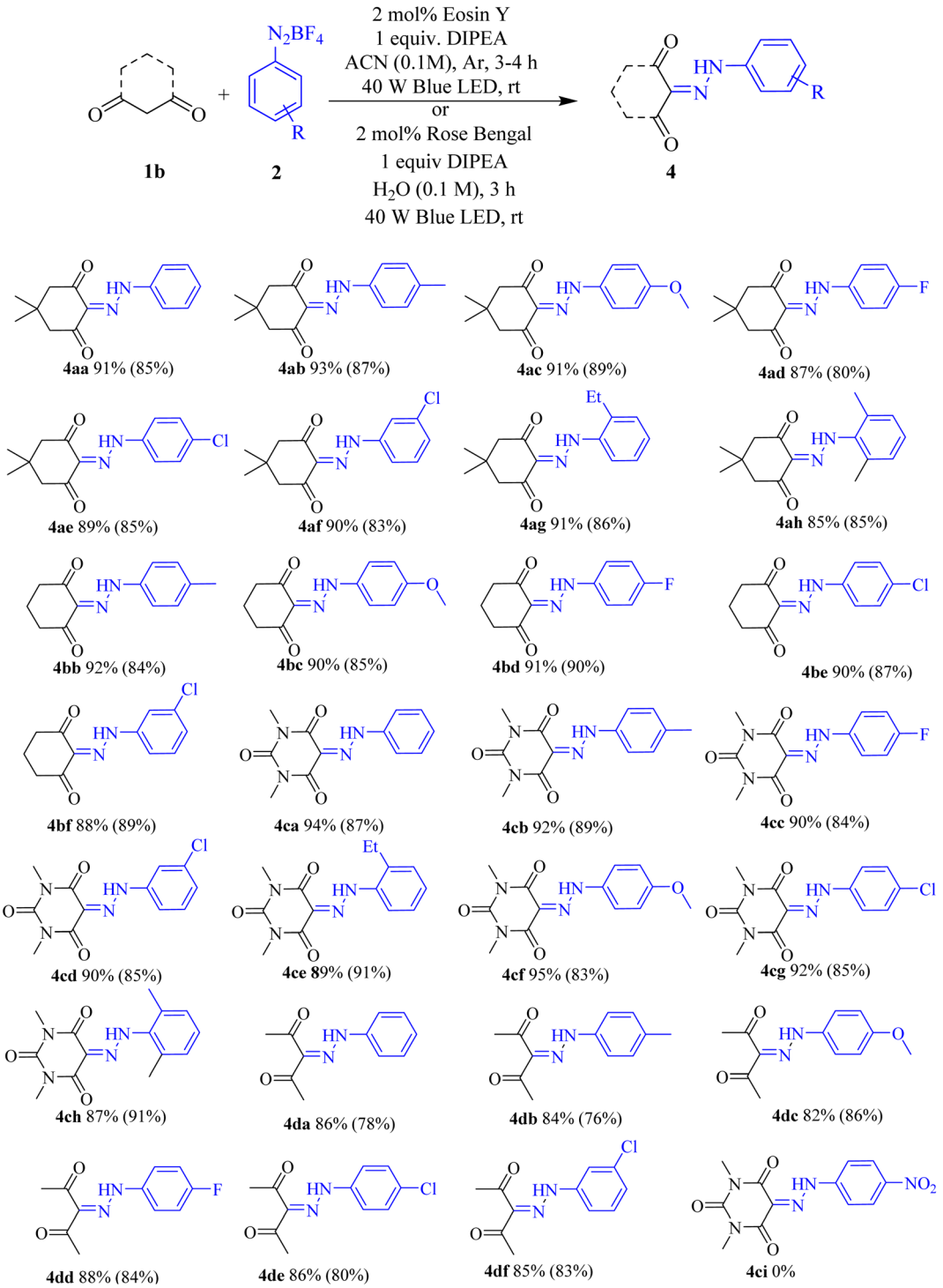


Fig. 2 Time profile UV-vis spectroscopic analysis.



Scheme 3 Reaction of barbiturate with *p*-nitro aryldiazonium salt.



