

Cite this: *Chem. Sci.*, 2024, 15, 14188

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 25th June 2024
Accepted 5th August 2024

DOI: 10.1039/d4sc04199b

rsc.li/chemical-science

Triyl isocyanide as a general reagent for visible light mediated photoredox-catalyzed cyanations†

Irene Quirós,^a María Martín,^b Carla Pérez-Sánchez,^a Thomas Rigotti^b and Mariola Tortosa^b *^{abc}

A photoredox catalytic strategy has been developed to enable the functionalization of a variety of commercially available, structurally different radical precursors by the use of a bench-stable isonitrile as an efficient cyanating reagent. Specifically, a radical-based reaction has provided a mild and convenient procedure for the cyanation of primary, secondary and tertiary radicals derived from widely accessible sp^3 -hybridized carboxylic acids, alcohols and halides under visible light irradiation. The reaction tolerates a variety of functional groups and it represents a complementary method for the cyanation of structurally different scaffolds that show diverse native functionalities, expanding the scope of previously reported methodologies.

Introduction

Aliphatic nitriles are ranked among the most common functional groups in bioactive molecules.¹ The anticancer agent ruxolitinib, the antihyperglycemic vildagliptin and the antibacterial cefmetazole are examples of commercialized drugs containing alkyl cyanides. Additionally, nitriles are versatile synthetic handles used to introduce a broad variety of functional groups in organic molecules, and prevalent intermediates in the synthesis of heterocycles (Fig. 1).²

Traditionally, alkyl halides have been used to prepare aliphatic nitriles through a S_N2 or S_N1 reaction. Some drawbacks of this approach are the need to prepare the alkyl halides,

the use of toxic cyanide salts, high temperatures and competing elimination reactions.³ To complement this polar strategy different radical approaches have been developed, based on the generation of a nucleophilic radical from a suitable precursor followed by reaction with a cyanating reagent. With the expansion of photoredox catalysis⁴ and electrochemistry,⁵ radical approaches have become attractive ways to prepare alkyl nitriles from native and abundant functional groups under extremely mild conditions,⁶ complementing the use of transition metals and avoiding high temperatures.⁷ Carboxylic acids,^{8–10} redox-active esters,¹¹ alkyl halides,^{12,13} trifluoroborate salts,¹⁴ and specific C–H bonds^{10,15} have been used as carbon-centered alkyl radical precursors in photoredox-catalyzed and electrochemical cyanation reactions. The cyanating reagents used in these transformations include tosyl and trimethylsilyl cyanide, cyanobenziodoxolone, 4-cyano pyridine and inorganic salts such as sodium and potassium cyanides (Scheme 1). All of them are cyanide-containing reagents often used in superstoichiometric amounts. The introduction of cyanide-free reagents that could promote general photoredox catalyzed cyanations would be a convenient addition to the toolbox that chemists have at disposal to prepare aliphatic nitriles.

Our group recently demonstrated that isonitriles can unlock hydro- and deuterodeamination reactions under extremely mild conditions.¹⁶ Indeed, isonitriles can intercept visible light-generated silyl radicals to give an imidoyl radical intermediate that enables a β -scission, provoking the C–N bond fragmentation. Based on these results, we reasoned that a tunable isonitrile could intercept carbon-centered radicals generated under photoredox catalysis to provide a unified strategy for the cyanation of common functional groups.

Although isonitriles have been used as efficient radical traps¹⁷ and suitable reagents in radical cyanations,¹⁸ the nitrile

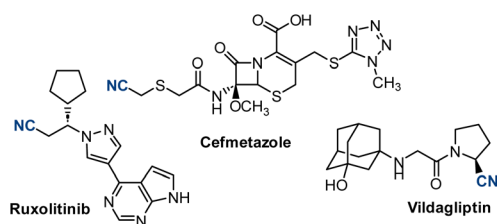


Fig. 1 Selected pharmaceuticals containing aliphatic nitriles.

