# ChemComm



### COMMUNICATION

View Article Online
View Journal | View Issue



# Direct N-formylation of nitroarenes with CO<sub>2</sub>†

Ni Shen, Da Shi-Jing Zhai, Chi Wai Cheung \* and Jun-An Ma \* \* and Jun-An M

**Cite this:** *Chem. Commun.*, 2020

Received 29th April 2020, Accepted 14th July 2020

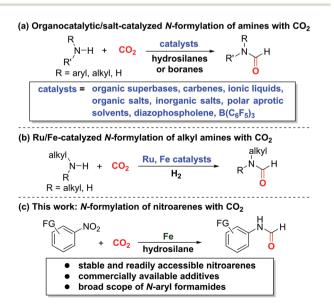
DOI: 10.1039/d0cc03098h

rsc.li/chemcomm

Herein we describe a straightforward N-formylation of nitroarenes with  $CO_2$  to access N-aryl formamides exclusively in the presence of iron and hydrosilane as additives. This protocol showcases a good tolerance of a wide range of nitroarenes and nitroheteroarenes.

Carbon dioxide (CO<sub>2</sub>) constitutes an ideal C1 source in organic synthesis owing to its abundance and stability. In particular, CO<sub>2</sub> serves as the best-suited substitute of more reactive C1 building blocks, such as carbon monoxide (CO), methyl iodide, and phosgene.<sup>2</sup> Despite its high activation barrier and thermodynamic stability,<sup>2</sup> CO<sub>2</sub> has been widely exploited for decades to access a diverse array of functionalized compounds via carboxylation,<sup>3</sup> carbonylation,<sup>4</sup> or C-H bond construction.<sup>5</sup> In this context, the incorporation of amines and CO2 towards synthesis of value-added nitrogen-containing compounds,6 especially N-formylation of amines with  $CO_{2}$ , 7-13 is among the most important chemical transformations due to the versatility of nitrogen-based compounds in academia and industry. Taking the advantage of commercially available hydrosilanes as activating and hydrogenating agents along with various catalysts, such as organic superbases, <sup>7</sup> carbenes, <sup>8</sup> ionic liquids and organic salts, inorganic salts, polar aprotic solvents, in diazophospholene, 12 and B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub>, 13 a variety of formamides can be accessed based on amines and CO2 (Scheme 1a). Additionally, the Ding14 and Bernskoetter15 groups described the seminal Ru- and Fe-catalyzed N-formylation of alkylamines based on the CO<sub>2</sub>/H<sub>2</sub> system, respectively (Scheme 1b). On the other hand, nitroarenes prove to be reliable aminating agents

<sup>†</sup> Electronic supplementary information (ESI) available: Experimental and spectral data. See DOI: 10.1039/d0cc03098h



Scheme 1 Developments of N-formylation based on CO<sub>2</sub>.

for direct synthesis of amines<sup>16</sup> and amides<sup>17</sup> without preforming the more reactive anilines via hydrogenation. Recently, Beller, <sup>17a</sup> Driver, <sup>17b</sup> Hu, <sup>17c</sup> Mankad, <sup>17f</sup> Wu, <sup>17d,e</sup> as well as our group 17g disclosed the aminocarbonylation reactions to access aryl amides, a class of important compounds in chemical, pharmaceutical, and agrochemical industries, based on nitroarenes and CO or its surrogates. To our knowledge, the merger of CO<sub>2</sub> and nitroarenes for straightforward amide synthesis remains unexplored. We envisioned that the use of suitable and compatible reductants and activating agents could induce the integration of both CO2 and nitroarenes for amide formation. Herein, we unveil the direct N-formylation of nitroarenes with CO<sub>2</sub> in the presence of iron powder and hydrosilane additives (Scheme 1c). This alternative and complementary method would open a conceptually novel avenue for more step-economic and expedient access to formamides without the need of conventional anilines.

