RSC Advances

PAPER

View Article Online
View Journal | View Issue

Cite this: *RSC Adv.*, 2023, **13**, 6993

Copper-catalyzed selective C5-H bromination and difluoromethylation of 8-aminoquinoline amides using ethyl bromodifluoroacetate as the bifunctional reagent†

Changdong Shao,* Tianyi Xu, Chen Chen, Qionglin Yang, Chao Tang, Ping Chen, Mingzhu Lu, Zhengsong Hu, Huayou Hu and Tingting Zhang*

Received 5th January 2023
Accepted 13th February 2023

DOI: 10.1039/d3ra00088e

rsc.li/rsc-advances

A simple and effective method for the copper-catalyzed selective C5-H bromination and difluoromethylation of 8-aminoquinoline amides with ethyl bromodifluoroacetate as the bifunctional reagent was developed. The combination of cupric catalyst and alkaline additive results in a C5-bromination reaction, whereas cuprous catalyst combined with silver additive results in the C5-difluoromethylation reaction. This method has a broad substrate scope and allows for easy and convenient access to desired C5-functionalized quinolones with good to excellent yields.

Introduction

8-Aminoquinoline derivatives have attracted widespread interest over the past decades because the privileged scaffold can be found in a wide variety of important compounds, including natural products,[1] bioactive molecules,[2] pharmaceuticals,[3] agrochemicals,[4] pesticides,[5] optoelectronic materials, and fluorescence probe materials.[6] Moreover, the efficient and reversible coordination to transition metal catalysts, the low cost, and ease of attachment and detachment from most carboxylic acid substrates make the 8-aminoquinoline a widely applicable auxiliary group for proximal C–H functionalization (Fig. 1).[7–9] However, extensive research on the structural optimization of lead compounds suggests that the introduction of functional groups onto 8-aminoquinoline motifs could enhance their bioactivities, such as antimalarial and antitumor properties.[10] Therefore, the synthesis of substituted 8-aminoquinolines is crucial.

In recent years, direct C–H activation has emerged as an elegant method for the rapid generation of functionalized 8-aminoquinolines due to its mild conditions, atom economy, and high tolerance to various functional groups. Numerous studies have reviewed the regioselective functionalization of 8-aminoquinolines through C–H activation at the positions of C2–C7.[11] Since Stahl *et al.*[12] reported the first instance of cuprous-catalyzed chlorination using lithium chloride in an oxygen atmosphere, remote C5-functionalization has garnered particular interest.[13] Recent efforts have been focused on C–C,[14] C–N,[15] C–P,[16] C–O,[17] C–S[18] and C–X[19] bond construction through direct C5-H functionalization *via* transition-metal-catalyzed reactions as well as by employing metal-free conditions.

The difluoromethylene group, which can be proposed as the bioisostere of hydroxyl, carbonyl, amino, and sulfhydryl groups, has evolved as an important structural motif in drug research

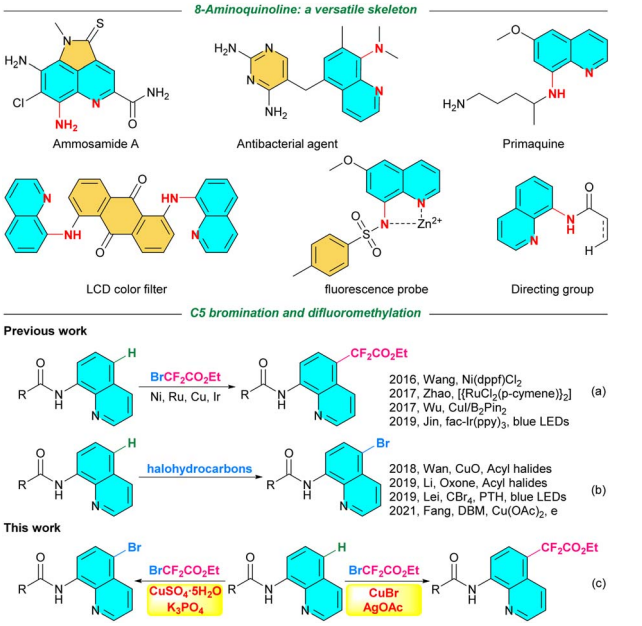


Fig. 1 Synthetic strategies toward C5-brominated and difluoromethylated 8-aminoquinolines and representative 8-aminoquinoline-containing molecules.

Jiangsu Provincial Key Laboratory for Chemistry of Low-Dimensional Materials, School of Chemistry and Chemical Engineering, Huaiyin Normal University, Huai'an, 223300, Jiangsu, China. E-mail: shaochangdong@hytc.edu.cn

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d3ra00088e

and development. Previous research revealed that bromodifluoroacetates are attractive reagents to incorporate difluoromethylene group due to their post functionalization potential. As illustrated in Fig. 1a, Wang, Zhao, Wu, and Jin, performed the ethoxycarbonyldifluoromethylation of 8-aminoquinolines with the aid of Ni, Ru, Cu, and Ir catalysts through direct C5-H functionalization employing ethyl bromodifluoroacetate as the difluoromethylation reagent.[20] These intelligent strategies demonstrated that ethyl difluorobromoacetate is an excellent reagent for introducing the CF_2CO_2Et group on the C5-position of 8-aminoquinolines.