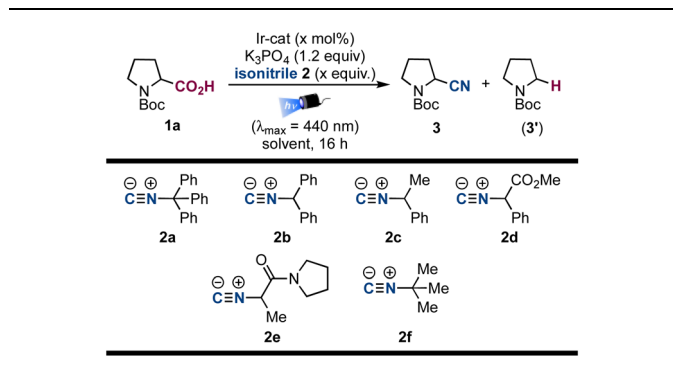
^aOrganic Chemistry Department, Faculty of Science, Autonomous University of Madrid (UAM), Madrid, 28049, Spain. E-mail: mariola.tortosa@uam.es

^bCenter for Innovation in Advanced Chemistry (ORFEO-CINQA), Autonomous University of Madrid (UAM), Madrid, 28049, Spain

^cInstitute for Advanced Research in Chemical Sciences (IAdChem), Autonomous University of Madrid (UAM), Madrid, 28049, Spain

† Electronic supplementary information (ESI) available: Synthetic procedures and characterization data for all starting materials and products. See DOI: <https://doi.org/10.1039/d4sc04199b>



Table 1 Optimization of the photocatalytic decarboxylative cyanation with isonitriles^a

Entry	Solvent	2 (equiv.)	Ir-cat (mol%)	Yield 3 (3') %
1	MeCN	2a (3.0)	2	68 (14)
2	MeCN	2b (3.0)	2	55 (35)
3	MeCN	2c (3.0)	2	30 (5)
4	MeCN	2d (3.0)	2	48 (52)
5	MeCN	2e (3.0)	2	24 (0)
6	MeCN	2f (3.0)	2	4 (12)
7	DMSO	2a (3.0)	2	74 (12)
8	DMF	2a (3.0)	2	60 (14)
9	DCM	2a (3.0)	2	0 (5)
10	PhCH ₃	2a (3.0)	2	36 (30)
11 ^{b,c}	DMSO	2a (2.5)	1	82 (8)
12 ^d	DMSO	2a (2.5)	1	0
13 ^e	DMSO	2a (2.5)	1	0

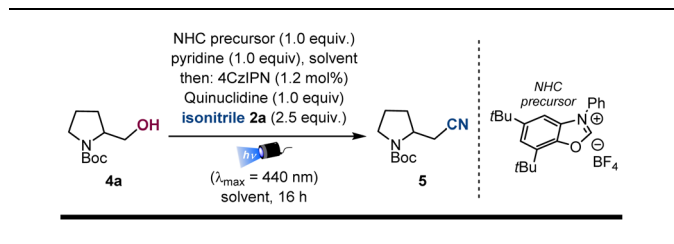
^a The reactions were performed on a 0.10 mmol scale and the yields were determined by ¹H NMR with CH₂Br₂ as an internal standard.

^b The reaction was performed on a 0.20 mmol scale. ^c Yield determined after isolation by column chromatography purification.

^d The reaction was performed in the absence of light. ^e The reaction was performed in the absence of photocatalyst. See ESI for further details.

a recently developed strategy that, upon oxidation of an alcohol-NHC (N-heterocyclic carbene) adduct [$E_{\text{ox}} \approx +0.6$ V vs. SCE], allows an efficient C–O bond homolysis.²⁹ Slightly adapting this methodology to our envisioned cyanation strategy, we obtained a promising 30% yield (Table 2, entry 1) when 1,2,3,5-tetrakis(carbazol-9-yl)-4,6-dicyanobenzene (4CzIPN) was used as the photoredox catalyst [$E_{\text{red}}^*(4\text{CzIPN}^*/4\text{CzIPN}^{\cdot-}) = +1.35$ V vs. SCE].³⁰ The use of MTBE or 1,4-dioxane as solvents improved the yields (entries 2 and 3), obtaining the product in 75% yield when a 1 : 1 mixture of dioxane and DMSO was employed (entry 4). After some additional optimization (see ESI† for further details) the reaction could be scaled up to 0.2 mmol with a 2.0 mol% of photocatalyst, delivering the desired nitrile **5** in a slightly diminished yield (60%, entry 5).