<sup>&</sup>lt;sup>a</sup> Department of Chemistry, Tianjin Key Laboratory of Molecular Optoelectronic Sciences, Frontiers Science Center for Synthetic Biology (Ministry of Education), and Tianjin Collaborative Innovation Centre of Chemical Science & Engineering, Tianjin University, Tianjin 300072, P. R. of China. E-mail: zhiwei.zhang@tju.edu.cn, majun\_an68@tju.edu.cn

<sup>&</sup>lt;sup>b</sup> Joint School of National University of Singapore and Tianjin University, International Campus of Tianjin University, Binhai New City, Fuzhou 350207,

Communication ChemComm

We commenced the study on N-formylation of CO2 using 4-nitroanisole (1a) as the model substrate (Table 1). In the presence of 3 equivalents of Zn powder as reductant and 3 equivalents of phenylsilane as additive, 1a reacted with CO<sub>2</sub> under balloon pressure in dimethylformamide (DMF) solvent at 110 °C to give N-4-methoxyphenyl formamide 2a exclusively in 49% yield (entry 1). In the absence of Zn or hydrosilane, no formylation took place, indicating that both metal reductant and hydrosilane are essential for reaction (entries 2 and 3). When triethoxysilane was used in place of phenylsilane, formylation underwent at 135 °C to offer 2a in 56% yield (entry 4). Further, when Fe powder was employed instead of Zn, 2a was also obtained in 51% yield (entry 5). Noteworthily, the yield could be enhanced to 63% when 10 mol% of KI was added as additive in the Fe-mediated reaction (entry 6). Subsequently, 1,1,3,3-tetramethyldisiloxane (TMDSO) was found to be the superior additive, giving 2a in 75% yield (entries 7-9). Intriguingly, the use of Fe nano powder allowed the reduction of loadings of both Fe and TMDSO to 2 equivalents in association with the yield enhancement to 83% yield (entries 10-12). Such promoting effect would be attributed to the more efficient reduction process provided by the more soluble and finely powdered Fe. In the presence of other polar aprotic solvents such as dimethylacetamide (DMA) and N-methylpyrrolidine (NMP), 2a was formed in similar yields without other side products (entries 13 and 14). Furthermore, no formamide was formed when CO2 was omitted (entry 15). These control experiments suggested that the carbonyl group of 2a originates from CO2 rather than solvent.

The optimized protocol (Table 1, entry 11) proved to be general in N-formylation of nitroarenes (Scheme 2). Electron-rich (1a-1f), electron-neutral (1g), and electron-deficient (1h-1m) nitroarenes

Table 1 Optimization of N-formylation of nitroarenes with CO<sub>2</sub><sup>a</sup>

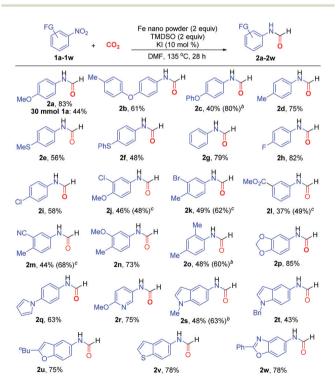
NO <sub>2</sub>	CO <sub>2</sub>	metal (equiv) hydrosilane (equiv) additive	H	
1a		solvent, 135 °C, 28 h	MeO 2a	

	<b>1a</b> solvent, 135 °C, 28 h <b>2a</b>			2a		
Entry	Metal (equiv.)	Hydrosilane (equiv.)	Additive (mol%)	Solvent	Yield <sup>b</sup> (%)	
<b>1</b> <sup>c</sup>	Zn (3)	PhSiH <sub>3</sub> (3)	None	DMF	49	
$2^c$	None	$PhSiH_3$ (3)	None	DMF	0	
$3^c$	Zn (3)	None	None	DMF	0	
4	Zn (3)	$(EtO)_3SiH(3)$	None	DMF	56	
5	Fe (3)	$(EtO)_3SiH(3)$	None	DMF	51	
6	Fe (3)	$(EtO)_3SiH(3)$	KI (10)	DMF	63	
7	Fe (3)	$Me(EtO)_2SiH$ (3)	KI (10)	DMF	25	
8	Fe (3)	PMHS (3)	KI (10)	DMF	32	
9	Fe (3)	TMDSO (3)	KI (10)	DMF	75	
$10^d$	Fe (3)	TMDSO (2)	KI (10)	DMF	83	
$11^d$	Fe (2)	TMDSO (2)	KI (10)	DMF	83	
$12^d$	Fe (1)	TMDSO (2)	KI (10)	DMF	35	
$13^d$	Fe (2)	TMDSO (2)	KI (10)	DMA	83	
$14^d$	Fe (2)	TMDSO (2)	KI (10)	NMP	75	
$15^{d,e}$	Fe (2)	TMDSO (2)	KI (10)	DMF	0	

