

## RESEARCH ARTICLE

View Article Online

View Journal | View Issue

Cite this: *Org. Chem. Front.*, 2022, **9**, 2169Received 12th January 2022,  
Accepted 1st March 2022

DOI: 10.1039/d2qo00045h

rsc.li/frontiers-organic

Radical hydrotrifluoromethylation of ynamides:  
a route toward  $\beta$ -CF<sub>3</sub> enamides†Wanqiao Huang,<sup>‡</sup> Ruzhong Zhang,<sup>‡</sup> Ruxue Zhang, Jianxin Yu and Mang Wang\*

We report here a radical hydrotrifluoromethylation of ynamides to provide an alternative route toward  $\beta$ -CF<sub>3</sub> enamides. By using PhICF<sub>3</sub>Cl as the CF<sub>3</sub> reagent and DMF as the H-donor, the reaction occurred smoothly in the presence of NaH at room temperature. Further reduction of the resulting  $\beta$ -CF<sub>3</sub> enamides efficiently delivered  $\beta$ -CF<sub>3</sub> amines. Gram-scale synthesis was conducted to demonstrate the practicability of the method.

## Introduction

Molecules containing two powerful functionals, trifluoromethyl and amino, in adjacent positions are valuable targets in drug design and synthetic chemistry.<sup>1</sup> Consequently, great efforts have been focused on the assembly of amino and trifluoromethyl at the *ortho* position.<sup>2</sup> In this field, the aminotrifluoromethylation of alkenes provides the main and step-economical route toward  $\beta$ -CF<sub>3</sub> amines (Scheme 1A).<sup>2i,j</sup> On the other hand, enamines have found wide synthetic applications,<sup>3</sup> which also encouraged investigations on the vicinal trifluoromethylated enamines. However, to date, there have been limited approaches established for preparing  $\beta$ -CF<sub>3</sub> enamines. Apart from several works on utilizing the amination of pre-synthesized CF<sub>3</sub>-containing substrates,<sup>4</sup> as well as a recent report involving a three-component reaction between trifluorodiazaoethane, aldehydes, and imines,<sup>5</sup> trifluoromethylation-based methods have been documented to deliver  $\beta$ -CF<sub>3</sub> enamines, including *via* the aminotrifluoromethylation of alkynes (Scheme 1A)<sup>6</sup> and direct Csp<sup>2</sup>-H trifluoromethylation of enamines (Scheme 1B).<sup>7</sup>

During our ongoing explorations in the field of trifluoromethylation, an externally coordinated CF<sub>3</sub>-containing  $\lambda^3$ -iodane (PhICF<sub>3</sub>Cl)<sup>8</sup> was synthesized to be used in a set of trifluoromethylation reactions.<sup>9</sup> Efficient trifluoromethylative bifunctionalization reactions of alkenes have been developed by our group recently.<sup>9a-d</sup> In order to extend the synthetic applications of PhICF<sub>3</sub>Cl, the trifluoromethylation of alkynes

was investigated in the follow-up work. As a result, when ynamides<sup>10</sup> were chosen as alkyne substrates for the reaction with PhICF<sub>3</sub>Cl in DMF, unprecedented  $\beta$ -CF<sub>3</sub> enamides were produced. It provides an alternative and mild route toward  $\beta$ -CF<sub>3</sub> enamides.  $\beta$ -CF<sub>3</sub> amines were obtained by further reduction. Herein, we report a new hydrotrifluoromethylation of ynamides (Scheme 1C).

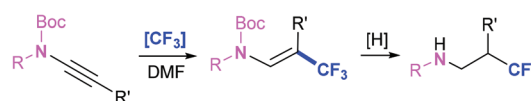
## Results and discussion

It was reported that CF<sub>3</sub> radical addition onto *N*-benzoyl ynamides afforded aryltrifluoromethylative cyclization products.<sup>11</sup> In order to avoid such possible side reactions, *tert*-butyl ethynyl(phenyl)carbamate **1a** was chosen in our initial attempt to carry out the trifluoromethylation of ynamides using

## A. Aminotrifluoromethylation of Alkenes/Alkynes



## B. Trifluoromethylation of Enamines

C. Hydrotrifluoromethylation of Ynamides *This Work*

**Scheme 1** Trifluoromethylation-based route toward  $\beta$ -CF<sub>3</sub> amines/enamides.

Jilin Province Key Laboratory of Organic Functional Molecular Design & Synthesis, College of Chemistry, Northeast Normal University, Changchun 130024, P. R. China. E-mail: wangm452@nenu.edu.cn

†Electronic supplementary information (ESI) available: <sup>1</sup>H, <sup>13</sup>C, <sup>19</sup>F and NOE NMR spectra and crystallographic data. CCDC 2141492. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d2qo00045h

‡These authors contributed equally to this work.