Next, with the aim of developing a complementary method that could provide an alternative to nucleophilic substitution reactions, we evaluate the possibility to exploit a halogen atom transfer (XAT) photocatalytic strategy to generate a carbon-centered radical from alkyl halides **6** (Table 3).³¹ Specifically, the photoredox catalyst engages in a SET with triethylamine [E_{ox}

Table 2 Optimization of the photocatalytic deoxygenative cyanation with isonitriles^a

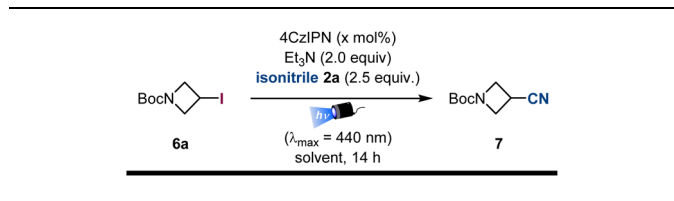
Entry	Solvent	4CzIPN (mol%)	Yield %
1	MTBE : DMA (1 : 1)	1.2	30
2	MTBE	1.2	46
3	Dioxane	1.2	52
4	Dioxane : DMSO (1 : 1)	1.2	75
5 ^b	Dioxane : DMSO (1 : 1)	1.2	60
6 ^c	Dioxane : DMSO (1 : 1)	1.2	0
7 ^d	Dioxane : DMSO (1 : 1)	—	0

^a The reactions were performed on a 0.10 mmol scale and the yields were determined after isolation by column chromatography purification. ^b The reaction was performed on a 0.20 mmol scale.

^c The reaction was performed in the absence of light. ^d The reaction was performed in the absence of photocatalyst. See ESI for further details.

= +0.77 V vs. SCE] by a reductive quenching cycle to deliver an α -amino alkyl radical as a powerful XAT reagent that abstract the iodine atom to deliver a new carbon-centered radical.

Gratifyingly, adding isonitrile **2a** to the reaction mixture, the transiently generated radical could be efficiently trapped to furnish the corresponding isonitrile **7** in 88% yield (Table 3, entry 1). Decreasing the photocatalyst loading to 2.0 mol% afforded the product in 91% yield (entry 2), whereas different

Table 3 Optimization of the photocatalytic XAT-enabled cyanation with isonitriles^a

Entry	Solvent	4CzIPN (mol%)	Yield %
1	MeCN	5.0	88
2	MeCN	2.0	91
3	DMSO	2.0	50
4	Acetone	2.0	69
5 ^b	MeCN	2.0	0
6 ^c	MeCN	2.0	0
7 ^d	MeCN	—	0

^a The reactions were performed on a 0.20 mmol scale and the yields were determined after isolation by column chromatography purification. ^b The reaction was performed in the absence of triethylamine. ^c The reaction was performed in the absence of light.

^d The reaction was performed in the absence of photocatalyst. See ESI for further details.






























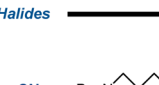
solvents than acetonitrile led to diminished yields (entries 3 and 4). Even in this case, the presence of all the reaction components was necessary for a successful reaction since it did not proceed in the absence of XAT reagent, light or photocatalyst.