Scheme 4 Substrate scope for other 1,3 diones. [a] Isolated yield; reaction condition: **1a** (0.20 mmol), **2** (0.24 mmol), Eosin Y (2 mol%), DIPEA (0.20 mmol), ACN (2 mL), Ar, 40 W Kessil 160WE Blue LED bulb and stirring at room temperature. [b] Reaction condition: **1a** (0.20 mmol), **2** (0.24 mmol), Rose Bengal (2 mol%), DIPEA (0.20 mmol), water (2 mL), 40 W Kessil 160WE Blue LED bulb and stirring at room temperature.

spectra were recorded in a periodic time interval of 15 minutes. It was seen that two new peaks were generated at 295 nm and 390 nm (Fig. 2). We have confirmed these peaks were responsible for the formation of our product **3ac** after purification (Fig. 2 inset). Further, these peaks gradually intensified and reached maximum at 105 minutes. It was also observed that the peak of aryl diazonium salt simultaneously kept decreasing and the peak of the catalyst (Eosin Y) at 530 nm remained practically static which confirms the regeneration of the catalyst in every cycle. To further evaluate the efficacy of the reaction, we

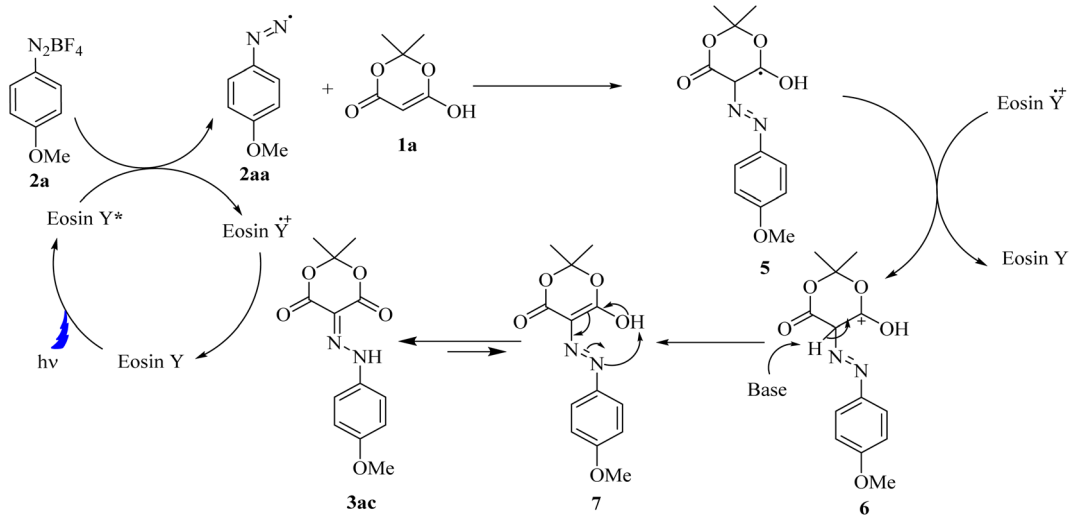


Fig. 3 Plausible mechanism for C–N bond forming C_{sp^3}–H functionalization of cyclic diones.

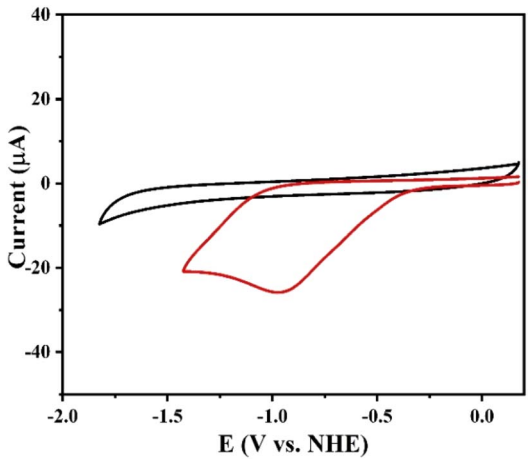


Fig. 4 Cyclic voltammogram of *p*-methoxy aryldiazonium tetrafluoroborates salt **2a** (red, 1 mM) and blank (black). Supporting electrolyte $LiClO_4$ (0.1 M); scan rate 0.1 V s^{-1}.

examined different cyclohexane 1,3-dione derivatives and barbiturates. Altogether, thirteen diazenylated cyclohexane 1,3-dione derivatives were synthesized in excellent yields (85–93% in ACN and 80–90% in water). Next, eight diazenylated barbiturate derivatives were also prepared in excellent yields (87–95% in ACN and 83–91% in water) (Scheme 4). We found that barbituric acid derivatives (**4ca–4ch**, Scheme 4) are the most reactive among all the diones used. On the other hand, aryl diazonium salts having an electron donating group (EDG) were found to be more reactive than those having an electron withdrawing group (EWG). Interestingly, chloro and fluoro-aryl diazonium salts furnished expected products, but *p*-nitro aryldiazonium salts failed to give the desired product (Scheme 3). Alkylation, arylation, or diazenylation reactions with acyclic 1,3-diones are rarely achieved. We were pleasantly surprised when we carried out the reaction of *p*-methoxy aryl diazonium salt with acetylacetone in ACN, the reaction was completed in 4 hours and the desired diazenyl product was isolated in 80% yield. The acetylacetone was carried out in ACN and Eosin Y with five other aryl diazonium salts. All five other aryl diazonium salts were also found to be well tolerated and furnished desired products (**4da–4df**, Scheme 4) in good yields. These alkyl diazenes are a very important class of biologically active scaffolds.[26]