On the other hand, brominated aromatics are important compounds in organic synthesis. To avoid the direct use of hazardous, toxic, and harmful molecular bromine, a large number of efficient brominating reagents and reaction systems for the bromination of arenes in a safe and environmentally friendly manner have been developed. Bromoamide derivatives and other Br-containing chemicals such as HBr, bromine salts, acyl bromides and bromoalkanes have been frequently employed as brominating reagents for the incorporation of the bromine atom into 8-aminoquinolines through direct C5-H functionalization pathway.[19] In addition, the use of halohydrocarbons as brominating reagents has gained traction due to their efficiency, safety, mild reaction conditions, and low pollution. Wan and Li independently reported two methods for the one-pot *N*-acylation and C5-H halogenation of 8-aminoquinolines using acyl halides as the donors of both the acyl and halide atoms. Lei and Fang developed the C5-bromination of 8-aminoquinoline amides using inert halomethanes as the halogen source, utilizing photocatalytic and electrocatalytic technologies (Fig. 1b).[21] However, to the best of our knowledge, the direct C5-H bromination of 8-aminoquinolines using ethyl difluorobromoacetate as the organic halogen source has not been previously reported. Hence, to address the gap in knowledge, this study presents a simple and efficient method for copper-catalyzed selective C5-H bromination and difluoromethylation of 8-aminoquinoline amides with ethyl bromodifluoroacetate as the bifunctional reagent (Fig. 1c).

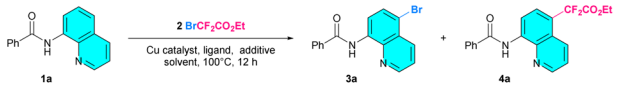
Results and discussion

N-(Quinolin-8-yl)benzamide (**1a**, 0.2 mmol) and ethyl bromodifluoroacetate (**2**, 0.8 mmol) were selected as the model substrates for the optimization of reaction conditions, and the results are shown in Table 1. Initially, the reaction was carried out in DMSO (1.0 mL) at 100 °C for 12 h under air in the presence of a catalytic amount of $CuCl_2$ (20 mol%) using K_2CO_3 as the additive. The result gave *N*-(5-bromoquinolin-8-yl) benzamide (**3a**) rather than ethyl 2-(8-benzamidoquinolin-5-yl)-2,2-difluoroacetate (**4a**) as the only product obtained with a 32% yield (Table 1, entry 1). The catalysts were then extensively screened, resulting in a significant improvement of the yield of the brominated product **3a** to 75% when $CuSO_4$ was employed, and the reaction yields improved further to 84% when $CuSO_4 \cdot 5H_2O$ was employed as the catalyst (Table 1, entries 2 and 3). Interestingly, cuprous salts were also capable of promoting the transformation with a significant yield (Table 1, entry 4). Numerous additives, including Li_2CO_3, Cs_2CO_3, $KHCO_3$, and K_3PO_4, were investigated, and the experimental results revealed that K_3PO_4 was the most efficient alkaline additive (96%) of the group (Table 1, entries 5–8). In addition, DMF, MeCN, and DCE solvents were also examined; the results were insignificant for the bromination reaction (Table 1, entries 9–11). The effects of some crucial factors, such as the loading of copper catalyst, the dosage of the additive, the amount of ethyl bromodifluoroacetate (**2**), as well as the reaction temperature, were also investigated (Table 1, entries 12–15).

Previous literature suggested that silver salts could be used as single electron oxidants to initiate radical transformations in α-carbonyl alkyl bromide reactions.[22] Further investigation of the copper catalyzed C5-difluoromethylation reaction of 8-aminoquinoline amides was carried out employingAgOAc as the additive. Based on the optimal conditions that were established for the C5-bromination, the reaction was carried out in the presence of $CuSO_4 \cdot 5H_2O$ (50 mol%) in DMSO (1.0 mL) with AgOAc (0.4 mmol) at 100 °C under an N_2 atmosphere for 12 h. This yielded no desired product (**4a**) (Table 1, entry 16). Subsequent screening revealed that CuBr outperformed $Cu(OAc)_2$ and CuI in terms of activity, and the desired product **4a** was obtained at a 62% yield (Table 1, entries 17–19). Other silver additives like Ag_2O and Ag_2CO_3 could not promote the difluoromethylation reaction (Table 1, entries 20 and 21). Several other solvents, such as DMF, MeCN, THF, and toluene, were examined, but none of them was as effective as DMSO (Table 1, entries 22–25). Then, a series of ligands were also screened; the addition of ligands did not significantly increase the yield of the desired product; however, the loading of the copper catalyst could be decreased to 20 mol% (Table 1, entries 26–30). Contradictory experiments revealed that the yield decreased with decreased amounts of AgOAc, ethyl bromodifluoroacetate (**2**) and the reaction temperature (Table 1, entries 31–33).

