Chinese Chemical Letters 37 (2026) 111718

Contents lists available at ScienceDirect

Chinese Chemical Letters

journal homepage: www.elsevier.com/locate/cclet

Selective synthesis of [6-6-7]/[6-6-6] core polycyclic heterocycles *via* Lewis acid-mediated cascade annulation of 1,6-enynols with aminonitriles

Zan Chen, Yi Wang, Yuxuan Zhou, Yunlang Li, Rong Xiong, Wenting Huang, Huanfeng Jiang, Wanqing Wu*

Key Laboratory of Functional Molecular Engineering of Guangdong Province, State Key Laboratory of Luminescent Materials and Devices, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 8 May 2025
Revised 25 July 2025
Accepted 12 August 2025
Available online 13 August 2025

Keywords:
Polycyclic heterocycles
Lewis acid-mediated
[4+2] Cycloaddition
Dehydroaromatization

ABSTRACT

Polycyclic heterocycles are prevalent in medicines, functional materials and natural products, making their synthesis a significant focus in modern organic chemistry. Herein, we present a Lewis acid-mediated cascade annulation of 1,6-enynols with *o*-aminobenzonitriles for the chemoselective synthesis of oxepino[3,4,5-*de*][1,6]naphthyridine and chromeno[2,3,4-*de*][1,6]naphthyridine derivatives. This reaction design enables selective control over the carbon-heteroatom and carbon-carbon bond formation in an efficient, atom-economical manner, allowing the one-step synthesis of rare [6-6-7] and [6-6-6] core polycyclic heterocycles containing three heteroatoms. Density functional theory (DFT) calculations and control experiments reveal that the reaction's high selectivity is achieved by modulating the reactivity of electron-rich alkenyl groups in the enynols, which selectively directs the intramolecular dehydroaromatization and cyclization processes.

© 2026 Published by Elsevier B.V. on behalf of Chinese Chemical Society and Institute of Materia Medica, Chinese Academy of Medical Sciences.

Polycyclic heterocycles exist in many natural products, agrochemicals, drug molecules, and materials [1–6]. Among them, nitrogen and oxygen-containing functionalized heterocycles have attracted significant attention due to their high pharmaceutical value and role as efficient building blocks of functional materials [7–11]. In particular, incorporation of heteroatoms increases the diversity of drug discovery libraries by adding key pharmacophores [12–17]. These heterocyclic core structures show significant biological activities, including roles as natural lignan products [12], DNA binders [13], telomerase inhibitors [14], anti-tumor agents, and antiplasmodial agents (Fig. 1a) [15]. Thus, it is necessary to develop concise and convenient methods to construct structurally novel polycyclic heterocycles.

Building polycyclic heterocycles is generally based on stepwise processes, including Diels-Alder cycloadditions [18–21], dehydrogenative cyclizations [22–24], oxidative C-H annulations [25–27], and cross-couplings [28–31]. Furthermore, multi-step assembly and cyclization of heteroatom-containing alkenyl or alkynyl substrates represent an effective construction method for polycyclic heterocycles, but suffer from poor atom and step economy (Fig. 1b) [32–40]. Recently, single-atom skeletal editing has emerged as a powerful tool for modifying individual carbocyclic skeletons in monocycles or fused rings into heterocyclic structures (Fig. 1c) [41–56]. Despite the elegant work already done, methods for incorporating multiple heteroatoms into polycyclic compounds is less developed. Designing simple, readily accessible acyclic functionalized substrates for the one step construction of polycyclic heterocycles containing tricyclic cores and multiple heteroatoms represents an ideal approach (Fig. 1d). However, there are challenges with this approach: (i) Controlling regio- and stereoselectivity; (ii) competitive inter- and intra-molecular reactions; (iii) efficiently introducing multiple heteroatoms while constructing the polycycles.

* Corresponding author.
E-mail address: cewuwq@scut.edu.cn (W. Wu).

https://doi.org/10.1016/j.cclet.2025.111718
1001-8417/© 2026 Published by Elsevier B.V. on behalf of Chinese Chemical Society and Institute of Materia Medica, Chinese Academy of Medical Sciences.

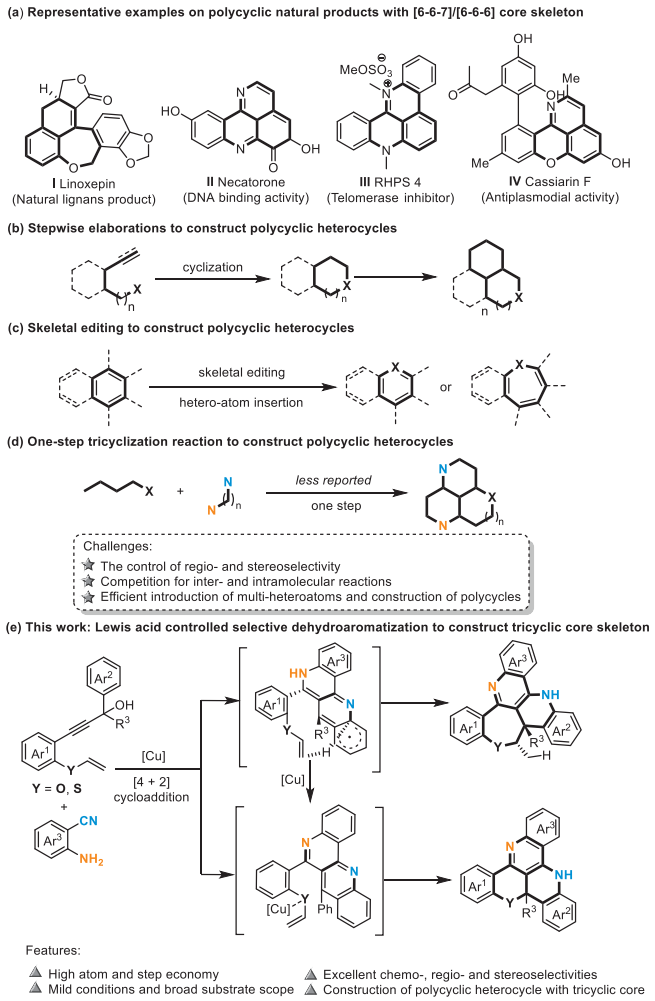
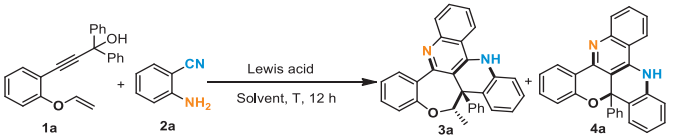


Fig. 1. Background and motivation for the synthesis of polycyclic heterocycles.