With the optimized conditions in hand for the three different radical precursors, we evaluated the scope of the photocatalytic cyanation reaction, employing a variety of carboxylic acids **1**,^{8–10} aliphatic alcohols **4**, and alkyl halides **6** (Table 4).^{12,13,25} *N*-Boc-piperidine-containing secondary carboxylic acids delivered the corresponding nitriles **8** and **9** in 66% and 65% yield. Acetal-, hydroxy- and catechol-containing products (**10–12**) were obtained in moderate to high yields, highlighting the functional group compatibility of the method. On the other hand, *N*-boc phenylalanine derived nitrile **13** was isolated in 63% yield, showcasing that *N*-protected α -amino acids are suitable substrates. Next, we employed tertiary carboxylic acids to study the influence of the radical stability and of its steric hindrance on the outcome of the reaction. We were pleased to observe high reactivity in all the cases, indicating an efficient β -scission of the imidoyl radical upon radical addition on isonitrile **2a**. Indeed, products **14–17** were obtained, allowing the introduction of a nitrile functionality at the bridgehead position of a bicyclo[2.2.2]octane and the modification of the lipid-regulating agent gemfibrozil. Stabilized and

not stabilized primary radicals could be employed, resulting in the formation of nitriles **18–20**, albeit with slightly lower yields. The general reactivity observed with primary, secondary and tertiary aliphatic carboxylic acids is striking as most previous examples are limited to carboxylic acids carrying an α -heteroatom.^{8–10} On the other hand, benzylic carboxylic acids were not suitable for this reaction. Indeed, although efficiently decarboxylated, the corresponding nitrile **21** was not observed and only a dimeric compound was detected (45% NMR yield of a 50% maximum theoretical yield), presumably due to a reluctance of the (more stable) benzyl radical to undergo radical addition to the isonitrile or to a more favourable and undesired α -scission of the transiently formed imidoyl radical.

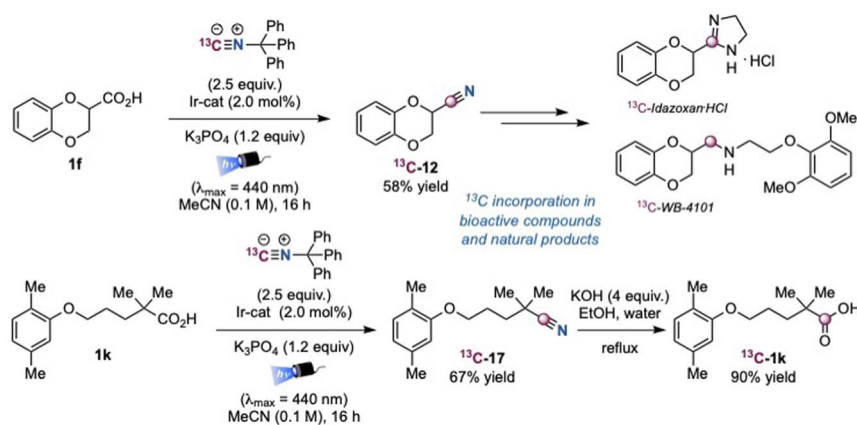
Subsequently, we evaluated the scope of the reaction employing aliphatic alcohols as radical precursors. Different β -amino alcohols, which are derived from ubiquitous α -amino acids and that present a primary alcohol as functional group, could be employed, delivering products **5** and **22** in 60% and 46% yield, respectively. Secondary aliphatic alcohols furnished a variety of cyclic nitriles (**7**, **8**, and **23**) with different ring size or a spirocyclic scaffold. Moreover, a tertiary alcohol was amenable to this transformation, delivering the spirocyclic tertiary nitrile **24** in 40% yield. To the best of our knowledge our protocol

Table 4 Reaction scope of the photoredox-catalyzed cyanation^{a,b}

Carboxylic Acids						
secondary						
						
3 82% yield	8 66% yield	9 65% yield <i>from nipecotic acid</i>	10 84% yield	11 74% yield	12 51% yield	13 63% yield
tertiary						
				limitations: benzylic  21 0% yield <i>undesired dimerization (45% yield^a)</i>  20 48% yield <i>from gabapentin</i>		
14 80% yield	15 61% yield ^a	16 52% yield	17 80% yield <i>from gemfibrozil</i>			
primary						
						
18 46% yield	19 43% yield	20 48% yield <i>from gabapentin</i>				
Aliphatic Alcohols						
						