With the optimized reaction conditions in hand, these protocols were then applied to a series of 8-aminoquinoline amides, and the results are shown in Fig. 2 and 3. Based on these results, it can be concluded that the present reactions possessed the advantages of broad substrate scopes, mild reaction conditions, moderate to excellent product yields, and remarkable functional group tolerance. Initially, the substrate scope for the C5-bromination reaction was explored (Fig. 2). 8-Aminoquinoline amides with a variety of substituted groups on different positions of benzene rings in the benzoic acid section exhibited high reactivity (**3b–3k**). Aromatic amides with electron-donating substituted groups (Me, OMe, OAc) and electron-withdrawing substituted groups (CF_3, F, Cl, Br, I, CO_2Me, CN) were well tolerated in this reaction, resulting in an 84% to almost quantitative yield. Furthermore, 8-aminoquinoline amide containing multiple methoxyl groups behaved well in the reaction and gave the product **3l** in a 96% yield. Notably, the compatibility with halogen atoms, particularly I, Br, and Cl, enables the brominated products to undergo downstream transformations (**3f–3h**). Moreover, to extend the substrate scope, various aliphatic amides, including phenylacetamide, isopropylamide, and pivalamide, were evaluated and provided

Table 1 Optimization of the copper-catalyzed C5-selective functionalization reaction[a]



Entry	Cu catalyst (mol%)	Ligand (mol%)	Additive (mmol)	Solvent	**3a** yield[b] (%)	**4a** yield[b] (%)
1	$CuCl_2$ (20)	—	K_2CO_3 (0.2)	DMSO	32	—
2	$CuSO_4$ (20)	—	K_2CO_3 (0.2)	DMSO	75	—
3	$CuSO_4 \cdot 5H_2O$ (20)	—	K_2CO_3 (0.2)	DMSO	84	—
4	CuCl (20)	—	K_2CO_3 (0.2)	DMSO	78	—
5	$CuSO_4 \cdot 5H_2O$ (20)	—	Li_2CO_3 (0.2)	DMSO	82	—
6	$CuSO_4 \cdot 5H_2O$ (20)	—	Cs_2CO_3 (0.2)	DMSO	88	—
7	$CuSO_4 \cdot 5H_2O$ (20)	—	$KHCO_3$ (0.2)	DMSO	92	—
8	**$CuSO_4 \cdot 5H_2O$ (20)**	**—**	**K_3PO_4 (0.2)**	**DMSO**	**96 (93)**	**—**
9	$CuSO_4 \cdot 5H_2O$ (20)	—	K_3PO_4 (0.2)	DMF	5	—
10	$CuSO_4 \cdot 5H_2O$ (20)	—	K_3PO_4 (0.2)	MeCN	—	—
11	$CuSO_4 \cdot 5H_2O$ (20)	—	K_3PO_4 (0.2)	DCE	—	—
12	$CuSO_4 \cdot 5H_2O$ (10)	—	K_3PO_4 (0.2)	DMSO	68	—
13	$CuSO_4 \cdot 5H_2O$ (20)	—	K_3PO_4 (0.1)	DMSO	—	—
14[c]	$CuSO_4 \cdot 5H_2O$ (20)	—	K_3PO_4 (0.2)	DMSO	81	—
15[d]	$CuSO_4 \cdot 5H_2O$ (20)	—	K_3PO_4 (0.2)	DMSO	—	—
16	$CuSO_4 \cdot 5H_2O$ (50)	—	AgOAc (0.4)	DMSO	—	—
17	$Cu(OAc)_2$ (50)	—	AgOAc (0.4)	DMSO	—	37
18	CuBr (50)	—	AgOAc (0.4)	DMSO	—	62
19	CuI (50)	—	AgOAc (0.4)	DMSO	—	49
20	CuBr (50)	—	Ag_2O (0.4)	DMSO	—	—
21	CuBr (50)	—	Ag_2CO_3 (0.4)	DMSO	—	—
22	CuBr (50)	—	AgOAc (0.4)	DMF	—	38
23	CuBr (50)	—	AgOAc (0.4)	MeCN	—	28
24	CuBr (50)	—	AgOAc (0.4)	THF	—	—
25	CuBr (50)	—	AgOAc (0.4)	Toluene	—	—
26	CuBr (50)	TMEDA (100)	AgOAc (0.4)	DMSO	—	43
27	CuBr (50)	$AdCO_2H$ (100)	AgOAc (0.4)	DMSO	—	50
28	CuBr (50)	Ac-Gly-OH (100)	AgOAc (0.4)	DMSO	—	66
29	**CuBr (20)**	**Ac-Gly-OH (40)**	**AgOAc (0.4)**	**DMSO**	**—**	**67 (62)**
30	CuBr (10)	Ac-Gly-OH (20)	AgOAc (0.4)	DMSO	—	40
31	CuBr (20)	Ac-Gly-OH (40)	AgOAc (0.2)	DMSO	—	35
32[c]	CuBr (20)	Ac-Gly-OH (40)	AgOAc (0.4)	DMSO	—	52
33[d]	CuBr (20)	Ac-Gly-OH (40)	AgOAc (0.4)	DMSO	—	63

[a] Reaction conditions: **1a** (0.2 mmol), **2** (0.8 mmol), Cu catalyst, ligand, additive, solvent (1.0 mL). [b] ^{1}H NMR yield with dibromomethane as the internal standard, isolated yield in parentheses. [c] 0.6 mmol **2** was used. [d] Stirred at 80 °C. TMEDA = *N*,*N*,*N*′,*N*′-tetramethylethylenediamine; $AdCO_2H$ = 1-adamantanecarboxylic acid; Ac-Gly-OH = *N*-acetylglycine.

the desired products in good yields (**3m–3o**). In addition, amides with tension rings and polycyclic structures also survived in this reaction, affording the target molecules good to excellent yields (**3p**,**3q**). Satisfactorily, the methoxy-substituted quinoline at the C6 position was compatible and provided the desired product **3r** in a 92% yield.

