


 Cite this: *RSC Adv.*, 2025, 15, 11582

 Received 4th March 2025
 Accepted 25th March 2025

DOI: 10.1039/d5ra01542a

rsc.li/rsc-advances

Modular reductive radical-polar crossover-based acyl migration reactions of *N*-vinylimides with alkyl, silyl, and acyl radicals†

 Yutao Jing,^a Li Zhang,^{*d} Li Qiu^{*a} and Yewen Fang^{id} ^{*bc}

Herein, novel SET reduction-based N → C acyl migration protocols for the preparation of functionalized α-amino ketones were successfully developed. In addition to alkyl and silyl radicals, acyl radicals derived from dihydroquinazolinones or acyl oxime acetates could react with enamides to give various 1,4-diketones. These photocatalytic radical addition/acyl migration cascade reactions feature broad substrate scope, good functional group compatibility, and mild reaction conditions.

Due to the remarkable progress of photoredox catalysis, the generation of radicals under mild and environmentally benign reaction conditions has become especially facile. In addition to the facile formation of radicals, their reduction or oxidation could proceed efficiently *via* the single-electron-transfer (SET) pathway. Consequently, a range of radical-polar crossover (RPC) process-based transformations enabled by photoredox catalysis has been designed and realized.¹ Recently, we employed a SET reduction-based formation of carbanion as a key strategy (Scheme 1), and a number of interesting and useful reactions were developed.² Impressively, the SET reduction-based generation of carbanions could proceed efficiently under base-free conditions. Owing to the facile generation of radicals from various radical precursors, the SET reduction of radicals is a complementary and reliable approach to the well-documented formation of carbanions or their analogues *via* a two-electron pathway. Moreover, with the proper combination of photocatalyst and radical precursors, many reductive RPC processes do not require exogenous reductants because the photoexcited photocatalyst and the reduced photocatalyst could serve as the oxidant and reductant, respectively, in the same catalytic cycle.

Realizing this interesting and useful characteristic of photocatalysis, many efficient and robust transformations bearing a reductive RPC process have been developed and employed.³

Due to its good sustainability and efficiency, synthetic chemists will undoubtedly be interested to uncover more novel methods using redox-neutral photocatalyzed reductive RPC process as the key strategy.

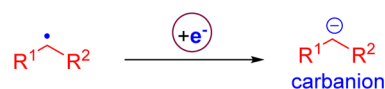
More than 20 years ago, Hamada and co-workers demonstrated a base-mediated N → C acyl migration reaction producing α-amino ketones.⁴ According to their proposed mechanism, a base-generated carbanion neighboring the imide nitrogen was the key intermediate for this migration reaction. Recently, we realized the cyclopropanation of enamides with a halomethyl radical *via* an RPC process.^{2c} Inspired by the formation of α-nitrogen carbanions from the corresponding radicals *via* SET reduction,^{2c,d} redox-neutral photocatalyzed N → C acyl migration reactions were successfully developed *via* the reactions of *N*-vinylimides with alkylsilicates.⁵ Owing to the low, relatively uniform redox potentials, the bis-catecholatosilicates were attractive radical precursors for the formation of nonstabilized primary alkyl radicals, which could be involved in the expected migration reactions. However, because of the limited availability of organofunctional tri-alkoxysilanes, silicates are not a suitable choice for secondary and tertiary C-centered radicals as well as acyl radicals. In light of the importance of α-amino ketones serving as expedient precursors for β-aminoalcohols, which are useful for the preparation of pharmaceuticals and chiral auxiliaries, a modular approach to α-amino ketones *via* the N → C acyl migration

^aCollege of Chemistry and Chemical Engineering, Taiyuan University of Technology, No. 79 West Street Yingze, Taiyuan 030024, China. E-mail: qiuli@tyut.edu.cn

^bSchool of Materials and Chemical Engineering, Ningbo University of Technology, No. 201 Fenghua Road, Ningbo 315211, China. E-mail: fang@nbut.edu.cn

^cZhejiang Institute of Tianjin University, No. 201 Fenghua Road, Ningbo 315211, China

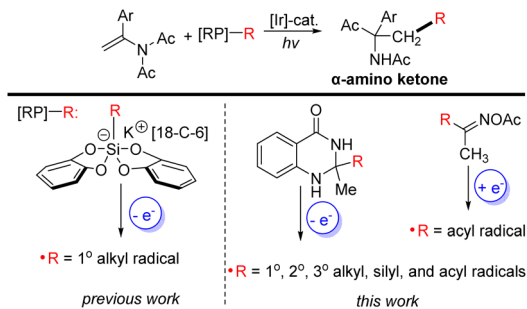
^dCollege of Basic Science, Zhejiang Pharmaceutical University, No. 666 Siming Road, Ningbo 315500, China. E-mail: zhangl@zjpu.edu.cn

 † Electronic supplementary information (ESI) available: Experimental procedures and compound characterisation data. CCDC 2415008. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d5ra01542a>


- SET reduction
- without the need of base
- catalytic formation
- mild reaction conditions

Scheme 1 SET reduction-based formation of carbanion.