5 60% yield <i>from L-proline</i>	22 46% yield	7 48% yield	8 61% yield	23 59% yield	24 40% yield	24 40% yield
Alkyl Halides						
						
7 91% yield	8 82% yield <i>(53% yield from bromide)</i>	11 80% yield	23 69% yield	25 37% yield <i>from alpha-D-galactopyranose</i>		

^a The reactions were performed on a 0.20 mmol scale and the yields were determined after isolation by column chromatography purification. ^b The yield was determined by ¹H NMR with CH₂Br₂ as internal standard. See ESI for further details.





Scheme 3 Incorporation of ^{13}C in bioactive compounds and natural products.

represents the first example of photoredox-catalyzed direct cyanation of aliphatic alcohols.

Next, we explored the possibility to carry out a photocatalytic cyanation starting from alkyl halides **6**.^{12,13,25} A variety of structurally different secondary iodides could be employed, obtaining nitriles **7**, **8**, **11**, and **23** in excellent yields. In addition, the same reaction could be performed over secondary bromides, despite a diminished yield in comparison with the parent iodide (53% vs. 82% yield). Primary halides were also suitable for this transformation, as exemplified by the α -D-galactopyranose-containing product **25**, which demonstrated the feasibility to employ more complex scaffolds and natural product cores. These results are comparable to those obtained using TMS-CN as cyanating reagent.¹²

Moreover, we decided to prepare the ^{13}C -labelled analogues of trityl isocyanide **2a**, employing ^{13}C -formic acid for its synthesis. Indeed, the use of this ^{13}C -labelled cyanating reagent would enable access to the corresponding isotopic nitrile analogues through functionalization of widely available carboxylic acids, aliphatic alcohols and alkyl halides, allowing the efficient incorporation of a carbon isotope starting from diversified starting materials. As representative examples, we chose to prepare the isotopic analogues of products **12** and **17**. When the photocatalytic reaction was performed in the presence of isonitrile ^{13}C -**2a** as a trapping agent, we smoothly observed the formation of compounds ^{13}C -**12** and ^{13}C -**17** in 58% and 70% yield (Scheme 3). Therefore, this labelling strategy could enable the synthesis of ^{13}C -labelled analogues of bioactive compounds such as idazoxan hydrochloride and WB-4101.³² Moreover, the potential of this methodology was showcased by the facile hydrolysis of ^{13}C -**17**, which allowed to access a ^{13}C -labelled gemfibrozil analogue ^{13}C -**1k** in 90% yield.

Conclusion

In summary, we have developed a general photocatalytic cyanation reaction employing trityl isocyanide as selective cyanating reagent. The use of a photoredox reductive quenching strategy, along with a judicious choice of the more appropriate isonitrile, avoids the formation of undesired nitrilium ions, shifting the

transformation towards the nitrile product. The suitability of carboxylic acids, aliphatic alcohols and alkyl halides as radical precursors enables a straightforward transformation from widely accessible building blocks. Besides enabling access to alkyl nitriles from common and diversified precursors, this methodology represents a valuable alternative to polar cyanation strategies that allows the easy preparation of isotopic analogues, avoiding the use of cyanide-containing reagents.

Data availability

The datasets supporting this article have been uploaded as part of the ESI.†

Author contributions

M. T. conceived and designed the project. I. Q., M. M., C. P.-S., and T. R. performed all optimization studies and photocatalytic reactions. M. T. and T. R. wrote the manuscript with the contribution of all the authors.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank the European Research Council (ERC Consolidator Grant – 101002715 – SCAN) and the Spanish Ministry of Science and Innovation (MICINN) [PID2022-142594NB-I00] for financial support. M. M. and C. P.-S. acknowledge Ministerio de Universidades and MICINN for FPU (FPU20/06320) and for FPI (PREP2022-000243) fellowships, respectively.