Next, the applicability of the C5-difluoromethylation reaction for different 8-aminoquinoline amides was extensively investigated. As listed in Fig. 3, the results clearly show that aromatic amides with a variety of functional groups on the benzene ring as well as different kinds of aliphatic amides were able to accomplish the difluoromethylation reaction with ethyl bromodifluoroacetate (**2**) smoothly, affording the desired coupling products **4a–4ai** in moderate to good yields. The ethoxycarbonyldifluoromethyl group could be introduced onto α,α-difluorophenylacetamide through this reaction to afford the bis-difluoromethylated product **4y** in 60% yield. In addition, halogen atoms could be preserved integrally in this transformation, although a silver acetate additive was involved (**4k–4p**). Moreover, the substrate with a methoxyl group on the quinoline scaffold proceeded well to afford the difluoromethylated product in a 71% yield (**4aj**).

Finally, to gain a preliminary understanding of these reactions, some extended investigations were performed (Scheme 1). Firstly, we failed to apply this method to *N*-methyl-*N*-(quinolin-8-yl)benzamide (**5**), quinolin-8-yl benzoate (**6**), *N*-(naphthalen-1-yl)benzamide (**7**), 8-aminoquinoline (**8**), and its alkylated derivatives (**9**, **10**). These revealed that the *N*,*N*-bidentate chelating coordination of the 8-aminoquinoline amide skeleton is necessary. Subsequently, several control experiments were carried out to investigate the mechanisms. It was observed that the bromination reaction continued in the

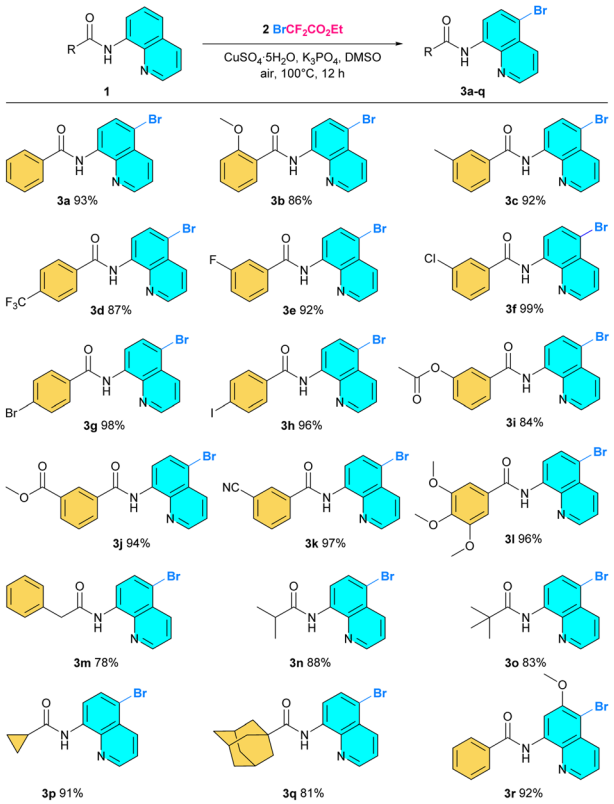


Fig. 2 Substrate scope for the C5-bromination of 8-aminoquinoline amides.

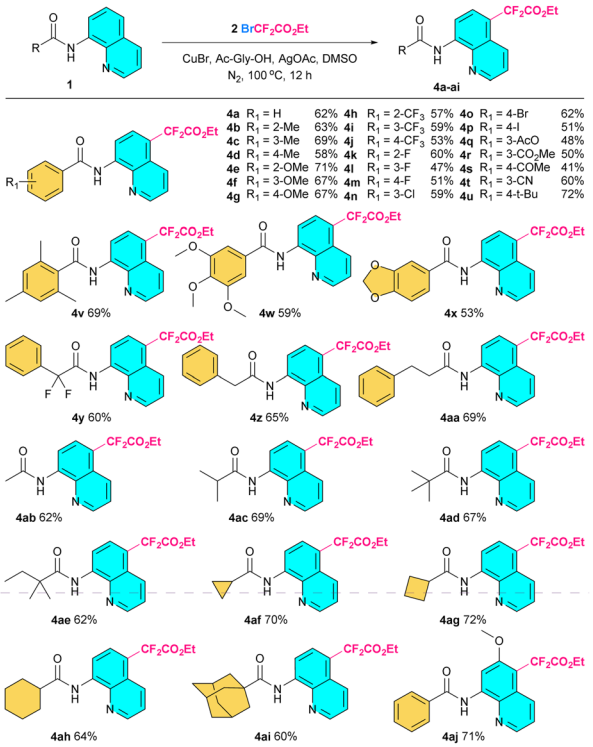
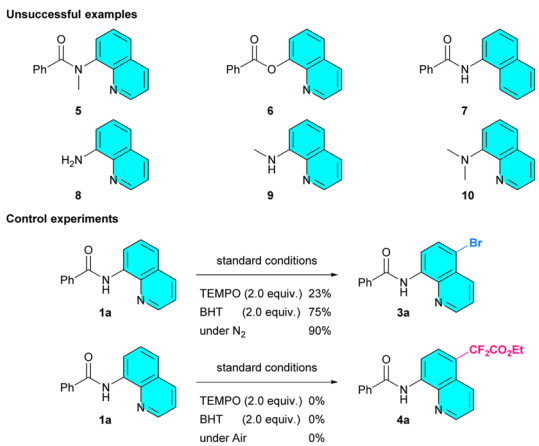


Fig. 3 Substrate scope for the C5-difluoromethylation of 8-aminoquinoline amides.