Lastly, to understand the mechanism, a series of controlled potential cyclic voltammetry (CV) experiment were conducted to rationalize the step propagation. From CV experiments, it was found that the redox potential of Eosin Y ($E_{1/2} = -1.1$ V *vs.* NHE in ACN), would likely reduce the *p*-methoxy aryldiazonium salts ($E_{1/2} = -1.0$ V *vs.* NHE in ACN) and itself would be oxidized to Eosin Y cationic radical (Eosin $Y^{+\bullet}$). Keeping all the factors in mind, a plausible mechanism is proposed in Fig. 3. First, in the presence of Blue LED light (455 nm), Eosin Y will be excited to generate Eosin Y* which will reduce the *p*-methoxy aryldiazonium salts to *p*-methoxy aryldiazonium radical and itself get oxidized to Eosin Y cationic radical (Eosin $Y^{+\bullet}$). The generated *p*-methoxy aryldiazonium radical will then combine with Meldrum's acid to give the radical intermediate **5**. To complete the catalytic cycle, the Eosin Y cationic radical (Eosin $Y^{+\bullet}$) will accept an electron from the intermediate **5** to give the cationic intermediate **6**, and Eosin Y* reverts to ground state. The base present, DIPEA will abstract the acidic proton to give diazo enol **7**. The intermediate **7** will then tautomerize to the more stable diazenyl compound **3ac**. To rationalize the reaction mechanism, cyclic voltammetry (CV) was performed in acetonitrile with *p*-methoxy aryldiazonium salt (**2a**) and *p*-nitro aryldiazonium salt (**2c**) using glassy carbon as the working electrode. Results are depicted in Fig. 4 and 5, respectively. From Fig. 4 it is observed that **2a** exhibits an irreversible reduction wave at −1.0 V *vs.* NHE at 0.1 V s^{-1} scan rate. On the other hand, in Fig. 5, a quasi-reversible redox wave is observed for **2c** with $E_{p,c} = -0.35$ V *vs.* NHE at 0.7 V s^{-1} scan rate. We were unable to detect any redox wave for **2c** at a lower scan rate which suggests that after reduction **2c** produced a very short-lived reduced

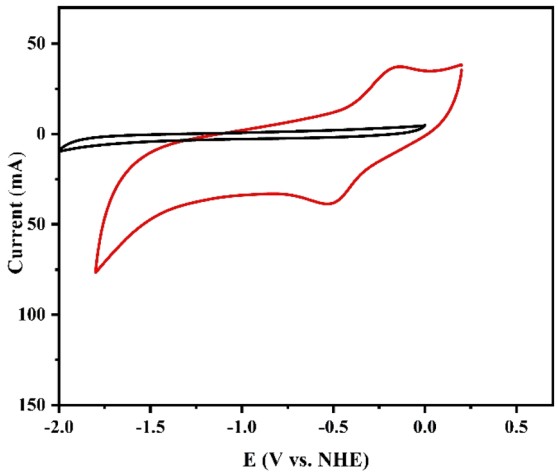


Fig. 5 Cyclic voltammogram of *p*-nitro aryldiazonium tetrafluoroborates salt **2c** (red, 1 mM) and blank (black). Supporting electrolyte $LiClO_4$ (0.1 M); scan rate 0.7 V s^{-1}.

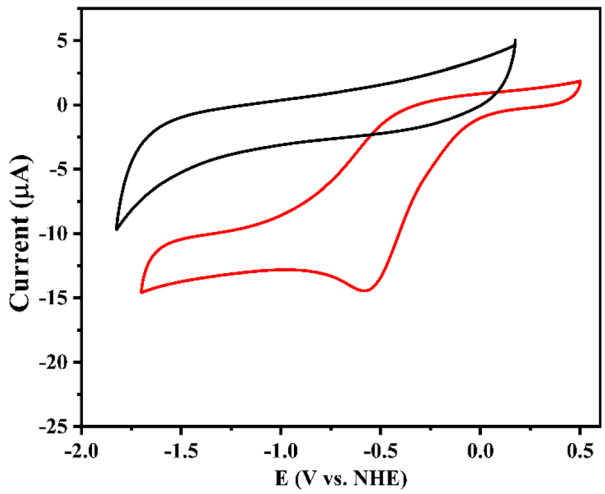
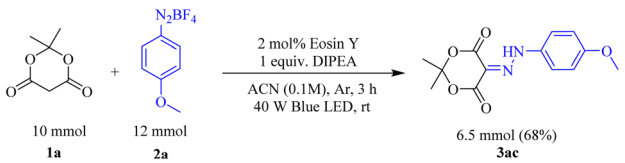