Propargyl alcohol derivatives are widely used important synthons in organic synthesis due to their versatile reactivity, allowing the construction of diverse functionalized acyclic and cyclic compounds [57–61]. Additionally, electron-rich olefins serve as useful synthetic feedstocks for high value products [62–74]. The strong electronegativity of the nitrogen, oxygen or sulfur atoms in electron-rich olefins and their lone pairs of electrons can influence reaction sites by coordinating with transition metals or Lewis acids, thereby controlling insertion reactivity and selectivity. We envisioned that a novel enyol substrate containing both propargyl alcohol and electron-rich alkenyl groups would have enhanced reactivities under Lewis acid activation. The propargyl alcohol moiety could react with a nucleophile to form a functionalized allene intermediate, followed by a cascade cyclization to generate polycyclic alkenyl heterocycles [75–80]. At the same time, the electron-rich moiety could participate in ring formation facilitated by Lewis acids. Herein, we report a Lewis acid-mediated cascade cyclization of 1,6-enynols with *o*-aminobenzonitriles for the chemodivergent synthesis oxepino[3,4,5-*de*][1,6]naphthyridine and chromeno[2,3,4-*de*][1,6]naphthyridine derivatives. In this reaction, *o*-aminobenzonitrile serves as both a nucleophile and the sole nitrogen source (Fig. 1e). This strategy enabled the first synthesis of novel polycyclic heterocycles containing [6-6-7] and [6-6-6] tricyclic cores bearing three heteroatoms by selectively controlling the construction of multiple carbon-hetero bonds and carbon-carbon bonds. This reaction features high atom economy, high chemoselectivity, high stereoselectivity and high regioselectivity, as well as mild conditions and a broad substrate scope.

Table 1
Screening of reaction conditions.[a]