PhICF<sub>3</sub>Cl as the trifluoromethylating reagent. Notably, the hydrotrifluoromethylation product **2a** was obtained in 57% NMR yield, accompanied by **3a** in 36% NMR yield only by stirring a mixture of **1a** and PhICF<sub>3</sub>Cl in DMF at room temperature (Table 1, entry 1). DMF was likely the H-donor in such a simple reaction mixture and a radical process was proposed for the formation of **2a**. According to our previous work in which radical trifluoromethylation of alkenes with PhICF<sub>3</sub>Cl could not occur at room temperature without the assistance of a reductant,<sup>9d</sup> ynamide substrate **1a** likely acted as a tertiary amine type electron donor<sup>12</sup> for the generation of the CF<sub>3</sub> radical from PhICF<sub>3</sub>Cl. Thus, an additional reductant was used for the above hydrotrifluoromethylation of **1a**. As we hypothesized, the addition of tertiary amines, including triethylamine (TEA), 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) and *N,N*-diisopropylethylamine (DIPEA), could indeed help increase the yield of **2a** a little bit (entries 2–4). Tetrabutylammonium iodide (TBAI) and zinc iodide showed poor performance (entries 5 and 6), and triethylsilane had no obvious influence on this reaction (entry 7). In comparison, NaH was proven to be an optimal reductant, leading to **2a** in 81% NMR yield (entry 8). No **3a** was detected in these cases (entries 2–6 and 8). Solvent screening showed that **2a** could also be obtained in good to moderate yields in *N,N*-dimethylacetamide (DMAc, entry 9), tetrahydrofuran (THF, entry 10) and *N*-methylpyrrolidone (NMP, entry 11). However, dichloromethane (DCM, entry 12) was not suitable for the reaction. The reaction time was then controlled precisely (entries

13–15). It was found that the NMR yield of **2a** was 75% within 2 h (entry 14). Finally, a gram-scale experiment was conducted and **2a** was obtained in 70% isolated yield, which demonstrated the robustness of the protocol (entry 16).

After establishing the optimal conditions for this reaction (Table 1, entry 14), the generality of this protocol was examined by using various kinds of ynamide substrates (Table 2).

First, a series of *N*-phenyl-substituted ynamides were selected and tested in this reaction. We were pleased to see that electronically and sterically distinct substituents at different positions were tolerated, affording the β-CF<sub>3</sub> enamides (**2b–x**) in good yields. Ynamides bearing electron-withdrawing groups, such as halide (**1b–e**, **1q**, **1t**, and **1w**), fluoroalkyl (**1p**) or carbonyl groups (**1k** and **1l**), could all provide the desired products in good yields. Electron-rich substituents like alkyl (**1f–h**, **1j**, **1r**, **1u** and **1v**), aryl (**1i**), and alkoxy/aryloxy (**1m–o**, **1s**, and **1x**) did not have obvious influences on the reactions. Remarkably, enamide **2w** could be generated in 90% yield from the reaction of sterically hindered ynamide **1w**. Secondly, the protecting groups of the ynamides were tested. Both *N*-Ac and *N*-Cbz ynamides were suitable for this reaction although the reactions afforded **2a** and **2aa** in reduced yields under identical conditions. However, *p*-toluenesulfonyl-ynamide **1ab** was not suitable for this reaction. The reaction was complex and the desired product **2ab** was not detected. Next, hydrotrifluoromethylations of *N*-benzyl ynamides were carried out under identical conditions. A series of *N*-benzyl ynamides substituted at different positions were selected and tested in this reaction. It was found that all the tested *N*-benzyl ynamides **1ac–ag** were efficiently transformed into the corresponding products **2ac–ag**. In addition, the enamide product **2ah** could also be generated from *N*-phenylethyl ynamide **1ah** in 70% yield.

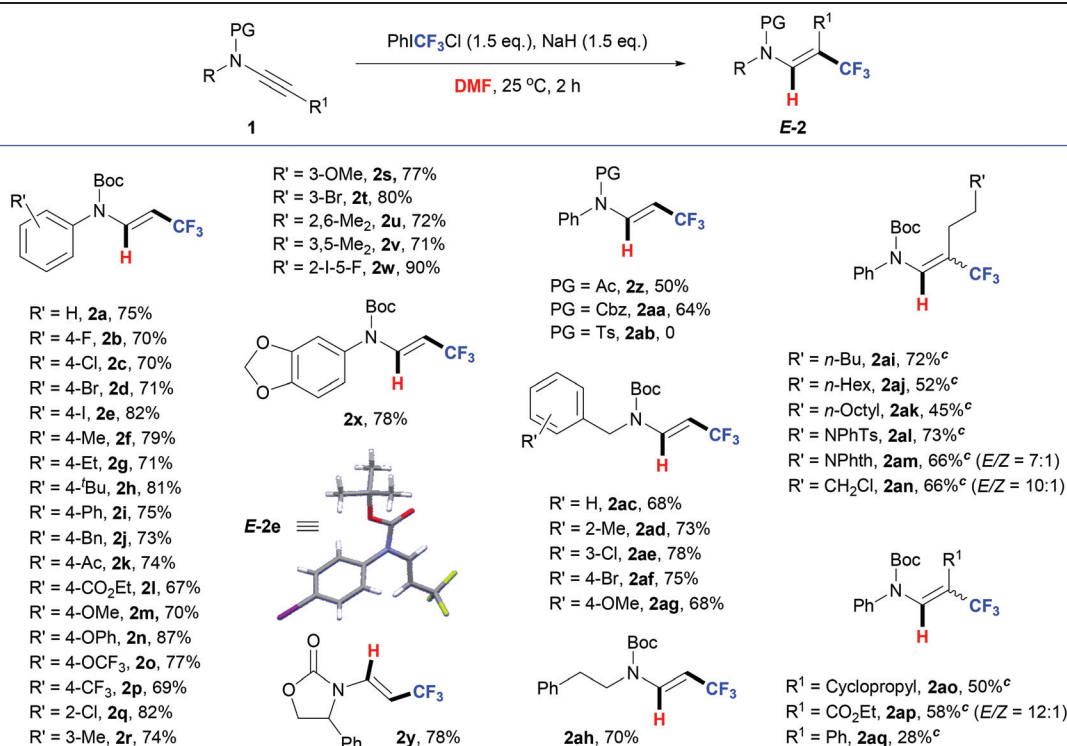
Finally, non-terminal ynamides were synthesized to test the substrate scope. As shown in Table 2, the desired products **2** could be obtained in moderate to good yields when the reaction time was prolonged. Long-chain alkyl- (**1ai–an**), cycloalkyl- (**1ao**) and ester-ynamides (**2ap**) all proved to be suitable for this reaction. In comparison, phenyl substituted ynamide **1aq** delivered **2aq** in 28% yield, along with the generation of regioisomeric isomers.<sup>13</sup> Note that the hydrotrifluoromethylation of ynamides **1** stereoselectively afforded enamines **2**. Thermodynamically stable *E*-isomeric enamines were obtained as the main products in most cases, which was proved by the X-ray crystal structure of **2e**.<sup>14</sup> In comparison, lower stereoselectivities were observed in some cases, such as **2am**, **2an** and **2ap**, likely caused by the little difference in the thermodynamic stability of the products.