Notes and references

- (a) F. F. Fleming, L. Yao, P. C. Ravikumar, L. Funk and B. C. Shook, Nitrile-containing pharmaceuticals: Efficacious roles of the nitrile pharmacophore, *J. Med.*



- Chem.*, 2010, **53**, 7902; (b) J. Wang and H. Liu, Application of nitrile in drug design, *Chin. J. Org. Chem.*, 2012, **32**, 1643.
- 2 (a) *The Chemistry of the Cyano Group*, ed. Z. Rappoport and S. Patai, John Wiley & Sons, 1970; (b) *Science of Synthesis*, ed. S.-I. Murahashi, Georg Thieme Verlag, Stuttgart, Germany, 2004, p. 19; (c) R. C. Larock, *Comprehensive Organic Transformations: A Guide to Functional Group Preparations*, VCH, New York, 2nd edn, 1999.
- 3 (a) M. T. Reetz, I. Chatziosifidis, H. Künzer and H. Müller-Starke, *Tetrahedron*, 1983, **39**, 961–965; (b) M. T. Reetz and I. Chatziosifidis, *Angew. Chem., Int. Ed.*, 1981, **20**, 1017–1018.
- 4 (a) M. D. Kärkäs, J. A. Porco Jr and C. R. J. Stephenson, *Chem. Rev.*, 2016, **116**, 9683–9747; (b) *Visible Light Photocatalysis in Organic Chemistry*, ed. C. R. J. Stephenson, T. P. Yoon and D. W. C. MacMillan, Wiley-VCH, 2018; (c) T. Rigotti and J. Alemán, *Chem. Commun.*, 2020, **56**, 11169–11190.
- 5 M. Yan, Y. Kawamata and P. S. Baran, *Chem. Rev.*, 2017, **117**, 13230–13319.
- 6 R. I. Patel, S. Sharma and A. Sharma, *Org. Chem. Front.*, 2021, **8**, 3166–3200.
- 7 (a) F. Yan, J.-F. Bai, Y. Dong, S. Liu, C. Li, C.-X. Du and Y. Li, *JACS Au*, 2022, **2**, 2522–2528; (b) J. Xu, J. C. Twitty and M. P. Watson, *Org. Lett.*, 2021, **23**, 6242–6245; (c) A. Xia, X. Xie, H. Chen, J. Zhao, C. Zhang and Y. Liu, *Org. Lett.*, 2018, **20**, 7735–7739.
- 8 (a) F. Le Vaillant, M. D. Wodrich and J. Waser, *Chem. Sci.*, 2017, **8**, 1790–1800; (b) N. P. Ramirez, B. König and J. C. Gonzalez-Gomez, *Org. Lett.*, 2019, **21**, 1368–1373.
- 9 For a photoelectrochemical asymmetric cyanation, see: X.-L. Lai, M. Chen, Y. Wang, J. Song and H.-C. Xu, *J. Am. Chem. Soc.*, 2022, **144**, 20201–20206.
- 10 For an electrochemical cyanation of carboxylic acids and activated C–H bonds, see: G. S. Kumar, P. S. Shinde, H. Chen, K. Muralirajan, R. Kancherla and M. Rueping, *Org. Lett.*, 2022, **24**, 6357–6363.
- 11 (a) D. Wang, N. Zhu, P. Chen, Z. Lin and G. Liu, *J. Am. Chem. Soc.*, 2017, **139**, 15632–15635; (b) H.-W. Chen, F.-D. Lu, Y. Cheng, Y. Jia, L.-Q. Lu and W.-J. Xiao, *Chin. J. Chem.*, 2020, **38**, 1671–1675; (c) For a pioneering photochemical reaction employing Barton esters, see: D. H. R. Barton, J. C. Jaszberenyi and E. A. Theodorakis, *Tetrahedron*, 1992, **48**, 2613–2626.
- 12 For a halogen atom transfer-enabled strategy *via* metallaphotoredox, see: L. Caiger, H. Zhao, T. Constantin, J. J. Douglas and D. Leonori, *ACS Catal.*, 2023, **13**, 4985–4991.
- 13 For a photochemical cyanation of unactivated alkyl chlorides that proceed through the use of UV light, see: T. S. Ratani, S. Bachman, G. C. Fu and J. C. Peters, *J. Am. Chem. Soc.*, 2015, **137**, 13902–13907.
- 14 J.-J. Dai, W.-M. Zhang, Y.-J. Shu, Y.-Y. Sun, J. Xu, Y.-S. Feng and H.-J. Xu, *Chem. Commun.*, 2016, **52**, 6793–6796.