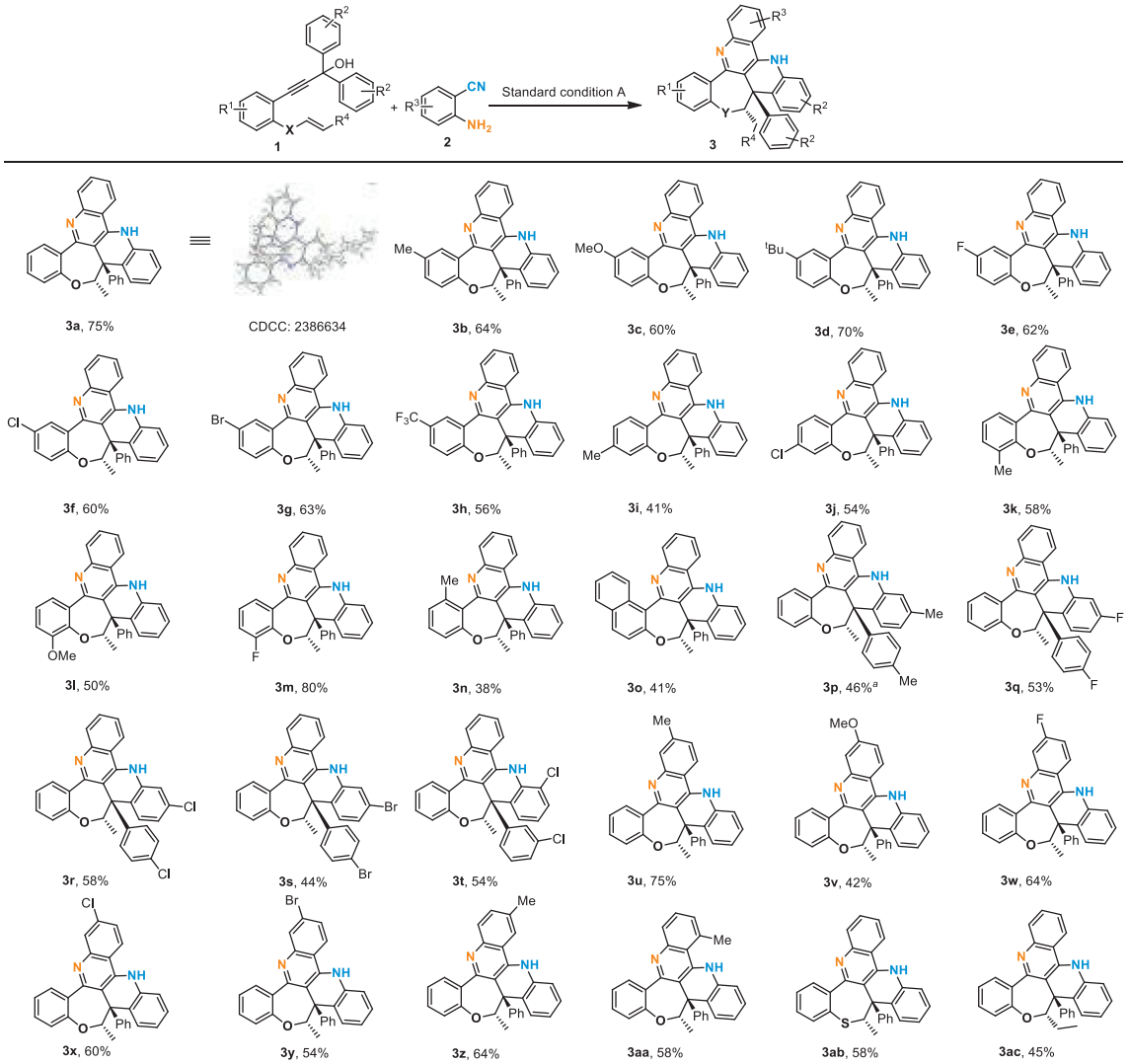


Entry	Lewis acid (equiv.)	Solvent	*T* (°C)	Yield (%)	
				3a [b]	**4a** [c]
1	$Cu(OTf)_2$ (0.2)	DCE	80	33	Trace
2	$Zn(OTf)_2$ (0.2)	DCE	80	n.d.	n.d.
3	$Al(OTf)_3$ (0.2)	DCE	80	n.d.	n.d.
4	AgOTf (0.2)	DCE	80	8	Trace
5	$B(C_6F_5)_3$ (0.2)	DCE	80	n.d.	n.d.
6	$BF_3{\cdot}Et_2O$ (0.2)	DCE	80	n.d.	n.d.
7	$Cu(OTf)_2$ (0.1)	DCE	80	20	Trace
8	$Cu(OTf)_2$ (0.3)	DCE	80	30	12
9	$Cu(OTf)_2$ (0.2)	DCE	70	24	Trace
10	$Cu(OTf)_2$ (0.2)	DCE	110	63	Trace
11	$Cu(OTf)_2$ (0.2)	DCM	110	30	Trace
12	$Cu(OTf)_2$ (0.2)	MeCN	110	n.d.	n.d.
13	$Cu(OTf)_2$ (0.2)	DMSO	110	Trace	n.d.
14	$Cu(OTf)_2$ (0.2)	Dioxane	110	32	Trace
15	$Cu(OTf)_2$ (0.2)	THF	110	75	Trace
16	$Cu(OTf)_2$ (0.4)	DCE	80	25	32
17	$Cu(OTf)_2$ (0.5)	DCE	80	8	51
18	$Cu(OTf)_2$ (1.0)	DCE	80	Trace	83

[a] All reactions were performed with **1a** (0.10 mmol), **2a** (0.11 mmol), Lewis acid (20 mol%), solvent (1 mL). n.d. = not detected.
[b] Isolated yield. The *dr* was determined by ^{1}H NMR, and all *dr* > 20:1.
[c] Isolated yield.

Our investigation began with 1,1-diphenyl-3-(2-(vinyloxy)phenyl)prop-2-yn-1-ol (**1a**) and *o*-aminobenzonitrile (**2a**) as the model substrates to establish the optimal reaction conditions (Table 1). Initially, the reaction was carried out with 20 mol% $Cu(OTf)_2$ catalyst in DCE at 80 °C which provided the oxepino[3,4,5-*de*][1,6]naphthyridine product **3a** in 33 % yield with a diastereomeric ratio (*dr*) > 20:1. A series of Lewis acids, $Zn(OTf)_2$, $Al(OTf)_3$, AgOTf, $ZnCl_2$, $B(C_6F_5)_3$ and $BF_3{\cdot}Et_2O$, were investigated (Table 1, entries 2-6). The results show that only the amount of $Cu(OTf)_2$ did not improve the yield (Table 1, entries 7 and 8). Optimizing the reaction temperatures showed AgOTf showed catalytic activity delivering **3a** in 8 % yield, whereas all the others failed to promote the reaction. Adjusting the maximum yield of **3a** (63 %) was obtained at 110 °C (Table 1, entries 9 and 10). Solvent screening showed that THF gave the maximum yield of **3a** (75 %) (Table 1, entries 11-15). Interestingly, when increasing the amount of $Cu(OTf)_2$ at 80 °C in dichloroethane, the yield of product **4a** significantly increased accompanied by a decrease in the yield of **3a** (Table 1, entries 16-18). The highest yield of **4a** (83 %) was formed when 1 equiv. of $Cu(OTf)_2$ was present (Table 1, entry 18; see Supporting information for details).

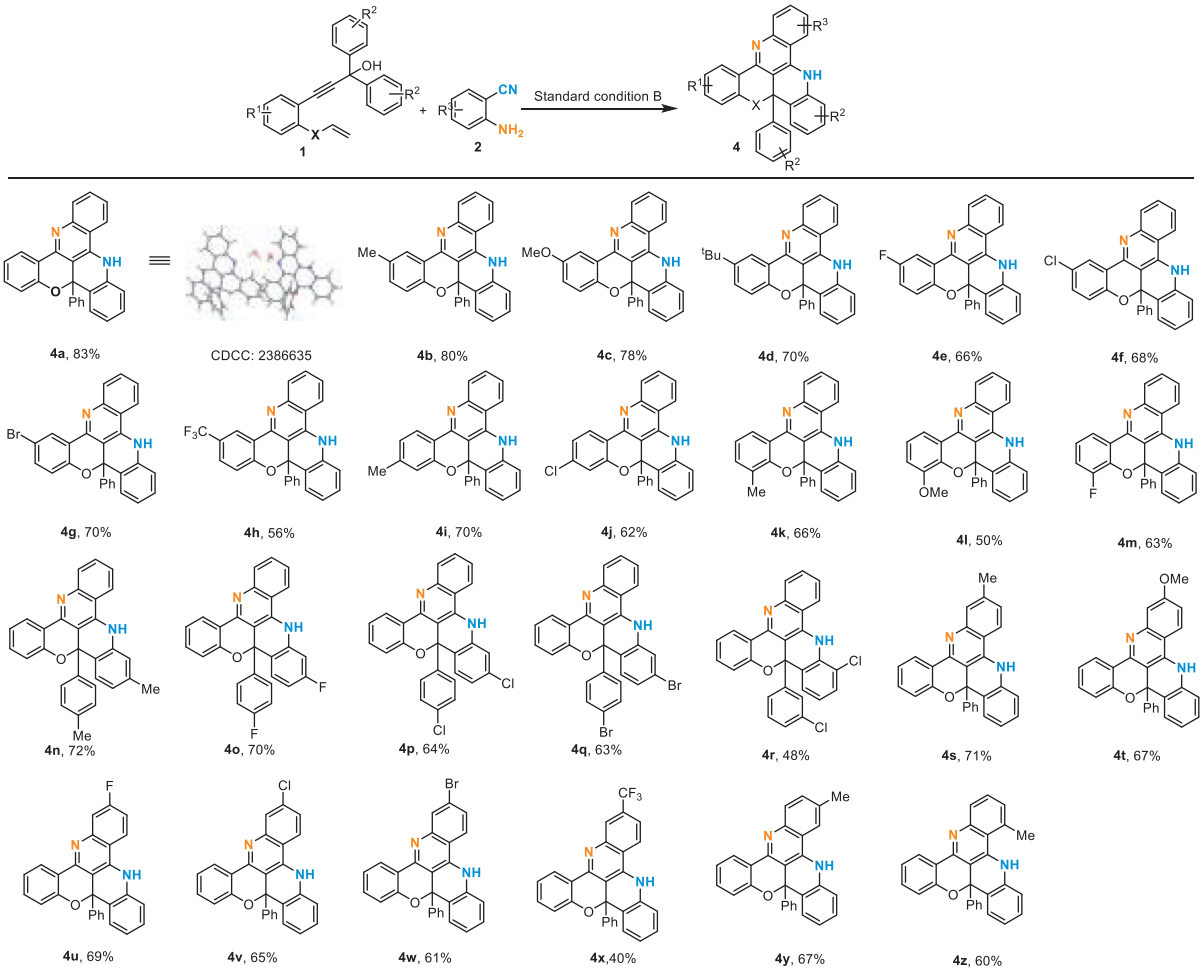
After establishing the optimum conditions, the substrate scope was investigated using a broad range of 1,6-enynols **1** and various substituted *o*-aminobenzonitriles **2** for the synthesis of oxepino[3,4,5-*de*][1,6]naphthyridine derivatives **3** (Scheme 1). Phenol-linked 1,6-enynols **1a-t** with different substituents were tested, and the corresponding products **3a-t** obtained inmoderate