<sup>&</sup>lt;sup>a</sup> General procedure: 1a (0.5 mmol), CO<sub>2</sub> (balloon), metal powder (1-1.5 mmol), hydrosilane (1-1.5 mmol), additive (10 mol%), solvent (1.5 mL), 135 °C, 28 h. <sup>b</sup> Isolated yield. <sup>c</sup> Reaction conducted at 110 °C. Fe nano powder used. <sup>e</sup> Argon atmosphere without CO<sub>2</sub>.

all reacted with CO<sub>2</sub> to form the corresponding N-aryl formamides in moderate to high yields. Additionally, both mono- (1a-2i, 1l) and di-substituted (1j, 1k, 1m-1o) nitroarenes could be incorporated into the formamide products 2a-2o. The sterically encumbered 1-nitro-2,4-dimethylbenzene (10) was also suitable reaction partner. Notably, a wide range of nitro-substituted heterocycles could be utilized for formylation, including benzodioxole (1p), pyrrole (1q), pyridine (1r), N-alkylated indole (1s, 1t), benzofuran (1u), benzothiophene (1v), and benzoxazole (1w), delivering the corresponding N-heteroaryl formamides 2p-2w in 43-85% yields. Noteworthily, the employment of 3 equivalents of Fe metal (Table 1, entry 10) could improve remarkably the formylation of electron-rich nitro(hetero)arenes 1c, 1o and 1s, affording the corresponding formamides 2c, 2o and 2s in 80%, 60% and 63% vields, respectively. On the contrary, the reactions of electrondeficient nitroarenes with the additional equivalent of Fe led to substantial diminishment of yields. Gratifyingly, by adding FeCl<sub>2</sub> (2 equiv.) and slightly increasing the loadings of TMDSO and KI, electron-deficient nitroarenes such as 1j-1m could react more efficiently to afford the formamides in higher yields (48–68%). This protocol was also amenable to multigram synthesis of 2a in synthetically useful yield.

In the course of reaction, nitroarene can be transformed to nitrosoarene, N-aryl hydroxylamine, azoxyarene, azoarene, 1,2diaryl hydrazine, and aniline under reductive conditions.<sup>18</sup> Thus, the reactions of these nitrogen-based species under otherwise



Scheme 2 Substrate scope of nitroarenes in N-formylation.<sup>a</sup> Reaction conditions: nitroarene (0.5 mmol), CO2 (balloon), nano Fe (1 mmol), TMDSO (1 mmol), KI (0.05 mmol), DMF (1.5 ml), 135 °C, 28 h. Isolated yields were shown. <sup>b</sup>3 equiv. of Fe. <sup>c</sup> Modified conditions: nitroarene (1 equiv.), CO2 (balloon), nano Fe (2 equiv.), FeCl2 (2 equiv.), TMDSO (3 mmol), KI (30 mol%), DMF (3 ml), 135 °C, 28 h.