As described above, we have established a novel hydrotrifluoromethylation reaction of ynamides, which provides a trifluoromethylative bifunctionalization pathway to synthesize β-CF<sub>3</sub> enamides. Further transformation of β-trifluoromethyl enamides **2** was investigated to highlight the synthetic potential of the approach. As shown in Table 3, by using silyl hydride as the reductant, reduction/deprotection products **4**, β-CF<sub>3</sub> amines,<sup>1a,b,15</sup> could be obtained in good to

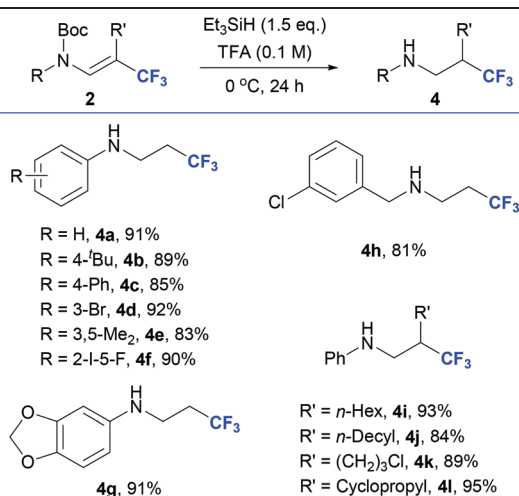
Table 1 Optimization of reaction conditions<sup>a</sup>

Entry	Reductant	Solv.	t/h	<b>2a</b> <sup>b</sup> /%	<b>3a</b> <sup>c,d</sup> /%
1	—	DMF	12	50	36
2	TEA	DMF	12	61	N.D.
3	DBU	DMF	12	65	N.D.
4	DIPEA	DMF	12	67	N.D.
5 <sup>e</sup>	TBAI	DMF	12	14	Trace
6	ZnI <sub>2</sub>	DMF	12	23	Trace
7	Et <sub>3</sub> SiH	DMF	12	52	17
8	NaH	DMF	12	81(75) <sup>f</sup>	N.D.
9	NaH	DMAc	12	69	N.D.
10	NaH	NMP	12	52	9
11	NaH	THF	12	54	21
12	NaH	DCM	12	9	Trace
13	NaH	DMF	1	66	N.D.
14	NaH	DMF	2	75(72) <sup>f</sup>	N.D.
15	NaH	DMF	6	72	N.D.
16 <sup>g</sup>	NaH	DMF	2	75(70) <sup>f</sup>	N.D.

<sup>a</sup> Reaction conditions: **1a** (0.2 mmol), PhICF<sub>3</sub>Cl (1.5 eq.), reductant (1.5 eq.), solvent (2.0 mL), 25 °C, N<sub>2</sub>. <sup>b</sup> <sup>19</sup>F NMR yield using benzotrifluoride as the internal standard. <sup>c</sup> <sup>1</sup>H NMR yield using dibromomethane as the internal standard. <sup>d</sup> N.D. = not detected. <sup>e</sup> 80% of **1a** was recovered. <sup>f</sup> Isolated yields of **E-2a** are shown in brackets. <sup>g</sup> Gram-scale reaction was performed at the 5.5 mmol scale.

Table 2 Substrate scope of hydrotrifluoromethylation of ynamides<sup>a,b</sup>

<sup>a</sup> Reaction conditions: **1** (0.2 mmol), PhICl<sub>3</sub> (0.3 mmol, 1.5 eq.), NaH (0.3 mmol, 1.5 eq.), DMF (2.0 mL), 25 °C, N<sub>2</sub>, 2 h. <sup>b</sup> Isolated yields of **E-2** unless the E/Z ratio is otherwise noted in the brackets. <sup>c</sup> Reaction conditions: 30 °C, 12 h.