Fig. 6 Cyclic voltammogram of *p*-fluoro aryldiazonium tetrafluoroborates salt **2d** (red, 1 mM) and blank (black). Supporting electrolyte $LiClO_4$ (0.1 M); scan rate 0.1 V s^{-1}.



Scheme 5 Gram scale synthesis.

species. But the quasi-reversible peak at a higher scan rate strongly suggests that the reduced species are stable enough and the available electron density on the radical undergoes delocalization into the conjugated π orbitals. On the contrary, another CV of *p*-fluoro aryldiazonium salt showed an irreversible reduction wave at −0.5 V *vs.* NHE at 0.1 V s^{-1} scan rate (Fig. 6) which suggests that the *p*-fluoro aryldiazonium radical is different from *p*-nitro aryldiazonium. Hence the reactivity of both the electron withdrawing groups are different.

Gram scale synthesis

We also tried the same model substrate **1a** and **2a** for gram scale synthesis of **3ac** which furnished a yield of 68%. Hence the reaction is practical for reasonably large-scale synthesis (Scheme 5).

Conclusion

In conclusion, we have developed a mild, visible light catalyzed atom economic approach towards the synthesis of diazenyl compounds. The reaction does not require use of any ligand, metal catalyst, work-up, or expensive starting materials. Here, we were able to modulate the activity of the diazonium cation and trap the unstable, somewhat elusive diazenyl radical by the diones and avoid arylation through loss of nitrogen. Here we have synthesized various chromophores of alkyl diazenes efficiently in a single step without heating or hydrolysis. Altogether 37 derivatives have been prepared in 80–94% (ACN); 76–91% (water) yields. Notably, all these reactions were completed within 3–4 hours compared to 20 hours reported earlier using other aryl azo derivatives. We have done mechanistic studies using cyclic voltammetry to explain differential reactivities of various aryldiazonium cations in terms of their reduction potentials. This strategy gives an effective method of C–N bond formation through C_{sp^3}–H functionalization giving access to diazenyl compounds useful for synthesis of aza substituted heterocycles and interesting bioactive scaffolds. Herein reported method shows high substrate scope and sufficient green chemistry quotient as the reactions were almost equally efficient in water compared to the optimized organic solvent acetonitrile.

Experimental

Method A

0.2–0.3 mmol of 1,3-diones, 2 mol% of Eosin Y, and 1.2 eq. of aryldiazonium tetrafluoroborate were dissolved in 2 mL of acetonitrile in a 20 mL oven-dried glass vial and argon were purged through a needle to the solution for 5 min, 1 eq. of diisopropyl ethyl amine was added slowly to the mixture and again argon was purged for another 5 min and sealed with a cap. The glass vial was irradiated with a 40 W Blue LED Kessil bulb with continuous stirring for 3–4 hours. The progress of the reaction was monitored by TLC.

Method B

0.2–0.3 mmol of 1,3-diones, 2 mol% of Rose Bengal, and 1.2 eq. of aryldiazonium tetrafluoroborate were dissolved in 2 mL of water in a 20 mL oven dried glass vial. 1 eq. of diisopropyl ethyl amine was added slowly to the mixture and sealed with a cap. The glass vial was irradiated with a 40 W Blue Led Kessil bulb with continuous stirring for 3–4 hours. The progress of the reaction was monitored by TLC.

After the completion of the reaction, the solvent was evaporated under reduced pressure in a rotary evaporator without any workup procedure. The resulting crude was purified in a column chromatography using petroleum ether and ethyl acetate as eluent.

Conflicts of interest

There are no conflicts to declare.