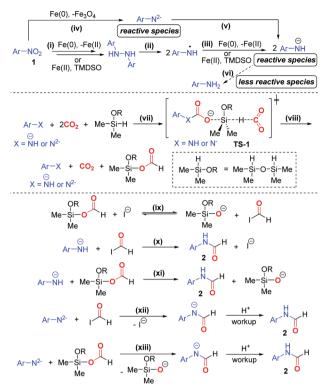
ChemComm Communication

(a) Reaction of possible nitrogen-containing intermediates							
Ph-NX + CO <sub>2</sub> 3a-3f	TMD KI	powder (2 equiv) SO (2 equiv) (10 mol %) 135 °C, 28 h	Ph H O				
Nitrogen-based Isol species (Ph-NX)	ated yield of <b>2g</b>	Nitrogen-based species (Ph-NX)	Isolated yield of <b>2g</b>				
Ph-NO (3a)	57%	Ph 1/2 N=N ( <b>3d</b> )	64%				
Ph-NHOH (3b)	55%	1/2 HN-NH ( <b>3e</b> )	70%				
Ph O (3c) 1/2 N=N⊕ (3c) Ph	49%	Ph Ph-NH <sub>2</sub> ( <b>3f</b> )	44%				
(b) Formylation without Fe(0)							
MeO NO <sub>2</sub> +	CO <sub>2</sub> TMDS	I <sub>2</sub> (2 equiv) SO (5 equiv) (10 mol%) MeO	2a, 45%				

**Scheme 3** Control experiments for *N*-formylation.

identical conditions were examined to probe their roles in formylation (Scheme 3a). Nitrosobenzene (3a), N-phenyl hydroxylamine (3b), azoxybenzene (3c) and azobenzene (3d) all reacted to give formamide 2g in 49-64% yields. Particularly, diphenyl hydrazine (3e) reacted most efficiently to afford 2g in 70% yield. Presumably, nitrobenzene is sequentially reduced to 3a, 3b, 3c, 3d, and finally 3e, 18 which acts as the ultimate intermediate to participate in the formylation reaction. Aniline 3f also reacted to give 2g in 44% yield, suggesting that it is likely the minor intermediate to induce the formylation. Furthermore, when Fe(0) was omitted, the addition of Fe(11) salt, which is a viable oxidized Fe species, could enable the formylation of nitroarene 1a in the presence of excess TMDSO to give formamide 2a in 45% yield. We surmised that hydrosilane can also act as a reductant and a hydrogen source for the reduction of nitroarene via the action of Fe-hydride species, 16a,b apart from its conventional application as CO2-activating agent.<sup>6h</sup>

Based on the experimental results, we proposed a plausible mechanism of the formylation protocol (Scheme 4). Nitroarene 1 is sequentially reduced to 1,2-diaryl hydrazine via the intermediacy of nitrosoarene, N-aryl hydroxylamine, azoxyarene, and/or azoarene<sup>18</sup> (pathway i). 1,2-Diaryl hydrazine then undergoes facile homolysis under heating to give aminyl radicals, <sup>17g</sup> which are then reduced to amide ion ArNH<sup>-</sup> (pathways ii and iii). Meanwhile, nitroarene can be reduced to amide dianion ArN<sup>2-</sup> followed by ArNH-, whereas Fe(0) is oxidized to Fe<sub>3</sub>O<sub>4</sub><sup>19</sup> (pathway iv and v). A small amount of aniline can also be generated (pathway vi). In the reduction processes, Fe(0) is likely the major reducing agent, while TMDSO likely acts as both mild reducing agent and hydrogenating agent. Owing to the strong nucleophilicity of ArNH and ArN2-, they likely activate both CO2 and TMDSO via the transition state TS-1, in which the carbamate ion formed further activates TMDSO to trigger the hydride attack to another CO<sub>2</sub> (pathway vii). Such transition state is regarded as the lowest energy pathway for CO<sub>2</sub> activation.<sup>6h</sup> Via TS-1, formoxysilane is formed with the concomitant regeneration of amide species (pathway viii). We proposed that iodide ion behaves as a



Scheme 4 Proposed mechanism of N-formylation.

strong nucleophile in polar aprotic solvent DMF, thereby facilitating the deformylation of formoxysilane to form a more reactive formyl iodide in conjunction with silanolate ion (pathway ix). Finally, ArNH reacts with both formyl iodide and formoxysilane to deliver the N-aryl formamide 2 (pathways x and xi). In the same vein, ArNH<sup>2-</sup> undergoes nucleophilic substitutions with formyl iodide and formoxysilane to give amidate ion, which furnishes formamide 2 upon acidic workup (pathways xii and xiii). On the other hand, the N-formylation based on aniline may proceed but tends to be a minor pathway due to the attenuated nucleophilicity of aniline. The detailed reaction mechanism is subjected to a dedicated study in the future.