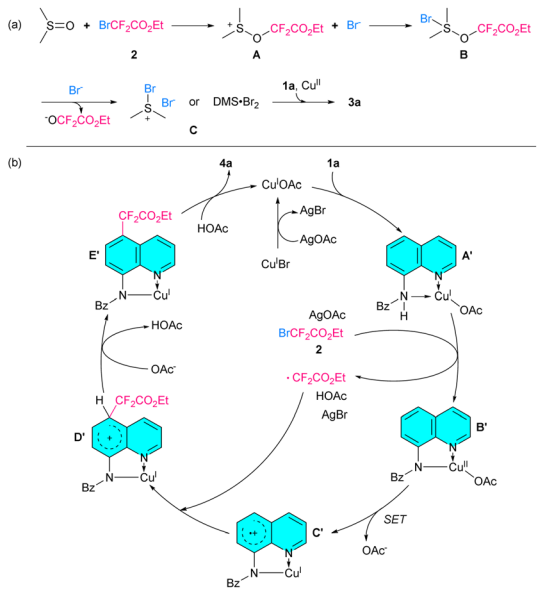
presence of free radical scavengers such as 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) and 2,6-di-tertbutyl-4-methyphenol (BHT), while the difluoromethylation reaction was completely inhibited. In addition, the corresponding product **3a** was obtained in 90% yield when the bromination reaction was conducted under nitrogen atmosphere. However, when the difluoromethylation reaction was carried out in an air atmosphere, no product was obtained, and the initial material was recovered. Meanwhile, the TEMPO-CF_2CO_2Et adduct was detected by GC-MS (see ESI†). These results indicated that the difluoromethylation might proceed *via* a free radical process and the bromination might be accomplished through an ionic pathway.

Although the precise mechanisms remain unclear to date, on the basis of our experimental results and literature,[23] plausible mechanisms are proposed. As shown in Scheme 2(a), the nucleophilic attack of DMSO on ethyl bromodifluoroacetate (**2**) to give intermediate **A**, which then reacts with the bromine anion to produce intermediate **B**. Subsequently, dimethylsulfonium bromide or dimethyl thioether/molecular bromine complex **C** is generated by the attack of the bromine anion on intermediate **B**.[23a,b] Finally, bromination is accomplished through the aromatic electrophilic substitution of intermediate **C** with **1a** with the help of copper salt. In Scheme 2(b), a mechanistic hypothesis for the difluoromethylation of 8-



Scheme 1 Extended investigations.

aminoquinoline amide is also proposed. Firstly, CuOAc is provided by the anion exchange of CuBr with AgOAc. The Cu(I)-quinoline complex **A′** is then formed *via* bidentate nitrogen atom chelation. The intermolecular SET from **A′** to ethyl bromodifluoroacetate (**2**) followed by the deprotonation in the presence of AgOAc produces $\cdot CF_2CO_2Et$ radical and the Cu(II) complex **B′**.[23c,d] Subsequently, the intramolecular SET process within **B′** produces a cationic radical **C′**.[18g] The radical coupling reaction of **C′** with CF_2CO_2Et affords the cationic intermediate



Scheme 2 Proposed mechanisms.

D′. The obtained **D′** undergoes deprotonation and demetallation to yield the desired product **4a** as well as the regenerated Cu(I) catalyst for the next catalytic cycle. Further investigation is being conducted to provide evidence for the proposed mechanism.

Conclusions

In summary, we have established a simple and efficient method for copper-catalyzed selective C5-H bromination and difluoromethylation of 8-aminoquinoline amides with ethyl bromodifluoroacetate. The results showed that when cupric catalyst is combined with an alkaline additive, it leads to the C5-bromination reaction while the C5-difluoromethylation reaction is dominant for cuprous catalyst combined with a silver additive. This method has mild reaction conditions, moderate to excellent product yields, and a wide range of substrates. Future investigations will focus on mechanism details and other selective functionalization reactions employing halogenated hydrocarbons as bifunctional reagents.

Experimental

General procedure for the C5-bromination

A 35 mL sealed tube equipped with a stir bar was charged with *N*-(quinolin-8-yl)benzamide (49.6 mg, 0.2 mmol, 1.0 equiv.), $BrCF_2CO_2Et$ (104 μL, 0.8 mmol, 4.0 equiv.), $CuSO_4 \cdot 5H_2O$ (10.0 mg, 0.04 mmol, 20 mol%), K_3PO_4 (42.5 mg, 0.2 mmol, 1.0 equiv.) and DMSO (1.0 mL). The tube was sealed with a Teflon cap under air, then the mixture was stirred at 100 °C for 12 h. After completion, the reaction mixture was diluted with ethyl acetate (20 mL) and washed successively with saturated sodium bicarbonate, saturated sodium sulfide, and brine. The organic layer was dried over anhydrous sodium sulfate and concentrated *in vacuo*. The residue was purified on preparative thin layer chromatography (PTLC) to afford the desired product **3a**.