- 15 For examples of photocatalytic hydrogen atom transfer-enabled C–H cyanations, see: (a) S. Kamijo, T. Hoshikawa and M. Inoue, *Org. Lett.*, 2011, **13**, 5928–5931; (b) K. Kim, S. Lee and S. H. Hong, *Org. Lett.*, 2021, **23**, 5501–5505; (c) For a photoredox-catalyzed C–H cyanation enabled by deprotonation of a radical cation, see: I. Robb and J. A. Murphy, *Org. Lett.*, 2024, **26**, 2218–2222; (d) For an electrochemical cyanation of an activated C–H bond, see: G. S. Kumar, P. S. Shinde, H. Chen, K. Muralirajan, R. Kancherla and M. Rueping, *Org. Lett.*, 2022, **24**, 6357–6363.
- 16 I. Quirós, M. Martín, M. Gomez-Mendoza, M. J. Cabrera-Afonso, M. Liras, I. Fernández, L. Nóvoa and M. Tortosa, *Angew. Chem., Int. Ed.*, 2024, **63**, e202317683.
- 17 (a) D. Nanni, Isonitriles: a Useful Trap in Radical Chemistry, in *Radicals in Organic Synthesis*, ed. P. Renaud and M. P. Sibi, Wiley-VCH Verlag GmbH, 2001; (b) R. Leardini, D. Nanni and G. Zanardi, *J. Org. Chem.*, 2000, **65**, 2763–2772; (c) J. Lei, D. Li and Q. Zhu, Synthesis of Nitrogen-Containing Heterocycles *via* Imidoyl or Iminyl Radical Intermediates, In *Free-Radical Synthesis and Functionalization of Heterocycles, Topics in Heterocyclic Chemistry 54*, ed. Y. Landais, Springer, Cham, Switzerland, 2018; (d) B. Zhang and A. Studer, *Chem. Soc. Rev.*, 2015, **44**, 3505–3521.
- 18 (a) G. Stork and P. M. Sher, *J. Am. Chem. Soc.*, 1983, **105**, 6765–6766; (b) Y. Shan, X. Zhang, G. Liu, J. Li, Y. Liu, J. Wang and D. Chen, *Chem. Commun.*, 2024, **60**, 1546–1562.
- 19 (a) S. Tang, R. Guillot, L. Grimaud, M. R. Vitale and G. Vincent, *Org. Lett.*, 2022, **24**, 2125–2130; (b) W. Huang, Y. Wang, Y. Weng, M. Shrestha, J. Qu and Y. Chen, *Org. Lett.*, 2020, **22**, 3245–3250; (c) For a chemoselective one-pot sequence towards benzylic nitriles using BF_3OEt_2 to promote dehydration: X. Jia, Z. Zhang and V. Gevorgyan, *ACS Catal.*, 2021, **11**, 13217–13222.
- 20 (a) R. C. Cioc, P. Schuckman, H. D. Preschel, T. Vlaar, E. Ruijter and R. V. A. Orru, *Org. Lett.*, 2016, **18**, 3562–3565; (b) R. C. Cioc, H. D. Preschel, G. Heijden, E. Ruijter and R. V. A. Orru, *Chem.–Eur. J.*, 2016, **22**, 7837–7842; (c) For a Mn(III) mediated oxidative radical cyanation of arylboronic acids with trityl isocyanide, see: Z. Xu, X. Liang and H. Li, *Org. Lett.*, 2022, **24**, 9403–9407.
- 21 Y. Zabolotna, D. M. Volochnyuk, S. V. Ryabukhin, D. Horvath, K. S. Gavrilenko, G. Marcou, Y. S. Moroz, O. Oksiuta and A. Varnek, *J. Chem. Inf. Model.*, 2022, **62**, 2171–2185.
- 22 (a) M. Minozzi, D. Nanni and P. Spagnolo, *Curr. Org. Chem.*, 2007, **11**, 1366–1384; (b) J. Lei, J. Huang and Q. Zhu, *Org. Biomol. Chem.*, 2016, **14**, 2593–2602; (c) S. Sharma, A. P. Pandey and A. Sharma, *Adv. Synth. Catal.*, 2020, **362**, 5196–5218.
- 23 M. Poncelet, B. Driesschaert, A. A. Bobko and V. V. Khramtsov, *Free Radical Res.*, 2017, **52**, 373–379.
- 24 For selected examples of nitrilium ion formation through oxidation of an imidoyl radical, see: (a) C. Russo, F. Brunelli, G. C. Tron and M. Giustiniano, *Eur. J. Org. Chem.*, 2023, **26**, e202300743; (b) S. Pelliccia, A. I. Alfano, P. Luciano, E. Novellino, A. Massarotti, G. C. Tron, D. Ravelli and M. Giustiniano, *J. Org. Chem.*, 2020, **85**, 1981–1990; (c) R. Cannalire, J. Amato, V. Summa, E. Novellino, G. C. Tron and M. Giustiniano, *J. Org. Chem.*, 2020, **85**, 14077–14086; (d) Y. Lv, P. Bao, H. Yue, J.-S. Li and W. Wei, *Green Chem.*, 2019, **21**, 6051–6055; (e) W. Wei, P. Bao, H. Yue, S. Liu, L. Wang, Y. Li and D. Yang, *Org.*