Scheme 2 Generation of α -amino ketone bearing a quaternary carbon center *via* acyl migration reaction.

reaction would be highly desirable (Scheme 2). Herein, with reductive RPC as the strategy, a modular access to functionalized α -amino ketones was generally developed *via* reactions of *N*-vinylimides with various radicals derived from dihydroquinazolinones (DHQs)⁶ or acyl oxime acetates.⁷ The decisive advantage of such a photo-driven strategy was the facile generation of α -imidocarbanion in the absence of a base and exogenous reductant under mild reaction conditions. Moreover, our method could significantly extend the applications of DHQs and acyl oxime acetates as radical precursors.

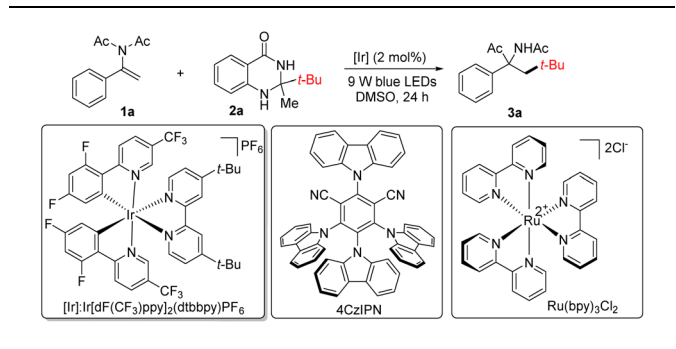
Our initial study of acyl migration reaction commenced with the reaction of *N*-acetyl-*N*-(1-phenylethenyl)acetamide **1a** with pinacolone-derived dihydroquinazolinone **2a** and the results are listed in Table 1. A simple survey of experimental parameters led us to identify the optimal reaction conditions (2 mol% Ir

[dF(CF₃)ppy]₂(dtbbpy)PF₆, 9 W blue LEDs irradiation, DMSO, rt, 24 h) (entry 1). As for the photocatalyst, the organic photocatalyst 4CzIPN proved ineffective for this transformation (entry 2). The reaction also gave a low yield using Ru(bpy)₃Cl₂ as the photocatalyst (entry 3). The subsequent screening of solvents indicated that both DMA and CH₃CN are suitable solvents for this reaction (entries 4 and 5). Moreover, the lack of either [Ir] or light suggested the indispensable role of each in the desired reactivity (entries 6 and 7).

Having established the optimal conditions (entry 1, Table 1), we next set out to investigate the scope with respect to the *N*-vinylimides **1** using dihydroquinazolinone derivative **2a** as the radical precursor. As shown in Table 2, *N*-vinylimides **1** having *para*-, *meta*-, or *ortho*-substituents were all eligible to forge the desired α -amino ketones **3b–3d** in 31–66% yields. Clearly, steric variance on the phenyl ring had an influence on the reaction efficiency. Not surprisingly, substrates bearing a methoxy or methylenedioxy group on the phenyl ring were well tolerated, giving the corresponding products **3e–3g** in good yields (64–79%). Moreover, enamides containing electron-withdrawing groups (–Cl and –Br) reacted smoothly to give the expected products **3h** and **3i** in 83% and 44% yields, respectively. In addition to the smooth reactions of monoaryl-substituted radical acceptors, enamides with biphenyl and naphthyl substituents could be efficiently transformed into the expected products **3j** and **3k** with good results. Interestingly, after the aryl substituent of enamides was replaced with a thiophene group, the yield of product **3l** was 85%. Besides *N*-Boc-*N*-(1-phenylvinyl)acetamide **1m** proved to be a viable substrate, giving **3m** in 74% yield.