General procedure for the C5-difluoromethylation

A 35 mL Schlenk tube equipped with a stir bar was charged with *N*-(quinolin-8-yl)benzamide (49.6 mg, 0.2 mmol, 1.0 equiv.), CuBr (5.8 mg, 0.04 mmol, 20 mol%), Ac-Gly-OH (9.4 mg, 0.08 mmol, 40 mol%), and AgOAc (67 mg, 0.4 mmol, 2.0 equiv.) under air. The tube was sealed with a rubber stopper and then evacuated and backfilled with N_2 five times. $BrCF_2CO_2Et$ (104 μL, 0.8 mmol, 4.0 equiv.) and DMSO (1.0 mL) were injected *via* syringe. After the reaction was stirred at 100 °C for 12 h, it was allowed to cool to room temperature. The reaction mixture was diluted with ethyl acetate (20 mL) and then washed successively with saturated sodium bicarbonate, saturated sodium sulfide, and brine. The organic layer was dried over anhydrous sodium sulfate and concentrated *in vacuo*. The residue was purified on PTLC to afford the desired product **4a**.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (21801088), the Natural Science Foundation of Jiangsu Province (BK20181065), and the Natural Science Foundation of the Higher Education Institutions of Jiangsu Province (18KJB150006).

Notes and references

1 (*a*) H. Nagata, K. Ochiai, Y. Aotani, K. Ando, M. Yoshida, I. Takahashi and T. Tamaoki, *J. Antibiot.*, 1997, **50**, 537; (*b*) C. C. Hughes, J. B. MacMillan, S. P. Gaudêncio, P. R. Jensen and W. Fenical, *Angew. Chem., Int. Ed.*, 2009, **48**, 725.

2 (*a*) G. White, S. M. Daluge, C. W. Sigel, R. Ferone and H. R. Wilson, *Res. Vet. Sci.*, 1993, **54**, 372; (*b*) R. Singh, A. Sran, D. C. Carroll, J. Huang, L. Tsvetkov, X. Zhou, J. Sheung, J. McLaughlin, S. D. Issakani, D. G. Payan and S. J. Shaw, *Bioorg. Med. Chem. Lett.*, 2015, **25**, 5199.

3 (*a*) J. K. Baird, *Clin. Microbiol. Rev.*, 2019, **32**, e00011; (*b*) J. E. Frampton, *Drugs*, 2018, **78**, 1517; (*c*) N. Vale, R. Moreira and P. Gomes, *Eur. J. Med. Chem.*, 2009, **44**, 937.

4 J. A. Bond and T. W. Walker, *Weed Technol.*, 2012, **26**, 183.

5 R. Yang, W. Du, H. Yuan, T. Qin, R. He, Y. Ma and H. Du, *Mol. Diversity*, 2020, **24**, 1065.

6 (*a*) N. S. Mohamad, N. H. Zakaria, N. Daud, L. L. Tan, G. C. Ta, L. Y. Heng and N. I. Hassan, *Sensors*, 2021, **21**, 311; (*b*) S. Lee, S. Park and J. Park, *Mol. Cryst. Liq. Cryst.*, 2013, **583**, 29.

7 (*a*) Y.-H. Zhang, G.-F. Shi and J.-Q. Yu, in *Comprehensive Organic Synthesis II*, Elsevier, 2014, p. 1101; (*b*) *C-H*

Activation, ed. J.-Q. Yu and Z. Shi, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010, vol. 292; (*c*) R. G. Bergman, *Nature*, 2007, **446**, 391; (*d*) V. G. Zaitsev, D. Shabashov and O. Daugulis, *J. Am. Chem. Soc.*, 2005, **127**, 13154; (*e*) J. A. Labinger and J. E. Bercaw, *Nature*, 2002, **417**, 507.

8 (*a*) S. St John-Campbell and J. A. Bull, *Adv. Synth. Catal.*, 2019, **361**, 3662; (*b*) B. Zhang, H. Guan, B. Liu and B. Shi, *Chin. J. Org. Chem.*, 2014, **34**, 1487; (*c*) G. Rouquet and N. Chatani, *Angew. Chem., Int. Ed.*, 2013, **52**, 11726.

9 (*a*) L. S. Fitzgerald and M. L. O'Duill, *Chem.–Eur. J.*, 2021, **27**, 8411; (*b*) M. R. Yadav, R. K. Rit, M. Shankar and A. K. Sahoo, *Asian J. Org. Chem.*, 2015, **4**, 846.

10 W.-B. Kuang, R.-Z. Huang, Y.-L. Fang, G.-B. Liang, C.-H. Yang, X.-L. Ma and Y. Zhang, *RSC Adv.*, 2018, **8**, 24376.

11 (*a*) A. Corio, C. Gravier-Pelletier and P. Busca, *Molecules*, 2021, **26**, 5467; (*b*) Z. Xu, X. Yang, S.-F. Yin and R. Qiu, *Top. Curr. Chem.*, 2020, **378**, 42; (*c*) T. Iwai and M. Sawamura, *ACS Catal.*, 2015, **5**, 5031.

12 A. M. Suess, M. Z. Ertem, C. J. Cramer and S. S. Stahl, *J. Am. Chem. Soc.*, 2013, **135**, 9797.

13 (*a*) B. Khan, H. S. Dutta and D. Koley, *Asian J. Org. Chem.*, 2018, **7**, 1270; (*b*) L. Zhu, X. Cao, Y. Li, T. Liu, X. Wang, R. Qiu and S. Yin, *Chin. J. Org. Chem.*, 2017, **37**, 1613.