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References

1 (*a*) A. A. Beharry and G. A. Woolley, *Chem. Soc. Rev.*, 2011, **40**, 4422–4437; (*b*) W. Szymański, J. M. Beierle, H. A. V. Kistemaker, W. A. Velema and B. L. Feringa, *Chem. Rev.*, 2013, **113**, 6114–6178; (*c*) M. Dong, A. Babalhavaeji, S. Samanta, A. A. Beharry and G. A. Woolley, *Acc. Chem. Res.*, 2015, **48**, 2662–2670; (*d*) J. F. Hartwig, *Nature*, 2008, **455**, 314–322; (*e*) A. K. Yudin and J. F. Hartwig, *Catalysed Carbon-Heteroatom Bond Formation*, Wiley-VCH, Weinheim, 2010; (*f*) N. Yasukawa, M. Kuwata, T. Imai, Y. Monguchi, H. Sajiki and Y. Sawama, *Green Chem.*, 2018, **20**, 4409–4413; (*g*) J. Shi, T. Yuan, R. Wang, M. Zheng and X. Wang, *Green Chem.*, 2021, **23**, 3945–3949.

2 (*a*) Y. Yu, M. Nakano and T. Ikeda, *Nature*, 2003, **425**, 145; (*b*) S. M. Sondhi, M. Dinodia and A. Kumar, *Bioorg. Med. Chem.*, 2006, **14**, 4657–4663; (*c*) T. Fehrentz, M. Schönberger and D. Trauner, *Angew. Chem., Int. Ed.*, 2011, **50**, 12156–12182; (*d*) A. A. Beharry and G. A. Woolley, *Chem. Soc. Rev.*, 2011, **40**, 4422–4437; (*e*) B. K. Ho, Z. Ngaini, P. Matthew Neilsen, S. S. Hwang, R. Entigu Linton, E. L. Kong and B. K. Lee, *J. Chem.*, 2017, **2017**, 1–7; (*f*) S. H. Lee, E. Moroz, B. Castagner and J. C. Leroux, *J. Am. Chem. Soc.*, 2014, **136**, 12868–12871; (*g*) M. A. Sofan, A. El-Mekabaty, A. M. Hasel and S. B. Said, *J. Heterocycl. Chem.*, 2021, **58**, 1645–1655; (*h*) G. S. Kumar and D. C. Neckers, *Chem. Rev.*, 1989, **89**, 1915–1925.

3 (*a*) M. Roldo, E. Barbu, J. F. Brown, D. W. Laight, J. D. Smart and J. Tsibouklis, *Expert Opin. Drug Delivery*, 2007, **4**, 547–560; (*b*) R. Cassano, S. Trombino, A. Cilea, T. Ferrarelli, R. Muzzalupo and N. Picci, *Chem. Pharm. Bull.*, 2010, **58**, 103–105; (*c*) A. Jain, Y. Gupta and S. K. Jain, *Crit. Rev. Ther. Drug Carrier Syst.*, 2006, **23**, 349–400.

4 (*a*) S. Benkhaya, S. M'rabet and A. El Harfi, *Heliyon*, 2020, **6**, e03271; (*b*) S. M. Koshti, J. P. Sonar, A. E. Sonawane, Y. A. Pawar, P. S. Nagle, P. P. Mahulikar and D. H. More, *Indian J. Chem., Sect. B: Org. Chem. Incl. Med. Chem.*, 2008, **47**, 329–331; (*c*) R. Zhao, C. Tan, Y. Xie, C. Gao, H. Liu and Y. Jiang, *Tetrahedron Lett.*, 2011, **52**, 3805–3809; (*d*) A. Grirrane, A. Corma and H. García, *Science*, 2008, **322**, 1661–1664; (*e*) R. Z. Qiao, Y. Zhang, X. P. Hui, P. F. Xu, Z. Y. Zhang, X. Y. Wang and Y. L. Green, *Chem*, 2001, **3**, 186–188; (*f*) C. Zhang and N. Jiao, *Angew. Chem.*, 2010, **122**, 6310–6313.

5 (*a*) B. Deng, C. Li, J. Yuan, C. B. Rao, Y. Zhao, R. Zhang and D. Dong, *Tetrahedron*, 2019, **75**, 2273–2279; (*b*) G. B. Raju, M. Mahesh, G. Manjunath and P. V. Ramana, *Chem. Sci. Trans.*, 2016, **5**, 125–136; (*c*) J. M. dos Santos Filho, D. M. A. de Queiroz e Silva, T. S. Macedo, H. M. P. Teixeira, D. R. M. Moreira, S. Challal, J. L. Wolfender, E. F. Queiroz and M. B. P. Soares, *Bioorg. Med. Chem.*, 2016, **24**, 5693–5701; (*d*) D. Pranali and J. Kale, *Chem. Pharm. Res.*, 2013, **5**, 130–134.