After demonstrating the scope of *N*-vinylimides, we next set out to investigate the generality of DHQs using *N*-acyl-protected enamide **1a** as the model radical acceptor. As listed in Table 3,

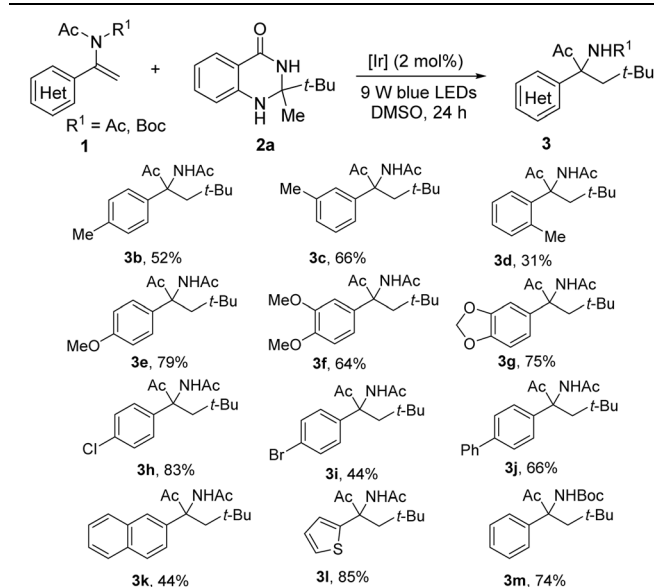
Table 1 Reaction optimization^{a,b}



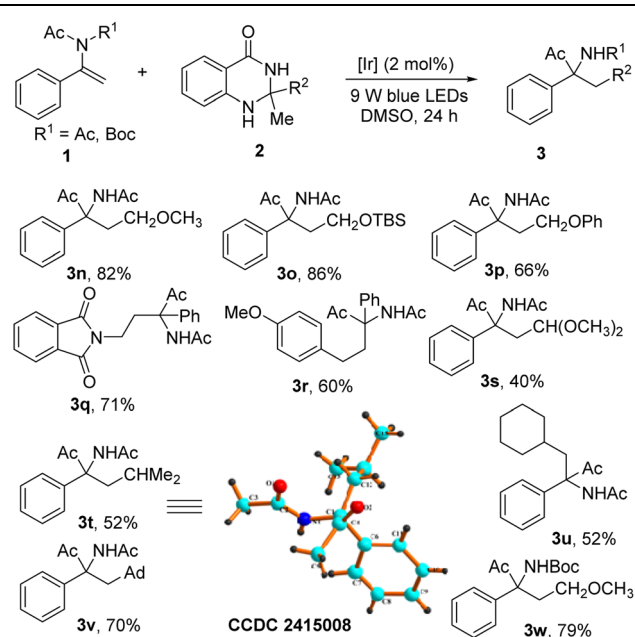
Entry	Deviation from standard conditions	Yield of 3a (%)
1	None	76
2	4CzIPN instead of [Ir]	20
3	Ru(bpy) ₃ Cl ₂ instead of [Ir]	22
4	DMA instead of DMSO	66
5	CH ₃ CN instead of DMSO	70
6 ^c	Without photocatalyst	ND
7 ^{cd}	Without light	ND

^a Standard reaction conditions: a reaction mixture of **1a** (0.2 mmol), **2a** (0.4 mmol), [Ir] (2 mol%), and DMSO (6.0 mL) was irradiated with 9 W blue LEDs for 24 h at room temperature (r.t.) (cooling with a fan). ^b Yield of the isolated product **3a**. ^c NMR analysis of crude reaction mixture. ^d The reaction was run in the dark. ND = not detected.

Table 2 Substrate scope of *N*-vinylimides **1**^a



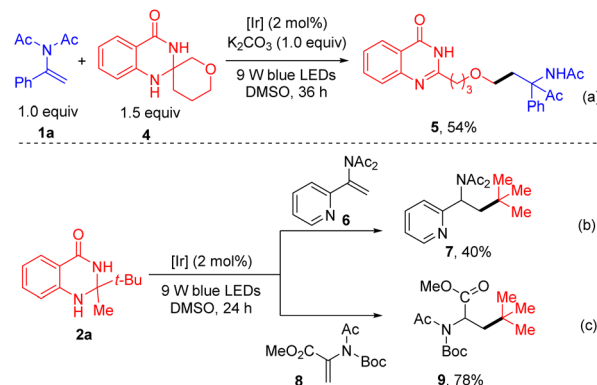
^a Reaction conditions: see entry 1, Table 1. Isolated yields.