Under the standard conditions, electron-rich nitro(hetero) arenes tended to react more efficiently to form higher product yields (~50-85%) than electron-deficient and sensitive groupbearing nitroarenes ( $\sim 40$ –60%, Scheme 2). We rationalized that the nitrogen-based intermediates derived from the latter are more unstable, especially in the reductive reaction conditions and in the presence of basic by-products (e.g. iron oxides, silanolate ions), and likely undergo over-reduction and decomposition at varying degrees in the course of reactions. Additionally, an additional equivalent of Fe(0) was found advantageous in the reactions of electron-rich nitro(hetero)arenes but detrimental for electrondeficient ones. We speculated that the contribution of Fe(0)and TMDSO-based reduction steps would vary with respect to the electronic effect of nitroarenes. The reduction of electron-rich nitro(hetero)arenes would mainly rely more on highly reducing Fe(0) to deliver more amide ions. Conversely, the excess Fe(0) would over-reduce the electron-deficient nitroarenes to less

Communication ChemComm

reactive anilines or other side products, but additional milder reduction given by Fe(II)/TMDSO system would in turn be more productive for formation of amide ions.

In conclusion, we have developed an alternative strategy to access formamides via direct N-formylation of nitroarenes with CO<sub>2</sub>. By using commercially available Fe powder and 1,1,3,3-tetramethyldisiloxane as additives, a variety of N-aryl and N-heteroaryl formamides are synthesized. Mechanistic study suggests that both Fe metal and hydrosilane can reduce nitroarenes to anionic nitrogen-based intermediates, which then activate CO<sub>2</sub> and hydrosilane for subsequent formylation.

We acknowledged the National Key Research and Development Program of China (No. 2019YFA0905100), National Natural Science Foundation of China (No. 21772142, 21971186, and 21961142015) and Tianjin University (start-up grants) for financial support. We thank Ms Yi-lin Yang (TJU), Mr Lei Li (TJU) and Mr Shao-Peng Wang (TJU) for assistance in scope study. We especially thank the anonymous Reviewer for valuable suggestions to improve the reaction outcomes.

#### Conflicts of interest

There are no conflicts to declare.

#### Notes and references

- 1 (a) E. A. Quadrelli, G. Centi, J.-L. Duplan and S. Perathoner, Chem-SusChem, 2011, 4, 1194; (b) W. Wang, S. Wang, X. Ma and J. Gong, Chem. Soc. Rev., 2011, 40, 3703; (c) J. Klankermayer, S. Wesselbaum, K. Beydoun and W. Leitner, Angew. Chem., Int. Ed., 2016, 55, 7296; (d) M. D. Burkart, N. Hazari, C. L. Tway and E. L. Zeitler, ACS Catal., 2019, 9, 7937.
- 2 (a) M. Aresta, Carbon Dioxide as Chemical Feedstock, Wiley-VCH, Weinheim, 2010; (b) Q. Liu, L. Wu, R. Jackstell and M. Beller, Nat. Commun., 2015, 6, 5933.
- 3 (a) A. Tortajada, F. Julia-Hernandez, M. Borjesson, T. Moragas and R. Martin, Angew. Chem., Int. Ed., 2018, 57, 15948; (b) S.-S. Yan, Q. Fu, L.-L. Liao, G.-Q. Sun, J.-H. Ye, L. Gong, Y.-Z. Bo-Xue and D.-G. Yu, Coord. Chem. Rev., 2018, 374, 439; (c) Y.-G. Chen, X.-T. Xu, K. Zhang, Y.-Q. Li, L.-P. Zhang, P. Fang and T.-S. Mei, Synthesis, 2018, 35; (d) J. Hong, M. Li, J. Zhang, B. Sun and F. Mo, Chem-SusChem, 2019, 12, 6.
- 4 (a) K. Dong and X.-F. Wu, Angew. Chem., Int. Ed., 2017, 56, 5399; (b) L. Wang, W. Sun and C. Liu, Chin. J. Chem., 2018, 36, 353; (c) L. Song, Y.-X. Jiang, Z. Zhang, Y.-Y. Gui, X.-Y. Zhou and D.-G. Yu, Chem. Commun., 2020, DOI: 10.1039/D0CC00547A.
- 5 (a) A. Tlili, X. Frogneux, E. Blondiaux and T. Cantat, Angew. Chem., Int. Ed., 2014, 53, 2543; (b) Y. Li, X. Cui, K. Dong, K. Junge and M. Beller, ACS Catal., 2017, 7, 1077; (c) F. N. Al-Rowaili, A. Jamal, M. S. Ba Shammakh and A. Rana, ACS Sustainable Chem. Eng., 2018, **6**, 15895; (d) X.-F. Liu, X.-Y. Li and L.-N. He, Eur. J. Org. Chem., 2019, 2437; (e) I. I. Alkhatiba, C. Garlisia, M. Pagliarob, K. Al-Alia and G. Palmisano, Catal. Today, 2020, 340, 209.
- 6 (a) A. Tlili, E. Blondiaux, X. Frogneux and T. Cantat, Green Chem., 2015, 17, 157; (b) B. Yu and L.-N. He, ChemSusChem, 2015, 8, 52; (c) J. Rintjema and A. Kleij, Synthesis, 2016, 3863; (d) N. A. Tappe, R. M. Reich, V. D'Elia and F. E. Kghn,, Dalton Trans., 2018, 47, 13281;