14 (*a*) D. Liu, Z. Xia, Y. Xiao, Y. Yu, L. Yu, Z. Song, Q. Wu, J. Zhang and Z. Tan, *Eur. J. Org. Chem.*, 2021, **2021**, 5012; (*b*) W. Xu, M. Wu and N. Yoshikai, *Synthesis*, 2021, **53**, 3144; (*c*) W.-Y. Shi, Y.-N. Ding, C. Liu, N. Zheng, X.-Y. Gou, M. Li, Z. Zhang, H.-C. Liu, Z.-J. Niu and Y.-M. Liang, *Chem. Commun.*, 2020, **56**, 12729; (*d*) F. Zhan, W. Zhang and H. Zhao, *Synthesis*, 2020, **52**, 1007; (*e*) C. Wen, R. Zhong, Z. Qin, M. Zhao and J. Li, *Chem. Commun.*, 2020, **56**, 9529; (*f*) A. Mariappan, K. M. Das and M. Jeganmohan, *Org. Biomol. Chem.*, 2018, **16**, 3419; (*g*) M. Cui, J.-H. Liu, X.-Y. Lu, X. Lu, Z.-Q. Zhang, B. Xiao and Y. Fu, *Tetrahedron Lett.*, 2017, **58**, 1912; (*h*) M. D. Reddy, F. R. Fronczek and E. B. Watkins, *Org. Lett.*, 2016, **18**, 5620; (*i*) X. Cong and X. Zeng, *Org. Lett.*, 2014, **16**, 3716; (*j*) K. Wang, J. Hou, Y. Lv, T. Wei, R. Bai and Y. Xie, *Asian J. Org. Chem.*, 2021, **10**, 559; (*k*) S. Han, Q. Wu, L. Mele, L. Ding, J. Li, D. Zou, Y. Wu and Y. Wu, *Tetrahedron Lett.*, 2019, **60**, 151077; (*l*) T. Sahoo, C. Sen, H. Singh, E. Suresh and S. C. Ghosh, *Adv. Synth. Catal.*, 2019, **361**, 3950; (*m*) P. B. Arockiam, L. Guillemard and J. Wencel-Delord, *Adv. Synth. Catal.*, 2017, **359**, 2571.

15 (*a*) M. Pei, C. Zu, Z. Liu, F. Yang and Y. Wu, *J. Org. Chem.*, 2021, **86**, 11324; (*b*) R. Zhao, Y. Yang, X. Wang, P. Ren, Q. Zhang and D. Li, *RSC Adv.*, 2018, **8**, 37064; (*c*) Y. Yin, J. Xie, F.-Q. Huang, L.-W. Qi and B. Zhang, *Adv. Synth. Catal.*, 2017, **359**, 1037; (*d*) H. Yi, H. Chen, C. Bian, Z. Tang, A. K. Singh, X. Qi, X. Yue, Y. Lan, J.-F. Lee and A. Lei, *Chem. Commun.*, 2017, **53**, 6736; (*e*) Y. Dou, Z. Xie, Z. Sun, H. Fang, C. Shen, P. Zhang and Q. Zhu, *ChemCatChem*, 2016, **8**, 3570; (*f*) C. J. Whiteoak, O. Planas, A. Company and X. Ribas, *Adv. Synth. Catal.*, 2016, **358**, 1679; (*g*) Y. He, N. Zhao, L. Qiu, X. Zhang and X. Fan, *Org. Lett.*, 2016, **18**, 6054.

16 H. Qiao, S. Sun, Y. Zhang, H. Zhu, X. Yu, F. Yang, Y. Wu, Z. Li and Y. Wu, *Org. Chem. Front.*, 2017, **4**, 1981.

17 (*a*) C.-K. Liu, M.-Y. Chen, X.-X. Lin, Z. Fang and K. Guo, *Green Chem.*, 2020, **22**, 6437; (*b*) T. Liang, X. He, D. Ji, H. Wu, Y. Xu, Y. Li, Z. Wang, Y. Xu and Q. Zhu, *Eur. J. Org. Chem.*, 2019, **2019**, 2513; (*c*) G. Wang, J. Han, K. Wang, H. Li, G. Duan, C. Xia and F. Li, *Catal. Commun.*, 2018, **114**, 37; (*d*) X. Yao, X. Weng, K. Wang, H. Xiang and X. Zhou, *Green Chem.*, 2018, **20**, 2472; (*e*) Z. Begum, G. Bhavani, B. Sridhar and B. Reddy, *Synthesis*, 2018, **50**, 4089.

18 (*a*) X. Liu, H. Zhang, F. Yang and B. Wang, *Org. Biomol. Chem.*, 2019, **17**, 7564; (*b*) K. Wang, G. Wang, G. Duan and C. Xia, *RSC Adv.*, 2017, **7**, 51313; (*c*) G. Chen, X. Zhang, Z. Zeng, W. Peng, Q. Liang and J. Liu, *ChemistrySelect*, 2017, **2**, 1979; (*d*) S. Liang and G. Manolikakes, *Adv. Synth. Catal.*, 2016, **358**, 2371; (*e*) C. Xia, K. Wang, J. Xu, Z. Wei, C. Shen, G. Duan, Q. Zhu and P. Zhang, *RSC Adv.*, 2016, **6**, 37173; (*f*) Q. Yu, Y. Yang, J.-P. Wan and Y. Liu, *J. Org. Chem.*, 2018, **83**, 11385; (*g*) J. Chen, T. Wang, T. Wang, A. Lin, H. Yao and J. Xu, *Org. Chem. Front.*, 2017, **4**, 130; (*h*) L. Zhu, R. Qiu, X. Cao, S. Xiao, X. Xu, C.-T. Au and S.-F. Yin, *Org. Lett.*, 2015, **17**, 5528.