Table 3 Scope of dihydroquinazolinones 2^a

^a Reaction conditions: see entry 1, Table 1. Isolated yields.

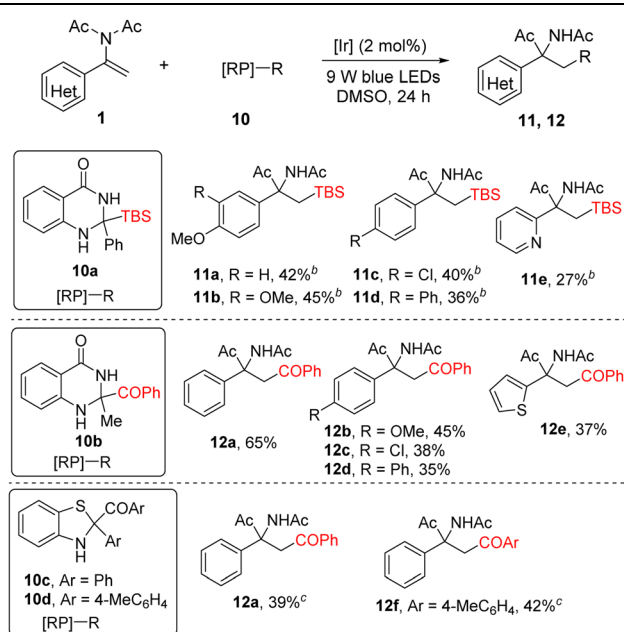
oxygen- or nitrogen-stabilized primary alkyl radicals were all readily accessed by the use of Me-substituted dihydroquinazolinones, giving the products 3n–3q in 66–86% yields. Interestingly, the products 3o and 3q could serve as the precursors of 1,3-aminoalcohol⁸ and 1,3-diamine,⁹ respectively. Moreover, stable 4-methoxybenzyl radical also gave the corresponding product 3r in 60% yield. Secondary oxygen-stabilized dimethoxymethyl radical¹⁰ generated from pyruvic aldehyde participated in this transformation, forging 3s in 40% yield. Both acyclic and cyclic secondary alkyl radicals could react with 1a efficiently to produce the desired products 3t and 3u in good yields. The structure of 3t was further confirmed by single-crystal X-ray analysis (CCDC 2415008).¹¹ Dihydroquinazolinone, derived from 1-adamantly methyl ketone, was also effective in delivering the expected 3v in 70% yield under these redox-neutral conditions. Again, this straightforward acyl migration reaction can be applied to *N*-Boc-*N*-(1-phenylvinyl)acetamide 1m, producing 3w in 79% yield.

As an extension, with 1a as the radical acceptor, spiro dihydroquinazolinone 4¹² successfully underwent the expected ring-opening/radical addition/acyl migration cascade reaction to give 5 in 54% yield (Scheme 3a). Of note, the acyl migration reaction is highly dependent on the electron properties of radical acceptors.⁵ Using enamide-bearing pyridine moiety 6 as the radical acceptor, the Giese-type reaction instead of acyl migration reaction was observed, yielding 7 in 40% yield (Scheme 3b). Similarly, only the Giese-type reaction product 9 was isolated for the reaction of 2a with *N*-Boc-*N*-acetyldehydroalanine methyl ester 8 (Scheme 3c).



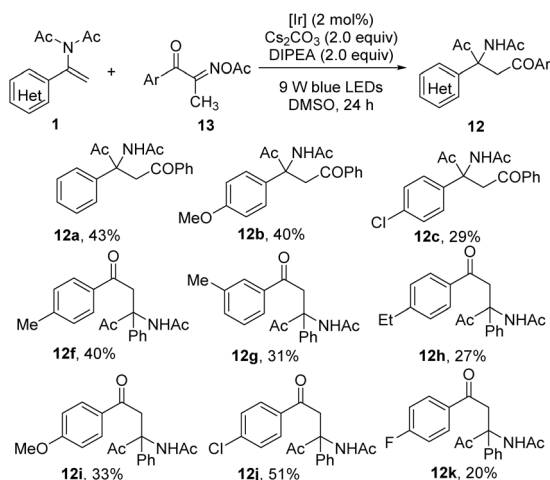
Scheme 3 Acyl migration and Giese-type reactions.