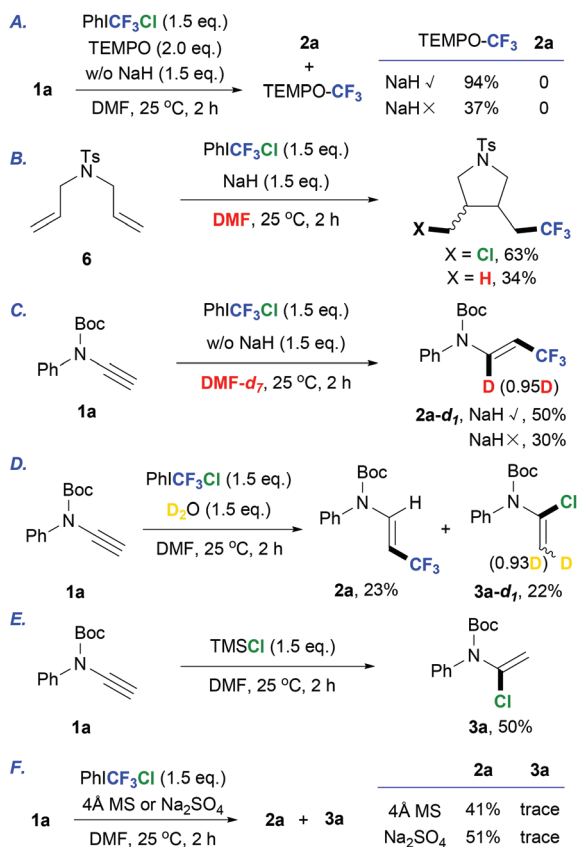
Table 3 Deprotected reduction of β-CF<sub>3</sub> enamines<sup>a,b</sup>

<sup>a</sup> Reaction conditions: **2** (0.1 mmol), Et<sub>3</sub>SiH (0.15 mmol, 1.5 eq.), TFA (1.0 mL), 0 °C, N<sub>2</sub>, 24 h. <sup>b</sup> Isolated yields of **4**.

excellent yields in the presence of trifluoroacetic acid.<sup>16</sup> β-CF<sub>3</sub> enamides generated from substituted *N*-phenyl ynamides (**1a**, **1h**, **1j**, **1t**, **1v**, **1w**, and **1x**), *N*-benzyl ynamide (**1ae**) and non-terminal ynamides (**1ai**, **1ak**, **1an** and **1ao**), were all suitable

for this reductive deprotection reaction to generate the corresponding β-CF<sub>3</sub> amines **4a-l**.

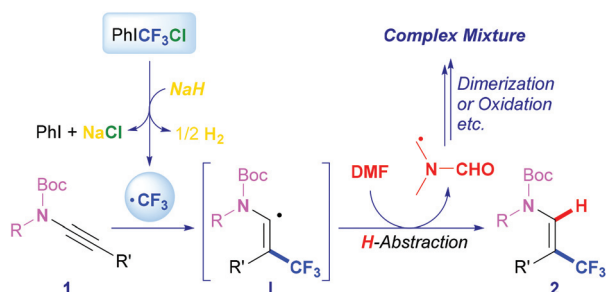
A set of control experiments were conducted to verify the possible reaction mechanism. Radical trapping experiments were carried out under the standard conditions by the addition of 2,2,6,6-tetramethylpiperidine-1-oxide (TEMPO, Scheme 2A). The desired product **2a** could not be obtained in the presence or absence of NaH, which suggested the involvement of a radical process. A radical clock experiment was also conducted by using *N,N*-diallyl-4-methylbenzenesulfonamide under the standard reaction conditions (Scheme 2B). As a result, both chloro-<sup>9d</sup> and hydro-cyclization products<sup>17</sup> were obtained to demonstrate a radical mechanism. To identify the hydrogen source, deuterated DMF was used in the reaction of **1a**. As shown in Scheme 2C, the reactions were carried out in DMF-*d*<sub>7</sub> with or without NaH, and the deuterated product **2a-d**<sub>1</sub> was obtained, demonstrating an H-abstraction process from the solvent involved in the reaction. No deuterated β-CF<sub>3</sub> enamide was detected when D<sub>2</sub>O was added in this reaction (Scheme 2D), which excluded the formation of **2a** via protonation from water; meanwhile, the deuterated chloro-enamide **3a-d**<sub>1</sub> was detected as the background product. To further verify the formation of **3a** from an electrophilic addition of alkynes, we performed an additional reaction of **1a** in DMF using TMSCl as the Cl-source instead of PhICl<sub>3</sub>Cl. **3a** was obtained in 50% yield, suggesting that a background reaction



Scheme 2 Control experiments.

existed in our hydrotrifluoromethylation of ynamides **1**. This experimental result indicated that NaH may also help in the removal of water from the reaction mixture, which is beneficial for inhibiting the formation of byproducts **3**. Further investigations on the role of NaH were carried out by the reaction of **1a** and  $\text{PhICF}_3\text{Cl}$  in the presence of desiccants without NaH (Scheme 2F). As a result, the formation of **3a** was inhibited, but the yield of **2a** was still moderate. These experimental results showed that NaH not only acted as a water removal reagent but also assisted in the radical hydrotrifluoromethylation of ynamides.

According to the literature<sup>12c,18</sup> and experiment results, a plausible mechanism is proposed as described in Scheme 3.



Scheme 3 A plausible radical mechanism.