- (e) X.-F. Liu, X.-Y. Li, C. Qiao and L.-N. He, Synlett, 2018, 548; (f) J. R. Cabrero-Antonino, R. Adam and M. Beller, Angew. Chem., Int. Ed., 2019, 58, 12820; (g) J.-Y. Li, Q.-W. Song, K. Zhang, P. Liu, J.-Y. Li, Q.-W. Song, K. Zhang and P. Liu, Molecules, 2019, 24, 182; (h) M. Hulla and P. J. Dyson, Angew. Chem., 2020, 132, 1014.
- 7 (a) C. D. N. Gomes, O. Jacquet, C. Villiers, P. Thuery, M. Ephritikhine and T. Cantat, Angew. Chem., Int. Ed., 2012, 51, 187; (b) R. L. Nicholls, J. A. McManus, C. M. Rayner, J. A. Morales-Serna, A. J. P. White and B. N. Nguyen, ACS Catal., 2018, 8, 3678; (c) G. Li, J. Chen, D.-Y. Zhu, Y. Chen and J.-B. Xia, Adv. Synth. Catal., 2018, 360, 2364.
- 8 (a) O. Jacquet, C. D. N. Gomes, M. Ephritikhine and T. Cantat, J. Am. Chem. Soc., 2012, 134, 2934; (b) S. Das, F. D. Bobbink, S. Bulut, M. Soudania and P. J. Dyson, Chem. Commun., 2016, 52, 2497.
- 9 (a) H. Zhou, G.-X. Wang, W.-Z. Zhang and X.-B. Lu, ACS Catal., 2015, 5, 6773; (b) L. Hao, Y. Zhao, B. Yu, Z. Yang, H. Zhang, B. Han, X. Gao and Z. Liu, ACS Catal., 2015, 5, 4989; (c) M. Hulla, F. D. Bobbink, S. Das and P. J. Dyson, ChemCatChem, 2016, 8, 3338; (d) X.-F. Liu, X.-Y. Li, C. Qiao, H.-C. Fu and L.-N. He, Angew. Chem., Int. Ed., 2017, 56, 7425; (e) C. Xie, J. Song, H. Wu, B. Zhou, C. Wu and B. Han, ACS Sustainable Chem. Eng., 2017, 5, 7086; (f) Y. Hu, J. Song, C. Xie, H. Wu, Z. Wang, T. Jiang, L. Wu, Y. Wang and B. Han, ACS Sustainable Chem. Eng., 2018, 6, 11228; (g) M. Hulla, D. Ortiz, S. Katsyuba, D. Vasilyev and P. J. Dyson, Chem. - Eur. J., 2019, 25, 11074; (h) W. Zhao, X. Chi, H. Li, J. He, J. Long, Y. Xu and S. Yang, Green Chem., 2019, 21, 567.
- 10 (a) K. Motokura, M. Naijo, S. Yamaguchi, A. Miyaji and T. Baba, Chem. Lett., 2015, 44, 1217; (b) D. B. Nale and B. M. Bhanage, Synlett, 2016, 1413; (c) C. Fang, C. Lu, M. Liu, Y. Zhu, Y. Fu and B.-L. Lin, ACS Catal., 2016, 6, 7876; (d) M.-Y. Wang, N. Wang, X.-F. Liu, C. Qiao and L.-N. He, Green Chem., 2018, 20, 1564.