To investigate the generality of this method, we focused on the acyl migration reactions of enamides with silyl and acyl radicals instead of alkyl radicals (Table 4). Interestingly, under the optimized reaction conditions in combination with K₂CO₃ (2.0 equiv.), using 2-silylated dihydroquinazolinone 10a as the silyl radical precursor,¹³ a range of *N,N*-diacetylimidostyrenes bearing various functional groups underwent acyl migrations to give 11a–11d in 36–45% yields. Furthermore, pyridine-containing enamide was also applied, producing 11e in moderate yields. In addition, the benzoyl radical generated from 2-benzoyl-2-methyl-2,3-dihydroquinazolin-4(1*H*)-one 10b readily reacted with various *N*-acetyl-*N*-(1-arylvinyl)acetamides 1, furnishing the expected products 12a–12d in moderate to good yields ranging from 35 to 65% yields. Moreover, enamide

Table 4 Reactions of 1 with silyl and acyl radicals^a

^a Reaction conditions: see entry 1, Table 1. Isolated yields. ^b K₂CO₃ (0.4 mmol) was used. ^c Cs₂CO₃ (0.4 mmol) was used.



Table 5 Preparation of 1,4-diketones^a

^a Reaction conditions: a reaction mixture of **1** (0.2 mmol), **13** (0.4 mmol), [Ir] (2 mol%), Cs₂CO₃ (0.4 mmol), DIPEA (0.4 mmol) and DMSO (6.0 mL) was irradiated with 9 W blue LEDs for 24 h at room temperature (rt) (cooling with a fan). Isolated yields.

bearing a heteroaryl unit, thiophene, was tolerated here, affording product **12e** in 37% yield. In addition to employing 2-benzyl-2-phenylbenzothiazoline **10c** as a benzoyl radical source,¹⁴ 4-methyl-substituted benzoyl radical derived from **10d** also reacted with **1a** to give product **12f** in 42% yield in the presence of a stoichiometric amount of Cs₂CO₃. Of note, compared to the broad substrate scope of 2,2-disubstituted DHQs for the formation of alkyl radicals, the generality of 2-acyl-substituted DHQs and benzothiazolines remains an issue.¹⁵

Considering the synthetic importance of 1,4-diketones and their unique biological activities,¹⁶ we decided to develop a simple and straightforward method for their access based on the acyl migration of enamides with acyl radicals. Fortunately, with *N,N*-diisopropylethylamine (DIPEA) as the reductant and Cs₂CO₃ as the base, we found easily accessible acyl oxime esters could serve as general and efficient acyl radical precursors enabled by photocatalysis (Table 5).^{7,17} The *para*-position of *N,N*-diacetylindostyrenes with electron-rich and electron-deficient groups proceeded smoothly, affording 1,4-diketones **12b** and **12c** in moderate yields. In addition to benzoyl radicals, aryl acyl radicals bearing substituents (*p*-Me, *m*-Me, *p*-Et, *p*-OMe, *p*-Cl, *p*-F) on the aromatic ring at different positions or with different electronic properties can uniformly undergo expected cascade reactions, delivering the desired 1,4-diketones (**12f–12k**, 20–51% yields). Note that in contrast to the oxidative generation of acyl radicals from 2-acyl-substituted DHQs, acyl oxime esters serve as precursors of acyl radicals under reductive conditions. In this regard, the current reductive method is complementary to the above-mentioned oxidative SET approaches (see the ESI† for details).¹⁸

In summary, with reductive RPC as the strategy, we have described a new protocol that enables modular access to functionalized α -amino ketones through photoredox catalysis. Using

DHQs or acyl oxime acetates as the radical precursors, a variety of *N*-vinylimides bearing various functional groups could undergo smooth radical addition/acyl migration cascade reactions under mild conditions. Both SET oxidation and photoreduction pathways for the generation of acyl radicals are compatible with the following catalytic cascade reaction for the preparation of 1,4-diketones. Expectedly, the modular preparation of functionalized α -amino ketones bearing quaternary carbon centers would be feasible using radical addition/acyl migration cascade reactions as the strategy under mild reaction conditions.¹⁹

Data availability

The data supporting this study have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 22271168) and the Specialty Fund of Zhejiang Institute of Tianjin University (No. ZITJU2024-ZYHT003).