Scheme 1. Standard conditions A: **1** (0.1 mmol), **2** (0.15 mmol), $Cu(OTf)_2$ (20 mol%), THF (1 mL), under air at 110 °C for 12 h. Isolated yield. The *dr* was determined by ^1H NMR, and all *dr* > 20:1. [a] $Cu(OTf)_2$ (5 mol%), 24 h.

to good yields. The relative configuration of **3a** was determined by X-ray diffraction analysis (XRD; see Supporting information for details). Phenol skeletons substituted at the 4-position with either electron-donating (-Me, *-tert*-Bu, -OMe) or electron-withdrawing groups (-F, -Cl, -Br, $-CF_3$) were well tolerated, providing the [6-6-7] polycyclic-heterocycle products **3b**-**3h** in 56 %-75 % yields. Notably, substrates with electron-donating groups exhibited higher reactivity than those with electron-withdrawing groups, indicating that the electronic effects played an important role in this process. In addition, 1,6-enynols with the phenol skeleton substituted at the 3-, 5- and 6-positions reacted smoothly providing the desired products **3i**-**n** in 38 %-80 % yields. Comparing the yields of **3b**, **3i**, **3k** and **3n** reveals that **3n** yield was the lowest, suggesting that steric hindrance substantially effects the naphthyridine ring formation, whereas the impacton oxepane construction was considerably less pronounced. Additionally, the reaction with naphthol-linked 1,6-enynol provided the corresponding product **3o** (41 %). The 1,6-enynols (**1p**-**1t**) containing the propargyl alcohol moiety with two equivalently substituted aromatic rings were efficiently converted to the target products (**3p**-**3t**) in moderate yields. Investigating the scope of substituted *o*-aminobenzonitriles **2**, led to the formation of [6-6-7] polycyclic heterocyclic products **3u**-**3aa** in moderate to good yields. Of particular interest, the thiophenol-linked 1,6-enynol **1ab** was a suitable substrate forming the corresponding product **3ab** in 58 % yield. It should be noted that the 1,6-enynol **1ac** with a methyl substituted alkenyl terminus was transformed to the the desired product **3ac** in moderate yield. However, 1,6-enynols having asymmetric aliphatic alkyl chains at the α-positon of the alcohol were incompatible with this reaction system.

The suitability of substrates for synthesizing chromeno[2,3,4-*de*][1,6]naphthyridine derivatives **4** was examined (Scheme 2). The 1,6-enynols containing monosubstituted phenol skeletons (-Me, *-tert*-Bu, -OMe, -F, -Cl, -Br, and $-CF_3$), were excellent substrates for the transformation, yielding the corresponding products **4a**-**4m** in good yields. The structure of product **4a** was confirmed by XRD (see Supporting information for details). In addition, 1,6-enynols **1n-1r** containing a *para*- or *meta*-substituted aromatic ring attached to the α-positon of the alcohol were converted



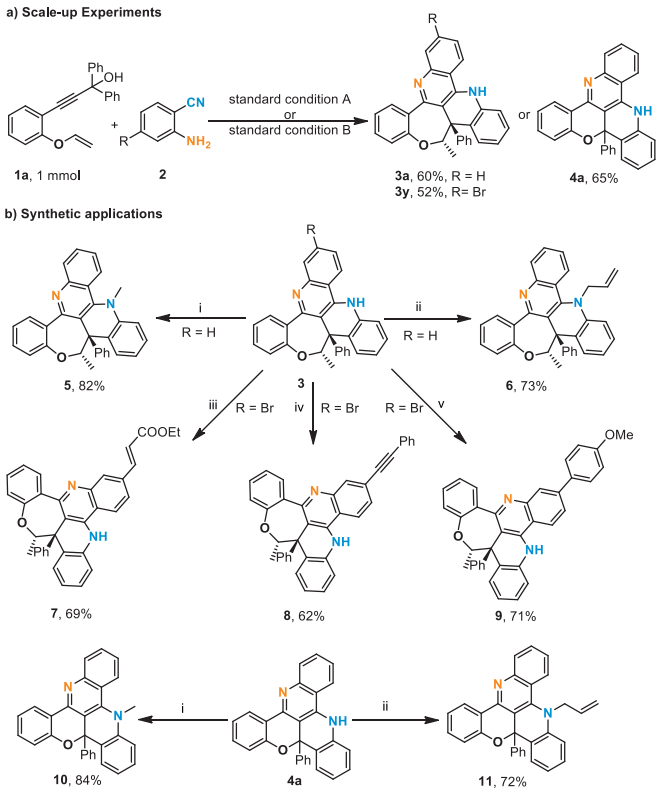
Scheme 2. Standard conditions B: **1** (0.1 mmol), **2** (0.11 mmol), $Cu(OTf)_2$ (0.1 mmol), DCE (1 mL), under air at 80 °C for 12 h. n.d. = not detected. Isolated yield.

into the desired products **4n-4r**, in yields ranging from 48 % to 72 %. Furthermore, substrates with various substituents attached to the *o*-aminobenzonitriles **2** led to the [6-6-6] heterocyclic products **4s**-**4z** in moderate to good yields. However, the 3-Me substituted, naphthol-linked and thiophenol-linked 1,6-enynols did not provide the target products, likely due to spatial and electronic effects.

To demonstrate the efficiency and practicality of this approach, the reaction was carried out on a 1 mmol scale and the corresponding products **3a**, **3y** and **4a** were obtained in the yields of 60 %, 52 % and 65 % respectively (Scheme 3a). A series of product decorations were then explored (Scheme 3b). For example, the amino group of **3a** was replaced by different substituents in the presence of K_2CO_3, providing the methylated product **5** in 82 % yield and the acrylated product **6** in 73 % yield. Additionally, **3y** readily underwent the Heck, Sonogashira and Suzuki-Miyaura cross-coupling reactions to afford the conjugated products **7-9** in good yields, suggesting potential applications in materials science. Furthermore, when the [6-6-6] polycyclic heterocycle **4a** was substituted with methyl or alkenyl groups, it efficiently transformed to the desired products **10** or **11**, thus providing a handle for future modification of these complex nitrogen heterocycles.