- Lett.*, 2018, **20**, 5291–5295; (f) M. Chen, Y. Li, H. Tang, H. Ding, K. Wang, L. Yang, C. Li, M. Gao and A. Lei, *Org. Lett.*, 2017, **19**, 3147–3150; (g) Z. Guan, Y. Peng, D. Yang, S. Zhu, H. Zhang and A. Lei, *Green Chem.*, 2022, **24**, 3964–3968.
- 25 H. Zhao, V. D. Cuomo, J. A. Rossi-Ashton and D. J. Procter, *Chem*, 2024, **10**, 1–12.
- 26 (a) L. Chu, C. Ohta, Z. Zuo and D. W. C. MacMillan, *J. Am. Chem. Soc.*, 2014, **136**, 10886–10889; (b) S. B. Beil, T. Q. Chen, N. E. Intermaggio and D. W. C. MacMillan, *Acc. Chem. Res.*, 2022, **55**, 3481–3494.
- 27 (a) M. Galicia and F. J. Gonzalez, *J. Electrochem. Soc.*, 2002, **149**, D46; (b) H. G. Roth, N. A. Romero and D. A. Nicewicz, *Synlett*, 2016, **27**, 714–723.
- 28 M. S. Lowry, J. I. Goldsmith, J. D. Slinker, R. Rohl, R. A. Pascal, G. G. Malliaras and S. Bernhard, *Chem. Mater.*, 2005, **17**, 5712–5719.
- 29 Z. Dong and D. W. C. MacMillan, *Nature*, 2021, **598**, 451–456.
- 30 J. Luo and J. Zhang, *ACS Catal.*, 2016, **6**, 873–877.
- 31 T. Constantin, M. Zanini, A. Regni, N. S. Sheikh, F. Juliá and D. Leonori, *Science*, 2020, **367**, 1021–1026.
- 32 (a) C. B. Chapleo, P. L. Myers, R. C. M. Butler, J. C. Doxey, A. G. Roach and C. F. C. Smith, *J. Med. Chem.*, 1983, **26**, 823–831; (b) D. Giardina, P. Angeli, L. Brasili, U. Gulini, C. Melchiorre and G. Strappaghetti, *Eur. J. Med. Chem.*, 1984, **19**, 411–414.