$\text{PhICF}_3\text{Cl}$  is reduced by NaH to release the trifluoromethyl radical, which is added to substrate **1** immediately to generate alkenyl radical intermediate **I**. Meanwhile, iodobenzene and hydrogen<sup>19</sup> are generated, respectively, suggesting that NaH acts as a reductant of  $\text{PhICF}_3\text{Cl}$  through an electron transfer pathway. An H-atom-abstraction of **I** from the solvent DMF subsequently occurred and gave the hydrotrifluoromethylation product **2**. In this case, it is proposed that the *N*-methyl-H of DMF is abstracted<sup>20</sup> by the electrophilic trifluoromethylated radical **I**, which is supported by the fact that good transformations could also be obtained in either DMAc or NMP (Table 1, entries 9 and 10). The generated DMF-based carbon radical would further undergo dimerization, oxidation, hydrolysis, or other processes, resulting in the formation of mixed products.<sup>21</sup> Note that although this proposed mechanism is preferred, other plausible H-abstraction processes or reaction mechanisms cannot be ruled out at this stage.

## Conclusions

In conclusion, by using  $\text{PhICF}_3\text{Cl}$  as the trifluoromethyl source, the hydrotrifluoromethylation of ynamides was achieved successfully, in which a series of  $\beta\text{-CF}_3$  enamides were synthesized efficiently. The mild and transition-metal free reaction conditions, the good functional group tolerance and the capability to be performed at the gram scale make this method valuable and practical. Control experiments proved that the reaction occurred *via* a radical process, which is a new achievement in the field of underexplored free radical reactions of ynamides.

## Author contributions

W. Huang and R. Z. Zhang performed the experiments and co-wrote the ESI.† W. Huang wrote the initial draft of this manuscript. R. X. Zhang and J. Yu helped in preparing several substrates. Prof. M. Wang conceived the project and concept reviewed the manuscript. All authors read and contributed to the revisions and approved the final version to be published.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We thank the National Natural Science Foundation of China (21672032) and the Department of Science and Technology of Jilin Province (20200201067JC) for funding this work.