To gain more insight into the reaction mechanism, several control experiments were conducted (Scheme 4). Isotope labeling and kinetic experiments were performed (Schemes 4a-c). When the 1,6-enynol **1a-D** bearing fully deuterated aromatic rings α to the alcohol reacted with **2a** under standard conditions A, the deuteration rate of the methyl group in product **3a-D** exceeded 99 %, indicating that the methyl protons originate from the substrate's aryl hydrogen. The parallel experiments of **1a** and **1a-D** found that the k_H/k_D value was 1.07, while no kinetic isotope effect was observed in the intermolecular competitive experiment ($k_H/k_D = 1.0$), suggesting that the capture of aryl hydrogens by the alkenyl group is not the reaction's rate-determining step. Moreover, no deuterated product **3a** was detected when D_2O was added to the reaction system, which indicates H_2O is not involved in the formation of **3a**.

An attempt to capture the reaction intermediates resulted in the isolation of two compounds, **12** (45 % yield) and **13** (36 % yield) (Scheme 4d), whose structures were confirmed by XRD (see Supporting information for details). Compound **12** was also obtained in 10 % yield under standard conditions A (Scheme 4e). When **12** was used as the substrate under conditions A or B, product **3a** was not detected but **4a** was afforded in 87 % yield (Scheme 4f). However, when using **13** as the reaction partner, neither product **3a** nor **4a** was made (Scheme 4g). These results imply that **12** is an important intermediate in the formation of **4a**, while **13** is not involved in either process. ^{1}H nuclear magnetic resonance (NMR) of

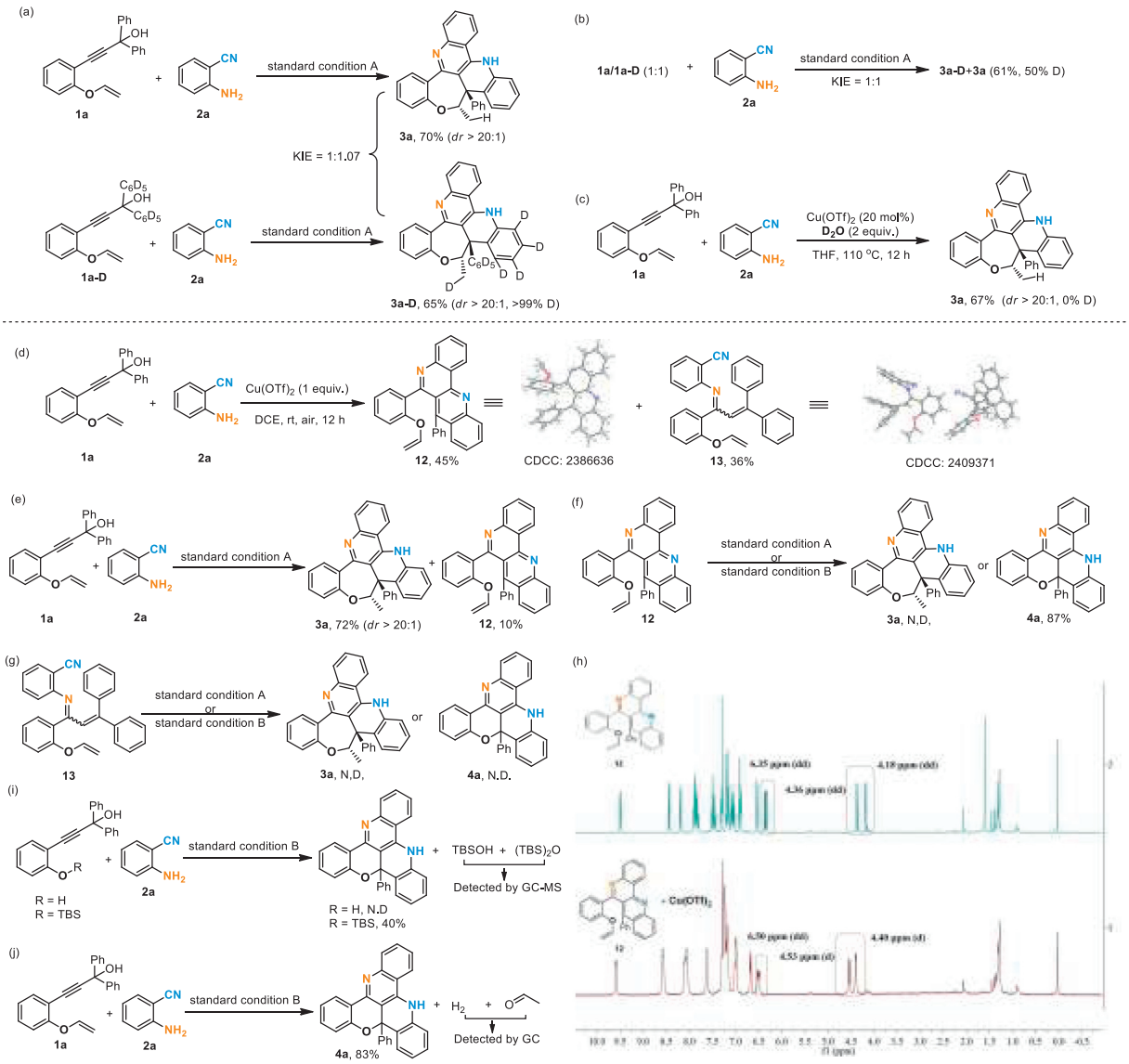


Scheme 3. The scale-up experiments and synthetic applications: (i) MeI, K_2CO_3, DMF, 60 °C, 12 h; (ii) 3-bromoprop-1-ene, K_2CO_3, DMF, 60 °C, 12 h; (iii) ethylacrylate, $Pd(PPh_3)_2Cl_2$, Et_3N, DMF, N_2, 90 °C, 24 h; (iv) ethynylbenzene, $PdCl_2(PPh_3)_2$, CuI, THF/Et_3N (1:1), N_2, 100 °C, 30 h; (v) (4-methoxyphenyl)-boronic acid, $Pd(PPh_3)_4$, K_2CO_3 (2.0 mol/L in H_2O), toluene, N_2, 110 °C, 24 h. See Supporting information for details.