6 (*a*) E. S. Zhilin, L. L. Fershtat, D. M. Bystrov, A. S. Kulikov, A. O. Dmitrienko, I. V. Ananyev and N. N. Makhova, *Eur. J. Org. Chem.*, 2019, **2019**, 4248–4259; (*b*) C. G. T. Oliveira, F. F. Miranda, V. F. Ferreira, C. C. Freitas, R. F. Rabello, J. M. Carballido and L. C. D. Corrêa, *J. Braz. Chem. Soc.*, 2001, **12**, 339–345; (*c*) H. Othman Abdulla, S. Scaringi, A. A. Amin, M. Mella, S. Protti and M. Fagnoni, *Adv. Synth. Catal.*, 2020, **362**, 2150–2154.

7 (*a*) W.-C. Gao, Y.-F. Cheng, Y.-Z. Shang, H.-H. Chang, X. Li, R. Zhou, Y. Qiao and W.-L. Wei, *J. Org. Chem.*, 2018, **83**, 11956–11962; (*b*) H. Jiang, Y. Chen, B. Chen, H. Xu, W. Wan, H. Deng, K. Ma, S. Wu and J. Hao, *Org. Lett.*, 2017, **19**, 2406–2409; (*c*) G. Feng, M. Zhu, L. Liu and C. Li, *Green Chem.*, 2019, **21**, 1769–1776; (*d*) A. Chakraborty, S. Jana, G. Kibriya, A. Dey and A. Hajra, *RSC Adv.*, 2016, **6**, 34146–34152; (*e*) M. Lv, J. Ma, Q. Li and H. Xu, *Bioorg. Med. Chem. Lett.*, 2018, **28**, 181–187.

8 C. Liu, J. Lv, S. Luo and J. P. Cheng, *Org. Lett.*, 2014, **16**, 5458–5461.

9 (*a*) D. S. Barak, S. U. Dighe, I. Avasthi and S. Batra, *J. Org. Chem.*, 2018, **83**, 3537–3546; (*b*) G. Shukla, T. Alam, H. K. Srivastava, R. Kumar and B. K. Patel, *Org. Lett.*, 2019, **21**, 3543–3547; (*c*) H. P. Zhou, J. B. Liu, J. J. Yuan and Y. Y. Peng, *RSC Adv.*, 2014, **4**, 25576–25579.

10 M. N. Weaver, S. Z. Janicki and P. A. Petillo, *J. Org. Chem.*, 2001, **66**, 1138–1145.

11 C. Galli, *Chem. Rev.*, 1988, **88**, 765–792.

12 (*a*) O. Blank, A. Wetzel, D. Ullrich and M. R. Heinrich, *Eur. J. Org. Chem.*, 2008, 3179–3189; (*b*) O. Blank and M. R. Heinrich, *Eur. J. Org. Chem.*, 2006, 4331–4334; (*c*) M. R. Heinrich, O. Blank and A. Wetzel, *J. Org. Chem.*, 2007, **72**, 476–484.

13 (*a*) F. Mo, D. Qiu, L. Zhang and J. Wang, *Chem. Rev.*, 2021, **121**, 5741–5829; (*b*) J. Chen, X. Xie, J. Liu, Z. Yu and W. Su, *React. Chem. Eng.*, 2022, **7**, 1247–1275; (*c*) S. Mahouche-Chergui, S. Gam-Derouich, C. Mangeney and M. M. Chehimi, *Chem. Soc. Rev.*, 2011, **40**, 4143–4166; (*d*) F. Mo, G. Dong, Y. Zhang and J. Wang, *Org. Biomol. Chem.*, 2013, **11**, 1582–1593.

14 (*a*) F. X. Felpin and E. Fouquet, *Adv. Synth. Catal.*, 2008, **350**, 863–868; (*b*) A. K. Singh and J. Kandasamy, *Org. Biomol. Chem.*, 2018, **16**, 5107–5112; (*c*) P. S. Gribanov, M. A. Topchiy, Y. D. Golenko, Y. I. Lichtenstein,

A. V. Eshtukov, V. E. Terekhov, A. F. Asachenko and M. S. Nechaev, *Green Chem.*, 2016, **18**, 5984–5988.

15 (*a*) L. Wang, J. Shen, S. Yang, W. Liu, Q. Chen and M. He, *Green Chem.*, 2018, **20**, 1290–1296; (*b*) S. S. Babu, M. Shahid and P. Gopinath, *Chem. Commun.*, 2020, **56**, 5985–5988; (*c*) S. Witzel, J. Xie, M. Rudolph and A. S. K. Hashmi, *Adv. Synth. Catal.*, 2017, **359**, 1522–1528; (*d*) D. P. Hari, P. Schroll and B. König, *J. Am. Chem. Soc.*, 2012, **134**, 2958–2961; (*e*) E. Tatunashvili, B. Chan, P. E. Nashar and C. S. P. McErlean, *Org. Biomol. Chem.*, 2020, **18**, 1812–1819; (*f*) R. C. Silva, L. F. Villela, T. J. Brocksom and K. T. De Oliveira, *RSC Adv.*, 2020, **10**, 31115–31122.