## Notes and references

- (a) Q. Li, W. Wang, K. B. Berst, A. Claiborne, L. Hasvold, K. Raye, M. Tufano, A. Nilius, L. L. Shen, R. Flamm, J. Alder, K. Marsh, D. Crowell, D. T. W. Chu and J. J. Plattner, Synthesis and Structure-Activity Relationships of 2-Pyridones: II. 8-(Fluoro-Substituted Pyrrolidinyl)-2-Pyridones as Antibacterial Agents, *Bioorg. Med. Chem. Lett.*, 1998, **8**, 1953–1958; (b) J. A. Sikorski, Oral Cholesteryl Ester Transfer Protein (CETP) Inhibitors: A Potential New Approach for Treating Coronary Artery Disease, *J. Med. Chem.*, 2006, **49**, 1–22; (c) I. I. Gerus, R. V. Mironets, E. N. Shaitanova and V. P. Kukhar, Synthesis of New  $\beta$ -Trifluoromethyl Containing GABA and  $\beta$ -Fluoromethyl Containing *N*-Benzylpyrrolidinones, *J. Fluorine Chem.*, 2010, **131**, 224–228; (d) T. Borisova, N. Pozdnyakova, E. Shaitanova, I. Gerus, M. Dudarenko, R. Mironets, G. Haufe and V. Kukhar, Synthesis of New Fluorinated Analogs of GABA, Pregabalin Bioisosteres, and Their Effects on [ $^3\text{H}$ ]GABA Uptake by Rat Brain Nerve Terminals, *Bioorg. Med. Chem.*, 2015, **23**, 4316–4323.
- For selected reviews, see: (a) H. Egami and M. Sodeoka, Trifluoromethylation of Alkenes with Concomitant Introduction of Additional Functional Groups, *Angew. Chem., Int. Ed.*, 2014, **53**, 8294–8308; (b) E. Merino and C. Nevado, Addition of  $\text{CF}_3$  Across Unsaturated Moieties: A Powerful Functionalization Tool, *Chem. Soc. Rev.*, 2014, **43**, 6598–6608; (c) C. Alonso, E. M. de Marigorta, G. Rubiales and F. Palacios, Carbon Trifluoromethylation Reactions of Hydrocarbon Derivatives and Heteroarenes, *Chem. Rev.*, 2015, **115**, 1847–7935; (d) P. Gao, X.-R. Song, X.-Y. Liu and Y.-M. Liang, Recent Developments in the Trifluoromethylation of Alkynes, *Chem. – Eur. J.*, 2015, **21**, 7648–7661; (e) T. Koike and M. Akita, A Versatile Strategy for Difunctionalization of Carbon-Carbon Multiple Bonds by Photoredox Catalysis, *Org. Chem. Front.*, 2016, **3**, 1345–1349; (f) T. Koike and M. Akita, Fine Design of Photoredox Systems for Catalytic Fluoromethylation of Carbon-Carbon Multiple Bonds, *Acc. Chem. Res.*, 2016, **49**, 1937–1945; (g) E. H. Oh, H. J. Kim and S. B. Han, Recent Developments in Visible-Light-Catalyzed Multicomponent Trifluoromethylation of Unsaturated Carbon-Carbon Bonds, *Synthesis*, 2018, **50**, 3346–3358; (h) Y. Tian, S. Chen, Q.-S. Gu, J.-S. Lin and X.-Y. Liu, Amino- and Azidotrifluoromethylation of Alkenes, *Tetrahedron Lett.*, 2018, **59**, 203–215; (i) H. Jiang and A. Studer, Intermolecular Radical Carboamination of Alkenes, *Chem. Soc. Rev.*, 2020, **49**, 1790–1811; (j) S. Barata-Vallejo and A. Postigo, New Visible-Light-Triggered Photocatalytic Trifluoromethylation Reactions of Carbon-Carbon Multiple Bonds and (Hetero)Aromatic Compounds, *Chem. – Eur. J.*, 2020, **26**, 11065–11084; (k) K. Keerthika, S. Nath and K. Geetharani, Transition-Metal-Free Trifluoromethylative Difunctionalization of Olefins and Alkynes: Approaches and Challenges Ahead, *Catal. Sci. Technol.*, 2020, **10**, 7142–7159.
- (a) H. Hayashi, A. Kaga and S. Chiba, Application of Vinyl Azides in Chemical Synthesis: A Recent Update, *J. Org. Chem.*, 2017, **82**, 11981–11989; (b) V. A. Bakulev, T. Beryozkina, J. Thomas and W. Dehaen, The Rich Chemistry Resulting from the 1,3-Dipolar Cycloaddition Reactions of Enamines and Azides, *Eur. J. Org. Chem.*, 2018, 262–294; (c) Y.-Q. Zou, F. M. Hörmann and T. Bach, Iminium and Enamine Catalysis in Enantioselective Photochemical Reactions, *Chem. Soc. Rev.*, 2018, **47**, 278–290; (d) L. Zhu, D. Wang, Z. Jia, Q. Lin, M. Huang and S. Luo, Catalytic Asymmetric Oxidative Enamine Transformations, *ACS Catal.*, 2018, **8**, 5466–5484.
- (a) V. M. Muzalevskiy, V. G. Nenajdenko, A. Y. Rulev, I. A. Ushakov, G. V. Romanenko, A. V. Shastin, E. S. Balenkova and G. Haufe, Selective Synthesis of  $\alpha$ -Trifluoromethyl- $\beta$ -Aryl Enamines or Vinylogous Guanidinium Salts by Treatment of  $\beta$ -Halo- $\beta$ -Trifluoromethylstyrenes with Secondary Amines under Different Conditions, *Tetrahedron*, 2009, **65**, 6991–7000; (b) A. Y. Rulev, I. A. Ushakov, E. V. Kondrashov, V. M. Muzalevskiy, A. V. Shastin and V. G. Nenajdenko, Mechanistic Study of Multi-Step Nucleophilic Substitution for Trifluoromethylated Styrenes, *J. Fluorine Chem.*, 2011, **132**, 945–950; (c) I. W. Davies, D. M. Tellers, C. S. Shultz, F. J. Fleitz, D. Cai and Y. Sun, A [2+2] Cycloaddition Route to Dimethylaminomethylene Vinamidinium Salts, *Org. Lett.*, 2002, **4**, 2969–2972; (d) H. Yamanaka, K. Shiomi and T. Ishihara, Reactions of Quaternary Ammonium Salt Having a Polyfluoroalkenyl Group with Secondary Amines. A New Convenient and Stereoselective Synthesis of  $\beta$ -Trifluoromethylated Enamines, *Tetrahedron Lett.*, 1995, **36**, 7267–7270.
- A. Kumar, A. Dhami, J. Fairroosa, R. Kant and K. Mohanan, Silver-Catalyzed Direct Synthesis of Trifluoromethylated Enaminopyridines and Isoquinolinones Employing Trifluorodiazethane, *Org. Lett.*, 2021, **23**, 5815–5820.
- (a) G.-C. Ge, X.-J. Huang, C.-H. Ding, S.-L. Wan, L.-X. Dai and X.-L. Hou, A New Strategy to Construct a  $\text{C}=\text{C}-\text{CF}_3$  Subunit via CuBr-Catalyzed Domino Reaction of Homopropargyl Amines: An Efficient Synthesis of Trifluoromethyl Containing Building Blocks 4-Trifluoromethyl-2,3-Dihydro-Pyrroliums, *Chem. Commun.*, 2014, **50**, 3048–3051; (b) G. C. Ge, X. J. Huang, C. H. Ding, H. Li, S. Wan and X. Hou, CuBr-Promoted Tandem Cyclization/Trifluoromethylation of 2-Alkynylanilines: Efficient Synthesis of 3-Trifluoromethylindoles, *Chin. J. Chem.*, 2014, **32**, 727–733; (c) F. Wang, N. Zhu, P. Chen, J. Ye and G. Liu, Copper-Catalyzed Trifluoromethylazidation of Alkynes: Efficient Access to  $\text{CF}_3$ -Substituted Azirines and Aziridines, *Angew. Chem., Int. Ed.*, 2015, **54**, 9356–9360; (d) Y.-T. He, Q. Wang, J. Zhao, X.-Y. Liu, P.-F. Xu and Y.-M. Liang, The Copper-Catalyzed Synthesis of  $\beta$ -Trifluoromethylated Acrylonitriles and Trifluoromethyl-Substituted 2*H*-Azirines, *Chem. Commun.*, 2015, **51**, 13209–13212; (e) Y. Xiang, Y. Kuang and J. Wu, Generation of Benzosultams via Trifluoromethylation of 2-Ethynylbenzenesulfonamide under Visible Light, *Org. Chem. Front.*, 2016, **3**, 901–905; (f) Y. Ye, K. P. S. Cheung, L. He and G. C. Tsui, Domino Cyclization/Trifluoromethylation of