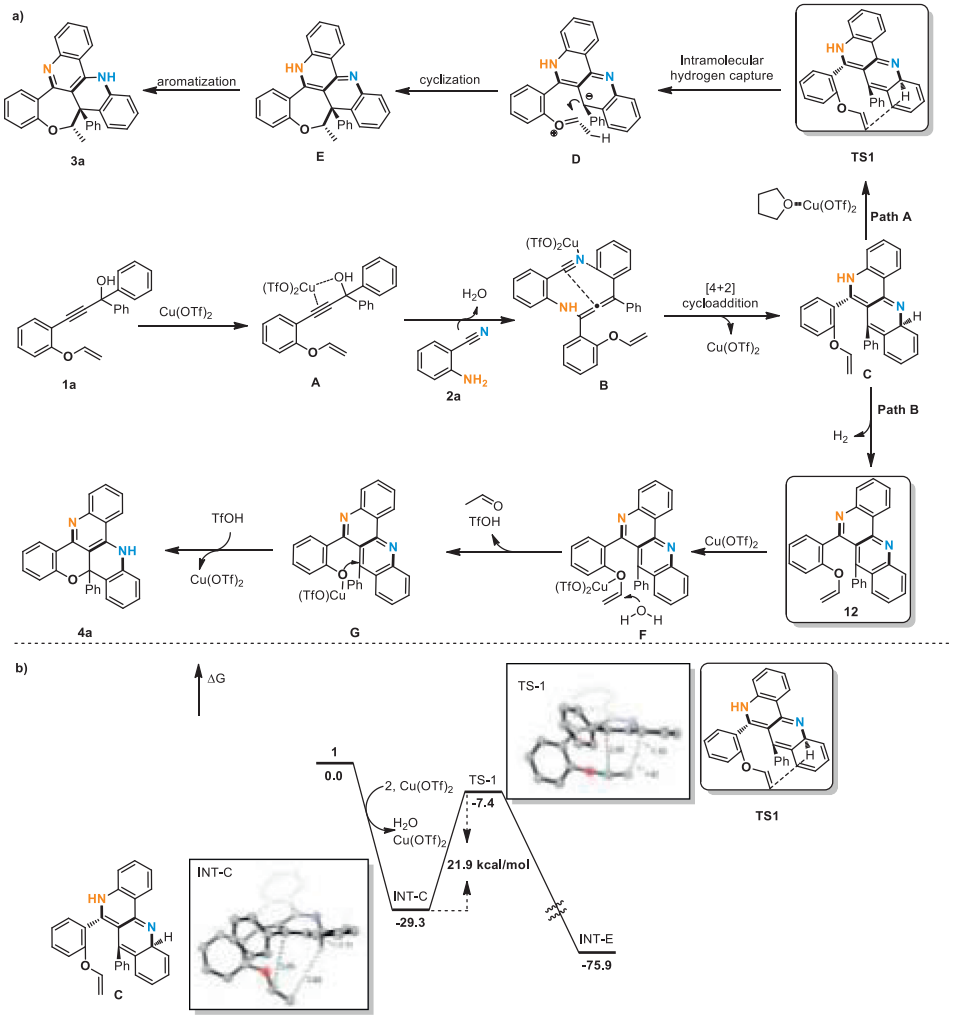
12 revealed that the addition of 1.0 equiv. of $Cu(OTf)_2$ increased **12**'s alkenyl hydrogen chemical shift indicating the alkenyl group's electron density decreases, thus corroborating $Cu(OTf)_2$'s preferential coordination to **12**'s enol ether oxygen (Scheme 4h). When the 1,6-enynol alkenyl group was replaced by hydrogen, product **4a** was not detected under standard conditions B. However, when the alkenyl group was substituted with TBS, **4a** was produced, and TBSOH and $(TBS)_2O$ were detected *via* GC-MS (Scheme 4i). Of note, when the reaction of **1a** and **2a** was conducted under standard conditions B, both hydrogen and acetaldehyde gases were detected by GC (Scheme 4j). This indicates that the substrate undergoes dehydrogenation to produce hydrogen during the reaction, while acetaldehyde is generated from the alkenyl groups dissociation.

Based on these results and previous reports [62–74,81–86], a plausible reaction mechanism is proposed in Scheme 5. First, 1,6-enynol **1a** and *o*-aminobenzonitrile **2a** undergo a $Cu(OTf)_2$ activated cationic rearrangement to form an allene cationic intermediate **A**. This is then attacked by the nucleophilic amino group of **2a** to give intermediate **B**, and the release of one H_2O molecule. Next, the $Cu(OTf)_2$ activated intermediate **B** undergoes an intramolecular [4 + 2] cycloaddition reaction to afford intermediate **C**. The oxygen heterocycle formation is selectively controlled by the amount of copper salt and the solvent. In Path A, under the treatment of catalytic copper salt, intermediate **C** undergoes an intramolecular dehydroaromatization, to form intermediate **D**. Density functional theory (DFT) calculations of **TS1** indicate that the alkenyl group in intermediate **C** and the aryl hydrogen, are in close proximity (1.42 Å). This alkenyl group serves as the hydrogen receptor, facilitating the completion of dehydroaromatization. The energy requirement for dehydroaromatization is 21.9 kcal/mol, a crucial factor that significantly impacts the reaction's temperature and product's high diastereoselectivity (see Supporting information for details). The solvent, tetrahydrofuran (THF), can also coordinate with copper, weakening the copper's effect on the electron-rich alkenyl group in intermediate **C**. Intermediate **D** subsequently cyclizes to produce intermediate **E**, which is aromatized to yield product **3a**. Alternatively, in the presence of a full equivalent amount of $Cu(OTf)_2$, the Lewis acid coordinates with intermediate **C**'s alkenyl ether's oxygen atom, as shown in Path B. This interaction weakens the alkenyl group's electron-donating ability, prompting the intramolecular dehydrogenative aromatization of **C** to form **12**, which can be isolated. Then the intermediate **F** formed by the coordination of **12** with $Cu(OTf)_2$ is hydrolyzed, resulting in a molecule of acetaldehyde and intermediate **G**. Finally, protonation of **G** affords the [6-6-7] cyclization product **4a**.