Notes and references

- (a) R. J. Wiles and G. A. Molander, *Isr. J. Chem.*, 2020, **60**, 281; (b) M. Liu, X. Ouyang, C. Xuan and C. Shu, *Org. Chem. Front.*, 2024, **11**, 895.
- (a) T. Guo, L. Zhang, X. Liu, Y. Fang, X. Jin, Y. Yang, Y. Li, B. Chen and M. Ouyang, *Adv. Synth. Catal.*, 2018, **360**, 4459; (b) W. Luo, Y. Yang, Y. Fang, X. Zhang, X. Jin, G. Zhao, L. Zhang, Y. Li, W. Zhou, T. Xia and B. Chen, *Adv. Synth. Catal.*, 2019, **361**, 4215; (c) L. Huai, L. Zhang, Z. Wang, H. Wu and Y. Fang, *Org. Chem. Front.*, 2023, **10**, 1245; (d) X. Jin and L. Zhang, *Org. Biomol. Chem.*, 2022, **20**, 5377.
- (a) L. Pitzer, J. L. Schwarz and F. Glorius, *Chem. Sci.*, 2019, **10**, 8285; (b) K. Donabauer and B. König, *Acc. Chem. Res.*, 2021, **54**, 242.
- O. Hara, M. Ito and Y. Hamada, *Tetrahedron Lett.*, 1998, **39**, 5537.
- L. Huai, L. Zhang, Z. Wang and Y. Fang, *Org. Chem. Front.*, 2024, **11**, 2344.
- S. Miñoza, I. L. Librando and H.-H. Liao, *Synlett*, 2024, **35**, 1072.
- (a) Y. Bao, Z.-J. Song, J.-L. Dai, S. Yan, Y. Zhang, J.-Y. Wang and G. Li, *Chin. J. Chem.*, 2024, **42**, 1399; (b) H. Shi, H. Dong and C. Wang, *Org. Chem. Front.*, 2023, **10**, 5843.
- S. M. Lait, D. A. Rankic and B. A. Keay, *Chem. Rev.*, 2007, **107**, 767.
- X. Ji and H. Huang, *Org. Biomol. Chem.*, 2016, **14**, 10557–10566.



- 10 T. Guo, L. Zhang, Y. Fang, X. Jin, Y. Li, R. Li, X. Li, W. Cen, X. Liu and Z. Tian, *Adv. Synth. Catal.*, 2018, **360**, 1352.
- 11 CCDC 2415008 (3t) contains the supplementary crystallographic data for this paper. These data are provided free of charge by the Cambridge Crystallographic Data Centre.
- 12 H.-J. Miao, J.-H. Zhang, W. Li, W. Yang, H. Xin, P. Gao, X.-H. Duan and L.-N. Guo, *Chem. Sci.*, 2024, **15**, 8993.
- 13 T. Uchikura, H. Nakamura, H. Sakai and T. Akiyama, *Chem. – Eur. J.*, 2023, **29**, e202301090.
- 14 L. Li, S. Guo, Q. Wang and J. Zhu, *Org. Lett.*, 2019, **21**, 5462.
- 15 (a) Z.-N. Tsai, L.-Y. Li, A. S. Paculba, S. Miñoza, Y.-T. Tsao, P.-S. Lin and H.-H. Liao, *Chem. – Asian J.*, 2024, **19**, e202301004; (b) X.-Y. Lv, R. Abrams and R. Martin, *Nat. Commun.*, 2022, **13**, 2394.
- 16 Y.-Y. Cheng, J.-X. Yu, T. Lei, H.-Y. Hou, B. Chen, C.-H. Tung and L.-Z. Wu, *Angew. Chem., Int. Ed.*, 2021, **60**, 26822.
- 17 C. Ai, T. Wang, Y. Bao, S. Yan, Y. Zhang and J.-Y. Wang, *Org. Biomol. Chem.*, 2024, **22**, 9197.
- 18 (a) Y. Zhang, T. Zhu, Y. Lin, X. Wei, X. Xie, R. Lin, Z. Zhang, W. Fang, J.-J. Zhang, Y. Zhang, M.-Y. Hu, L. Cai and Z. Chen, *Org. Biomol. Chem.*, 2024, **22**, 5561; (b) L. Zheng, P.-J. Xia, Q.-L. Zhao, Y.-E. Qian, W.-N. Jiang, H.-Y. Xiang and H. Yang, *J. Org. Chem.*, 2020, **85**, 11989.
- 19 (a) Y. Zhu and J. Zhang, *Macromol. Rapid Commun.*, 2024, **45**, 2300695; (b) Y. Zhu, D. Zhu, Y. Chen, Q. Yan, C.-Y. Liu, K. Ling, Y. Liu, D. Lee, X. Wu, T. P. Senftle and R. Verduzco, *Chem. Sci.*, 2021, **12**, 16092.