19 (*a*) X. He, Y. Jiang, H. Zhou and Q. Zhu, *ChemistrySelect*, 2021, **6**, 5191; (*b*) X. Yang, Q.-L. Yang, X.-Y. Wang, H.-H. Xu, T.-S. Mei, Y. Huang and P. Fang, *J. Org. Chem.*, 2020, **85**, 3497; (*c*) J. Hou, K. Wang, C. Zhang, T. Wei, R. Bai and Y. Xie, *Eur. J. Org. Chem.*, 2020, **2020**, 6382; (*d*) D. R. Motati, D. Uredi and E. B. Watkins, *Chem. Sci.*, 2018, **9**, 1782; (*e*) L. Qiao, X. Cao, K. Chai, J. Shen, J. Xu and P. Zhang, *Tetrahedron Lett.*, 2018, **59**, 2243; (*f*) H. Chen, P. Li, M. Wang and L. Wang, *Eur. J. Org. Chem.*, 2018, **2018**, 2091; (*g*) J.-Y. Jiao, Y.-J. Mao, A.-W. Feng, X.-F. Li, M.-T. Li and X.-H. Zhang, *Tetrahedron*, 2017, **73**, 1482; (*h*) J. Ding, Y. Zhang and J. Li, *Org. Chem. Front.*, 2017, **4**, 1528; (*i*) H. S. Dutta, B. Khan, A. A. Khan, Raziullah, A. Ahmad, R. Kant and D. Koley, *ChemistrySelect*, 2017, **2**, 6488; (*j*) H. Guo, M. Chen, P. Jiang, J. Chen, L. Pan, M. Wang, C. Xie and Y. Zhang, *Tetrahedron*, 2015, **71**, 70.

20 (*a*) H. Chen, P. Li, M. Wang and L. Wang, *Org. Lett.*, 2016, **18**, 4794; (*b*) C. Chen, R. Zeng, J. Zhang and Y. Zhao, *Eur. J. Org. Chem.*, 2017, **2017**, 6947; (*c*) S. Han, A. Liang, X. Ren, X. Gao, J. Li, D. Zou, Y. Wu and Y. Wu, *Tetrahedron Lett.*, 2017, **58**, 4859; (*d*) C. Jin, R. Zhu, B. Sun, L. Zhang, X. Zhuang and C. Yu, *Asian J. Org. Chem.*, 2019, **8**, 2213; (*e*) P. B. Arockiam, L. Guillemard and J. Wencel-Delord, *Adv. Synth. Catal.*, 2017, **359**, 2571; (*f*) X. Jiang, Y. Jiang, Q. Liu, B. Li, D.-Q. Shi and Y. Zhao, *J. Org. Chem.*, 2022, **87**, 3546.

21 (*a*) Y. Du, Y. Liu and J.-P. Wan, *J. Org. Chem.*, 2018, **83**, 3403; (*b*) D. Li, Z. Jia, Y. Jiang, J. Jia, X. Zhao, Z. Li and Z. Xu, *ChemistrySelect*, 2019, **4**, 13964; (*c*) B. Ma, F. Lu, H. Yang, X. Gu, Z. Li, R. Li, H. Pei, D. Luo, H. Zhang and A. Lei, *Asian J. Org. Chem.*, 2019, **8**, 1136; (*d*) X. Lin, C. Zeng, C. Liu, Z. Fang and K. Guo, *Org. Biomol. Chem.*, 2021, **19**, 1352; (*e*) B. Huang, Y. Zhao, C. Yang, Y. Gao and W. Xia, *Org. Lett.*, 2017, **19**, 3799; (*f*) V. Botla, A. Akudari and C. Malapaka, *Tetrahedron Lett.*, 2019, **60**, 115; (*g*) Y. Liang, F. Lin, Y. Adeli, R. Jin and N. Jiao, *Angew. Chem., Int. Ed.*,

2019, **58**, 4566; (*h*) F. Liu, N. Wu and X. Cheng, *Org. Lett.*, 2021, **23**, 3015.

22 (*a*) S. Luo, M. Min, Y. Wu, S. Jiang, Y. Xiao, R. Song and J. Li, *Adv. Synth. Catal.*, 2020, **362**, 2921; (*b*) R. Ding, Z.-D. Huang, Z.-L. Liu, T.-X. Wang, Y.-H. Xu and T.-P. Loh, *Chem. Commun.*, 2016, **52**, 5617; (*c*) X.-H. Ouyang, R.-J. Song, M. Hu, Y. Yang and J.-H. Li, *Angew. Chem., Int. Ed.*, 2016, **55**, 3187; (*d*) Y. Yu and U. K. Tambar, *Chem. Sci.*, 2015, **6**, 2777.

23 (*a*) X. Chen, W. Li, W. Zhang, Z. Wang and H. Cui, *Asian J. Org. Chem.*, 2022, **11**, e202200342; (*b*) J.-Q. Li, X.-H. Chen, X.-X. Wang and H.-L. Cui, *Tetrahedron Lett.*, 2021, **82**, 153375; (*c*) G.-H. Pan, R.-J. Song and J.-H. Li, *Org. Chem. Front.*, 2018, **5**, 179; (*d*) J. Wei, J. Jiang, X. Xiao, D. Lin, Y. Deng, Z. Ke, H. Jiang and W. Zeng, *J. Org. Chem.*, 2016, **81**, 946.