In conclusion, we have developed a novel methodology for the copper-mediated reaction of 1,6-enynols with *o*-aminobenzonitriles to chemoselectively synthesize oxepino[3,4,5-*de*][1,6]naphthyridine and chromeno[2,3,4-*de*][1,6]naphthyridine derivatives. These transformations efficiently construct polycyclic heterocycles containing [6-6-7] or [6-6-6] core skeletons, while providing high selectivity, efficiency, and atom economy. The reaction conditions are mild, and the substrate scope is broad. Control experiments and DFT calculations suggest that the key to the reaction's high stereoselectivity and chemoselectivity lies in the Lewis acid's control of the substrate's active site. This approach offers a new design concept to construct novel heterocyclic compounds, thereby inspiring further innovative synthetic designs of polycyclic heterocycles.



Scheme 4. (a) H/D transfer experiments. (b) Intermolecular KIE experiments. (c) H source experiment. (d) Synthesis of compounds **12** and **13**. (e) Isolation of compound **12** in standard conditions A. (f) Conversion of compound **12** in standard conditions A or B. (g) Conversion of compound **13** in standard conditions A or B. (h) Intermediate **12** with copper coordination effect. (i) The alkenyl group of substrate **1** was replaced with hydrogen or TBS reacts with **2a** under standard conditions B. (j) Detection of gas by-products of the reaction between **1a** and **2a** under standard conditions B.



Scheme 5. (a) Proposed mechanism. (b) Density functional theory (DFT) calculation of **TS1**.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Zan Chen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Yi Wang:** Writing – review & editing, Investigation, Data curation. **Yuxuan Zhou:** Methodology, Investigation. **Yunlang Li:** Methodology, Data curation. **Rong Xiong:** Investigation, Data curation. **Wenting Huang:** Investigation, Data curation. **Huanfeng Jiang:** Writing – review & editing, Formal analysis. **Wanqing Wu:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Acknowledgments

The authors thank the National Youth Talent Support Program, Guangdong Basic and Applied Basic Research Foundation (No. 2024B1515040027) and Guangzhou Science and Technology Projects (No. 2024A04J6248) for financial support.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cclet.2025.111718.