- 2-Alkynylanilines Using Fluoroform-Derived  $\text{CuCF}_3$ : Synthesis of 3-(Trifluoromethyl)indoles, *Org. Chem. Front.*, 2018, **5**, 1511–1515; (g) H. S. Han, E. H. Oh, Y.-S. Jung and S. B. Han, Photoredox-Catalyzed Trifluoromethylative Intramolecular Cyclization: Synthesis of  $\text{CF}_3$ -Containing Heterocyclic Compounds, *Org. Lett.*, 2018, **20**, 1698–1702; (h) J. Ge, Q. Ding, X. Wang and Y. Peng, Three-Component Cascade Synthesis of Fully Substituted Trifluoromethyl Pyrroles via A Cu(II)/Rh(III)-Promoted Aza-Michael Addition/Trifluoromethylation Cyclization/Oxidation Reaction, *J. Org. Chem.*, 2020, **85**, 7658–7665.
- 7 (a) C. Feng and T.-P. Loh, Copper-Catalyzed Olefinic Trifluoromethylation of Enamides at Room Temperature, *Chem. Sci.*, 2012, **3**, 3458–3462; (b) Y. Ohtsuka, D. Uraguchi, K. Yamamoto, K. Tokuhisa and T. Yamakawa, Fenton Reagent-Catalyzed Trifluoromethylation of Enamines of 3-Oxocarboxylates with  $\text{CF}_3\text{I}$ , *J. Fluorine Chem.*, 2016, **181**, 1–6; (c) H. Jiang, W. Huang, Y. Yu, S. Yi, J. Li and W. Wu, Transition-Metal-Free Synthesis of  $\beta$ -Trifluoromethylated Enamines with Trifluoromethanesulfinate, *Chem. Commun.*, 2017, **53**, 7473–7476.
- 8 C. Xu, X. Song, J. Guo, S. Chen, J. Gao, J. Jiang, F. Gao, Y. Li and M. Wang, Synthesis of Chloro(phenyl)trifluoromethyl-iodane and Catalyst-Free Electrophilic Trifluoromethylations, *Org. Lett.*, 2018, **20**, 3933–3937.
- 9 (a) J. Guo, C. Xu, X. Liu and M. Wang, Aryltrifluoromethylative Cyclization of Unactivated Alkenes by the Use of  $\text{PhICl}_3\text{Cl}$  under Catalyst-Free Conditions, *Org. Biomol. Chem.*, 2019, **17**, 2162–2168; (b) J. Guo, C. Xu, L. Wang, W. Huang and M. Wang, Catalyst-Free and Selective Trifluoromethylative Cyclization of Acryloanilides Using  $\text{PhICl}_3\text{Cl}$ , *Org. Biomol. Chem.*, 2019, **17**, 4593–4599; (c) C. Xu, W. Huang, R. Zhang, C. Gao, Y. Li and M. Wang, Trifluoromethylations of Alkenes Using  $\text{PhICl}_3\text{Cl}$  as Bifunctional Reagent, *J. Org. Chem.*, 2019, **84**, 14209–14216; (d) W. Huang, C. Xu, J. Yu and M. Wang,  $\text{ZnI}_2$ -Catalyzed Aminotrifluoromethylation Cyclization of Alkenes Using  $\text{PhICl}_3\text{Cl}$ , *J. Org. Chem.*, 2021, **86**, 1987–1999; (e) R. Z. Zhang, R. X. Zhang, S. Wang, C. Xu, W. Guan and M. Wang, An *N*-Trifluoromethylation/Cyclization Strategy for Accessing Diverse *N*-Trifluoromethyl Azoles from Nitriles and 1,3-Dipoles, *Angew. Chem., Int. Ed.*, 2022, **61**, e202110749.
- 10 For selected reviews, see: (a) C. C. Lynch, A. Sripada and C. Wolf, Asymmetric Synthesis with Ynamides: Unique Reaction Control, Chemical Diversity and Applications, *Chem. Soc. Rev.*, 2020, **49**, 8543–8583; (b) Y.-B. Chen, P.-C. Qian and L.-W. Ye, Brønsted Acid-Mediated Reactions of Ynamides, *Chem. Soc. Rev.*, 2020, **49**, 8897–8909; (c) F.-L. Hong and L.-W. Ye, Transition Metal-Catalyzed Tandem Reactions of Ynamides for Divergent *N*-Heterocycle Synthesis, *Acc. Chem. Res.*, 2020, **53**, 2003–2019; (d) C. Mahe and K. Cariou, Ynamides in Free Radical Reactions, *Adv. Synth. Catal.*, 2020, **362**, 4820–4832; (e) J. Luo, G.-S. Chen, S.-J. Chen, J.-S. Yu, Z.-D. Li and Y.-L. Liu, Exploiting Remarkable Reactivities of Ynamides: Opportunities in Designing Catalytic Enantioselective Reactions, *ACS Catal.*, 2020, **10**, 13978–13992.
- 11 M. Cassé, C. Nisole, H. Dossmann, Y. Gimbert, J.-M. Fourquez, L. Haberkorn, C. Ollivier and L. Fensterbank, Trifluoromethyl Radical Triggered Radical Cyclization of *N*-benzoyl Ynamides Leading to Isoindolinones, *Sci. China: Chem.*, 2019, **62**, 1542–1546.
- 12 (a) Y. Cheng and S. Yu, Hydrotrifluoromethylation of Unactivated Alkenes and Alkynes Enabled by an Electron-Donor-Acceptor Complex of Togni's Reagent with a Tertiary Amine, *Org. Lett.*, 2016, **18**, 2962–2965; (b) G. M. F. Batista, P. P. de Castro, H. F. Dos Santos, K. T. de Oliveira and G. W. Amarante, Electron-Donor-Acceptor Complex-Enabled Flow Methodology for the Hydrotrifluoromethylation of Unsaturated  $\beta$ -Keto Esters, *Org. Lett.*, 2020, **22**, 8598–8602; (c) D. Wei, T. Liu, Y. He, B. Wei, J. Pan, J. Zhang, N. Jiao and B. Han, Radical 1,4/5-Amino Shift Enables Access to Fluoroalkyl-Containing Primary  $\beta(\gamma)$ -Aminoketones under Metal-Free Conditions, *Angew. Chem., Int. Ed.*, 2021, **60**, 26308–26313.
- 13 A mixture of regiomer products *E/Z*-**2aq'** was obtained in 35% yield. See the ESI for details of the characterization data and NMR spectra.†
- 14 For the crystal data for **2e**, please see the ESI. Deposition number 2141492 (**2e**) contains the supplementary crystallographic data for this paper.†
- 15 (a) Y. Yasu, T. Koike and M. Akita, Intermolecular Aminotrifluoromethylation of Alkenes by Visible-Light-Driven Photoredox Catalysis, *Org. Lett.*, 2013, **15**, 2136–2139; (b) A. Carboni, G. Dagousset, E. Magnier and G. Masson, Photoredox-Induced Three-Component Oxy-, Amino-, and Carbotrifluoromethylation of Enecarbamates, *Org. Lett.*, 2014, **16**, 1240–1243; (c) J.-S. Lin, F.-L. Wang, X.-Y. Dong, W.-W. He, Y. Yuan, S. Chen and X.-Y. Liu, Catalytic Asymmetric Radical Aminoperfluoroalkylation and Aminodifluoromethylation of Alkenes to Versatile Enantioenriched-Fluoroalkyl Amines, *Nat. Commun.*, 2017, **8**, 14841–14851; (d) C.-L. Zhu, C. Wang, Q.-X. Qin, S. Yruegas, C. D. Martin and H. Xu, Iron(II)-Catalyzed Azidotrifluoromethylation of Olefins and *N*-Heterocycles for Expedient Vicinal Trifluoromethyl Amine Synthesis, *ACS Catal.*, 2018, **8**, 5032–5037; (e) H. Xiao, H. Shen, L. Zhu and C. Li, Copper-Catalyzed Radical Aminotrifluoromethylation of Alkenes, *J. Am. Chem. Soc.*, 2019, **141**, 11440–11445; (f) P. Wang, S. Zhu, D. Lu and Y. Gong, Intermolecular Trifluoromethyl-Hydrazination of Alkenes Enabled by Organic Photoredox Catalysis, *Org. Lett.*, 2020, **22**, 1924–1928.
- 16 J. Yao, C.-L. Li, X. Fan, Z. Wang, Z.-X. Yu and J. Zhao, Ynamide Protonation-Initiated *Cis*-Selective Polyene Cyclization and Reaction Mechanism, *CCS Chem.*, 2021, **3**, 3133–3143.
- 17 J.-J. Ma, W.-B. Yi, G.-P. Lu and C. Cai, Decarboxylative and Denitrative Trifluoromethylation for the Synthesis of  $\text{C}_{\text{vinyl}}^{\text{CF}_3}$  Compounds with Togni (II) Reagent, *Adv. Synth. Catal.*, 2015, **357**, 3447–3452.
- 18 (a) B. Zhang and A. Studer, 2-Trifluoromethylated Indoles via Radical Trifluoromethylation of Isonitriles, *Org. Lett.*,