16 (*a*) R. A. Angnes, C. Potnis, S. Liang, C. R. D. Correia and G. B. Hammond, *J. Org. Chem.*, 2020, **85**, 4153–4164; (*b*) X. L. Yu, J. R. Chen, D. Z. Chen and W. J. Xiao, *Chem. Commun.*, 2016, **52**, 8275–8278; (*c*) S. Kindt, K. Wicht and M. R. Heinrich, *Org. Lett.*, 2015, **17**, 6122–6125; (*d*) M. Wang, B. C. Tang, J. G. Wang, J. C. Xiang, A. Y. Guan, P. P. Huang, W. Y. Guo, Y. D. Wu and A. X. Wu, *Chem. Commun.*, 2018, **54**, 7641–7644; (*e*) J. Rong, H. Jiang, S. Wang, Z. Su, H. Wang and C. Tao, *Org. Biomol. Chem.*, 2020, **18**, 3149–3157.

17 (*a*) S. S. Babu, P. Muthuraja, P. Yadav and P. Gopinath, *Adv. Synth. Catal.*, 2021, **363**, 1782–1809; (*b*) Ł. W. Ciszewski, K. Rybicka-Jasińska and D. Gryko, *Org. Biomol. Chem.*, 2019, **17**, 432–448; (*c*) M. E. Trusova, K. V. Kutonova, V. V. Kurtukov, V. D. Filimonov and P. S. Postnikov, *Resour. Technol.*, 2016, **2**, 36–42; (*d*) Q. Zhang, M. Yu, J. Yuan, R. Zhang, Y. Liang, J. Tian and D. Dong, *J. Org. Chem.*, 2016, **81**, 6036–6041; (*e*) X. Zhang, Y. Mei, Y. Li, J. Hu, D. Huang and Y. Bi, *Asian J. Org. Chem.*, 2021, **10**, 453–463; (*f*) N. Kvasovs and V. Gevorgyan, *Chem. Soc. Rev.*, 2021, **50**, 2244–2259.

18 G. Brahmachari, I. Karmakar and P. Karmakar, *Green Chem.*, 2021, **23**, 4762–4770.

19 (*a*) S. S. Dhaneshwar, N. Gairola, M. Kandpal, G. Vadnerkar, L. Bhatt, B. Rathi and S. S. Kadam, *Eur. J. Med. Chem.*, 2009, **44**, 3922–3929; (*b*) D. A. Kennedy, N. Vembu, F. R. Fronczek and M. Devocelle, *J. Org. Chem.*, 2011, **76**, 9641–9647; (*c*) P. S. Engel, C. Wang, Y. Chen, C. Rüchardt and H. D. Beckhaus, *J. Am. Chem. Soc.*, 1993, **115**, 65–74.

20 (*a*) C. R. J. Stephenson, T. P. Yoon and D. W. C. MacMillan, *Visible Light Photocatalysis in Organic Chemistry*, Wiley-VCH, Weinheim, 2018; (*b*) T. Xiong and Q. Zhang, *Chem. Soc. Rev.*, 2016, **45**, 3069–3087; (*c*) K. L. Skubi, T. R. Blum and T. P. Yoon, *Chem. Rev.*, 2016, **116**, 10035–10074; (*d*) A. K. Bagdi, M. Rahman, D. Bhattacherjee, G. V. Zyryanov, S. Ghosh, O. N. Chupakhin and A. Hajra, *Green Chem.*, 2020, **22**, 6632–6681; (*e*) S. Sharma and A. Sharma, *Org. Biomol. Chem.*, 2019, **17**, 4384–4405; (*f*) V. Srivastava and P. P. Singh, *RSC Adv.*, 2017, **7**, 31377–31392; (*g*) D. Ravelli, S. Protti and M. Fagnoni, *Chem. Rev.*, 2016, **116**, 9850–9913; (*h*) Y. Qin, L. Zhu and S. Luo, *Chem. Rev.*, 2017, **117**, 9433–9520; (*i*) P. G. Karmaker, M. A. Alam and F. Huo, *RSC Adv.*, 2022, **12**, 6214–6233.