References

[1] C. Schultz, A. Link, M. Leost, et al., J. Med. Chem. 42 (1999) 2909–2919.
[2] A.N. de Groot, P.W. van Dongen, T.B. Vree, Y.A. Hekster, J. van Roosmalen, Drugs 56 (1998) 523–535.
[3] A. Mishra, P. Bäuerle, Angew. Chem. Int. Ed. 51 (2012) 2020–2067.
[4] W. Liu, B. Hong, J. Wang, X. Lei, Acc. Chem. Res. 53 (2020) 2569–2586.
[5] H. Xin, B. Hou, X. Gao, Acc. Chem. Res. 54 (2021) 1737–1753.
[6] Y. Jiang, R.E. McNamee, P.J. Smith, et al., Chem. Soc. Rev. 50 (2021) 58–71.
[7] E. Delfourne, J. Bastide, Med. Res. Rev. 23 (2003) 234–252.
[8] K.M. Marshall, L.R. Barrows, Nat. Prod. Rep. 21 (2004) 731.
[9] M.D. Burke, S.L. Schreiber, Angew. Chem. Int. Ed. 43 (2004) 46–58.
[10] B. Liu, D. Shi, Y. Yang, et al., Eur. J. Org. Chem. 2018 (2018) 869–873.
[11] H.I. Boshoff, N. Malhotra, C.E. Barry, S. Oh, Pharmaceuticals 17 (2024) 211.
[12] L.F. Tietze, S.C. Duefert, J. Clerc, et al., Angew. Chem. Int. Ed. 52 (2013) 3191–3194.
[13] J. Stanslas, D.J. Hagan, M.J. Ellis, et al., J. Med. Chem. 43 (2000) 1563–1572.
[14] A. Rizzo, S. Iachettini, P. Zizza, et al., J. Exp. Clin. Cancer Res. 33 (2014) 81–88.
[15] J. Deguchi, T. Hirahara, S. Oshimi, et al., Org. Lett. 13 (2011) 4344–4347.
[16] A.R.O. Cousins, D. Ritson, P. Sharma, et al., Chem. Commun. 50 (2014) 15202–15205.
[17] M. Menna, E. Fattorusso, C. Imperatore, Molecules 16 (2011) 8694–8732.
[18] A. Narita, X. Wang, X. Feng, K. Mullen, Chem. Soc. Rev. 44 (2015) 6616–6643.
[19] H. Ito, K. Ozaki, K. Itami, Angew. Chem. Int. Ed. 56 (2017) 11144–11164.
[20] S. Zhu, R. Zhang, T. Xia, et al., Org. Lett. 26 (2024) 10746–10751.
[21] W.W. Zhao, M.Y. Tian, Y.L. Zhou, et al., Angew. Chem. Int. Ed. 63 (2024) e202318887.
[22] K. Fukuzumi, Y. Nishii, M. Miura, Angew. Chem. Int. Ed. 56 (2017) 12746–12750.
[23] J. Zhang, M. Qiao, L. Chen, et al., Org. Chem. Front. 6 (2019) 2844–2849.
[24] I. Kamiyoshi, Y. Kojima, S. Xu, et al., Chem. Sci. 15 (2024) 20413–20420.
[25] J. Yin, J. You, Angew. Chem. Int. Ed. 58 (2019) 302–306.
[26] H. Ito, Y. Segawa, K. Murakami, K. Itami, J. Am. Chem. Soc. 141 (2019) 3–10.
[27] Y. Zhang, S.H. Pun, Q. Miao, Chem. Rev. 122 (2022) 14554–14593.
[28] A. Narita, X. Wang, X. Feng, K. Mullen, Chem. Soc. Rev. 44 (2015) 6616–6643.
[29] M. Ball, Y. Zhong, Y. Wu, et al., Acc. Chem. Res. 48 (2015) 267–276.
[30] X. Yang, R. Sun, Adv. Synth. Catal. 365 (2023) 124–141.
[31] G.E. Clarke, J.D. Firth, L.A. Ledingham, et al., Nat. Commun. 15 (2024) 3968.
[32] P. Chauhan, S. Mahajan, D. Enders, Acc. Chem. Res. 50 (2017) 2809–2821.
[33] W.J. Kong, Z. Shen, L.H. Finger, L. Ackermann, Angew. Chem. Int. Ed. 59 (2020) 5551–5556.
[34] R. Liang, Y. Jia, Acc. Chem. Res. 55 (2022) 734–745.
[35] T.G. Fan, X.L. Ding, B.X. Sun, et al., Adv. Synth. Catal. 365 (2023) 579–583.
[36] J. Han, Y. Yang, Y. Gong, et al., Nat. Commun. 14 (2023) 5148.
[37] A. Luo, Y. Bao, X. Liu, et al., J. Am. Chem. Soc. 146 (2024) 6240–6251.
[38] Z. Wang, X. Fu, Q. Li, et al., Molecules 29 (2024) 2481.
[39] P. Langer, Eur. J. Org. Chem. 27 (2024) e202400153.
[40] Y. Fei, Z. Zhou, Z. Ni, et al., Angew. Chem. Int. Ed. 64 (2025) e202414726.
[41] B.D. Dherange, P.Q. Kelly, J.P. Liles, M.S. Sigman, M.D. Levin, J. Am. Chem. Soc. 143 (2021) 11337–11344.
[42] J.C. Reisenbauer, O. Green, A. Franchino, P. Finkelstein, B. Morandi, Science (1979) 377 (2022) 1104–1109.
[43] S. Liu, X. Cheng, Nat. Commun. 13 (2022) 425.
[44] C. Ren, B. Han, H. Guo, et al., Angew. Chem. Int. Ed. 63 (2024) e202407222.
[45] L. Wu, H. Xia, J. Bai, et al., Nat. Chem. 16 (2024) 1951–1959.
[46] Z. Liu, P. Sivaguru, Y. Ning, Y. Wu, X. Bi, Chem. Eur. J. 29 (2023) e202301227.
[47] S. Liu, Y. Yang, Q. Song, et al., Nat. Commun. 15 (2024) 9998.
[48] S. Liu, Y. Yang, Q. Song, et al., Nat. Chem. 16 (2024) 988–997.
[49] X. Zhang, Q. Song, S. Liu, et al., Nat. Chem. 17 (2025) 215–225.
[50] T.J. Pearson, R. Shimazumi, J.L. Driscoll, et al., Science (1979) 381 (2023) 1474–1479.
[51] P.Q. Kelly, A.S. Filatov, M.D. Levin, Angew. Chem. Int. Ed. 61 (2022) e202213041.
[52] S.C. Patel, N.Z. Burns, J. Am. Chem. Soc. 144 (2022) 17797–17802.
[53] J. Wang, H. Lu, Y. He, C. Jing, H. Wei, J. Am. Chem. Soc. 144 (2022) 22433–22439.
[54] H. Li, N. Li, J. Wu, et al., J. Am. Chem. Soc. 145 (2023) 17570–17576.
[55] Y. He, J. Wang, T. Zhu, Z. Zheng, H. Wei, Chem. Sci. 15 (2024) 2612–2617.
[56] H. Lu, Y. Zhang, X. Wang, et al., Nat. Commun. 15 (2024) 3772.
[57] Y. Zhu, L. Sun, P. Lu, Y. Wang, ACS Catal. 4 (2014) 1911–1925.
[58] J. Li, F. Yang, W. Hu, et al., Chem. Commun. 56 (2020) 9154–9157.
[59] X. Li, D. Xu, Z. Niu, et al., Org. Lett. 23 (2021) 832–836.
[60] X. Li, X. Kong, C. Wang, et al., Org. Lett. 23 (2021) 9457–9462.
[61] Dattatri, M.K.R. Singam, S. Vavilapalli, J.B. Nanubolu, M.S. Reddy, Angew. Chem. Int. Ed. 62 (2023) e202215825.
[62] W. Chen, Y. Li, Y. Chen, C.Y. Ho, Angew. Chem. Int. Ed. 57 (2018) 2677–2681.
[63] C. Chen, C. Shi, Y. Yang, B. Zhou, Chem. Sci. 11 (2020) 12124–12129.
[64] M. Slivka, M. Onysko, Synthesis 53 (2021) 3497–3512.
[65] Q. Huang, S.R. Suravarapu, P. Renaud, Chem. Sci. 12 (2021) 2225–2230.
[66] H. Jiang, X. Yu, C.G. Daniliuc, A. Studer, Angew. Chem. Int. Ed. 60 (2021) 14399–14404.
[67] M. Luo, Q. Xiao, J. Li, Chem. Soc. Rev. 51 (2022) 726–7237.
[68] Y. Gao, S. Yang, M. She, et al., Chem. Sci. 13 (2022) 2105–2114.
[69] L. Ouyang, J. Li, J. Zheng, et al., Angew. Chem. Int. Ed. 56 (2017) 15926–15930.
[70] F. Zhou, M. Li, H. Jiang, W. Wu, Adv. Synth. Catal. 363 (2021) 4841–4855.
[71] Z. Wu, M. Hu, Y. Jin, et al., Sci. Adv. 7 (2021) eabh4088.
[72] F. Zhou, C. Li, M. Li, et al., Chem. Commun. 57 (2021) 4799–4802.
[73] Z. Chen, W. Huang, Y. Su, H. Jiang, W. Wu, Chem. Commun. 59 (2023) 4523–4526.
[74] Y. Zheng, Y. Wu, J. Li, et al., Green Chem. 27 (2025) 1018–1022.
[75] L.J. Du, Y.P. Han, H.Y. Zhang, et al., Adv. Synth. Catal. 362 (2020) 1399–1404.
[76] X.Y. Liu, Y.L. Liu, L. Chen, Adv. Synth. Catal. 362 (2020) 5170–5195.
[77] X.R. Song, R. Yang, Q. Xiao, Adv. Synth. Catal. 363 (2021) 852–876.
[78] M. Shankar, K.C.K. Swamy, Org. Lett. 25 (2023) 3397–3401.
[79] X. Ren, X. Feng, H. Zhang, et al., J. Org. Chem. 88 (2023) 16007–16017.
[80] S. De, C. Chowdhury, Chem. Eur. J. 29 (2023) e202203993.
[81] X. You, X. Xie, H. Chen, Y. Li, Y. Liu, Chem. Eur. J. 21 (2015) 18699–18705.
[82] T. Wang, R.R. Naredla, S.K. Thompson, T.R. Hoye, Nature 532 (2016) 484–488.
[83] Z.Y. Tian, Q. Cui, C.H. Liu, Z.X. Yu, Angew. Chem. Int. Ed. 57 (2018) 15544–15548.
[84] S.K. Thompson, T.R. Hoye, J. Am. Chem. Soc. 141 (2019) 19575–19580.
[85] Q. Xu, T.R. Hoye, Angew. Chem. Int. Ed. 61 (2022) e202207510.
[86] N. Kraemer, R.R. Naredla, T.R. Hoye, Org. Lett. 24 (2022) 2327–2331.