- 2014, **16**, 1216–1219; (b) R. Beniazza, M. Douarre, D. Lastécouères and J.-M. Vincent, Metal-Free and Light-Promoted Radical Iodotrifluoromethylation of Alkenes with Togni Reagent as the Source of CF<sub>3</sub> and Iodine, *Chem. Commun.*, 2017, **53**, 3547–3550; (c) J. Huang, Y. Jia, X. Li, J. Duan, Z.-X. Jiang and Z. Yang, Halotrifluoromethylation of 1,3-Enynes: Access to Tetrasubstituted Allenes, *Org. Lett.*, 2021, **23**, 2314–2319.
- 19 Hydrogen generated during the model reaction was detected by gas chromatography. See the ESI for details.†
- 20 For selected works where DMF was used as an H-donor, see: (a) F. W. Wassmundt and W. F. Kiesman, Efficient Catalysis of Hydrodediazoniations in Dimethylformamide, *J. Org. Chem.*, 1995, **60**, 1713–1719; (b) C. M. Tam, C. T. To and K. S. Chan, Carbon-Carbon  $\sigma$ -Bond Transfer Hydrogenation with DMF Catalyzed by Cobalt Porphyrins, *Organometallics*, 2016, **35**, 2174–2177.
- 21 F. W. Wassmundt and W. F. Kiesman, Detection of Aryl Radicals in Hydrodediazoniations, *J. Org. Chem.*, 1997, **62**, 8304–8308.