21 (*a*) C. J. Clarke, W. C. Tu, O. Levers, A. Bröhl and J. P. Hallett, *Chem. Rev.*, 2018, **118**, 747–800; (*b*) F. P. Byrne, S. Jin, G. Paggiola, T. H. M. Petchey, J. H. Clark, T. J. Farmer, A. J. Hunt, C. Robert McElroy and J. Sherwood, *Sustainable Chem. Processes*, 2016, **4**, 1–24; (*c*) C. Capello, U. Fischer and K. Hungerbühler, *Green Chem.*, 2007, **9**, 927–993; (*d*) T. Welton, *Proc. R. Soc. A*, 2015, 471; (*e*) N. Winterton, *Clean Technol. Environ. Policy*, 2021, **23**, 2499–2522; (*f*) R. Chércoles, *RESEÑA LIBRO: Greener Solvents in Conservation: An Introductory Guide*, 2022, vol. 21.

22 (*a*) T. Kitanosono, K. Masuda, P. Xu and S. Kobayashi, *Chem. Rev.*, 2018, **118**, 679–746; (*b*) T. Kitanosono and S. Kobayashi, *Chem.–Eur. J.*, 2020, **26**, 9408–9429; (*c*) B. M. Sahoo and B. K. Banik, *Solvent-less reactions: Green and sustainable approaches in medicinal chemistry*, Elsevier, 2020; (*d*) M. Cortes-Clerget, J. Yu, J. R. A. Kincaid, P. Walde, F. Gallou and B. H. Lipshutz, *Chem. Sci.*, 2021, **12**, 4237–4266.

23 I. U. Hoque, S. R. Chowdhury and S. Maity, *J. Org. Chem.*, 2019, **84**, 3025–3035.

24 (*a*) A. K. Yadav and L. D. S. Yadav, *Green Chem.*, 2016, **18**, 4240–4244; (*b*) H. K. Singh, A. Kamal, S. Kumari, D. Kumar, S. K. Maury, V. Srivastava and S. Singh, *ACS Omega*, 2020, **5**, 29854–29863; (*c*) D. M. Yan, Q. Q. Zhao, L. Rao, J. R. Chen and W. J. Xiao, *Chem.–Eur. J.*, 2018, **24**, 16895–16901; (*d*) W. Wei, H. Cui, D. Yang, H. Yue, C. He, Y. Zhang and H. Wang, *Green Chem.*, 2017, **19**, 5608–5613; (*e*) J. Y. Tao, Y. X. Wang, Q. H. Zhang, K. Ni, T. H. Zhu and K. Zhao, *Green Chem.*, 2022, **24**, 4004–4011; (*f*) G. Kumar, G. Bhargava, Y. Kumar and R. Kumar, *J. Chem. Sci.*, 2022, **134**, 44.

25 (*a*) A. D. A. Bartolomeu, R. C. Silva, T. J. Brocksom, T. Noël and K. T. De Oliveira, *J. Org. Chem.*, 2019, **84**, 10459–10471; (*b*) A. Das and K. R. Justin Thomas, *Green Chem.*, 2022, **24**, 4952–4957; (*c*) M. Bu, C. Cai, F. Gallou and B. H. Lipshutz, *Green Chem.*, 2018, **20**, 1233–1237; (*d*) C. Russo, F. Brunelli, G. C. Tron and M. Giustiniano, *J. Org. Chem.*, 2022, DOI: **10.1021/acs.joc.2c00805**.

26 (*a*) H. Bin Yang, Y. Z. Zhao, R. Sang and M. Shi, *J. Org. Chem.*, 2014, **79**, 3519–3528; (*b*) F. R. Dietz, A. Prechter, H. Gröger and M. R. Heinrich, *Tetrahedron Lett.*, 2011, **52**, 655–657; (*c*) A. Prechter, H. Gröger and M. R. Heinrich, *Org. Biomol. Chem.*, 2012, **10**, 3384–3387; (*d*) C. J. Patil, D. S. Talele, S. P. Talele, P. R. Pohekar and D. S. Kolhe, *J. Pharm. Sci. Res.*, 2019, **11**, 2213–2219; (*e*) M. Stasevych, V. Zvarych, V. Lunin, N. Kopak, O. Komarovska-Porokhnyavets, N. G. Deniz, C. Sayil, M. Ozyurek, K. Guclu, M. Vovk and V. Novikov, *Monatsh. Chem.*, 2018, **149**, 1111–1119; (*f*) A. Budeev, G. Kantin, D. Dar'in and M. Krasavin, *Molecules*, 2021, **26**, 2530.