- 11 (a) J. Song, B. Zhou, H. Liu, C. Xie, Q. Meng, Z. Zhang and B. Han, Green Chem., 2016, 18, 3956; (b) H. Lv, Q. Xing, C. Yue, Z. Lei and F. Li, Chem. Commun., 2016, 52, 6545; (c) T.-X. Zhao, G.-W. Zhai, J. Liang, P. Li, X.-B. Hu and Y.-T. Wu, Chem. Commun., 2017, 53, 8046.
- 12 C. C. Chong and R. Kinjo, Angew. Chem., Int. Ed., 2015, 54, 12116.
- 13 V. B. Saptal, G. Juneja and B. M. Bhanage, New J. Chem., 2018, 42, 15847.
- 14 L. Zhang, Z. Han, X. Zhao, Z. Wang and K. Ding, Angew. Chem., Int. Ed., 2015, 54, 6186.
- 15 U. Jayarathne, N. Hazari and W. H. Bernskoetter, ACS Catal., 2018, 8, 1338.
- 16 For examples, see: (a) J. Gui, C.-M. Pan, Y. Jin, T. Qin, J. C. Lo, B. J. Lee, S. H. Spergel, M. E. Mertzman, W. J. Pitts, T. E. La Cruz, M. A. Schmidt, N. Darvatkar, S. R. Natarajan and P. S. Baran, Science, 2015, **348**, 886; (b) K. Zhu, M. P. Shaver and S. P. Thomas, *Chem. Sci.*, 2016, 7, 3031; (c) C. W. Cheung and X. Hu, Nat. Commun., 2016, 7, 12494; (d) J. Xiao, Y. He, F. Ye and S. Zhu, Chem, 2018, 4, 1645; (e) T. V. Nykaza, J. C. Cooper, G. Li, N. Mahieu, A. Ramirez, M. R. Luzung and A. T. Radosevich, J. Am. Chem. Soc., 2018, 140, 15200; (f) S. Suárez-Pantiga, R. Hernández-Ruiz, C. Virumbrales, M. R. Pedrosa and R. Sanz, Angew. Chem., Int. Ed., 2019, 58, 2129; (g) L. Wang, H. Neumann and M. Beller, Angew. Chem., Int. Ed., 2019, **58**, 5417; (h) M. Rauser, R. Eckert, M. Gerbershagen and M. Niggemann, Angew. Chem., Int. Ed., 2019, 58, 6713.
- 17 For examples, see: (a) X. Fang, R. Jackstell and M. Beller, Angew. Chem., Int. Ed., 2013, 52, 14089; (b) F. Zhou, D.-S. Wang, X. Guan and T. G. Driver, Angew. Chem., Int. Ed., 2017, 56, 4530; (c) C. W. Cheung, M. L. Ploeger and X. Hu, Chem. Sci., 2018, 9, 655; (d) J.-B. Peng, H.-Q. Geng, D. Li, X. Qi, J. Ying and X.-F. Wu, Org. Lett., 2018, 20, 4988; (e) J.-B. Peng, D. Li, H.-Q. Geng and X.-F. Wu, Org. Lett., 2019, 21, 4878; (f) S. Zhao and N. P. Mankad, Org. Lett., 2019, 21, 10106; (g) N. Shen, C. W. Cheung and J.-A. Ma, Chem. Commun., 2019, 55, 13709.
- 18 (a) H.-U. Blaser, Science, 2006, 313, 312; (b) H.-U. Blaser, H. Steiner and M. Studer, ChemCatChem, 2009, 1, 210.
- 19 R. Dey, N. Mukherjee, S. Ahammed and B. C. Ranu, Chem. Commun., 2012, 48, 7982.