ORGANIC CHEMISTRY FRONTIERS

RESEARCH ARTICLE

View Article Online
View Journal

Cite this: DOI: 10.1039/d5qo00355e

Enantioselective C–H amidation of sulfondiimines for the synthesis of 1,2,4-benzothiadiazine-1-imines under cobalt catalysis†

Ayami Murata,[a,b] Tomonori Endo,[b] Yuki Hirata,[a,b] Kosuke Higashida,[b] Tatsuhiko Yoshino *[b] and Shigeki Matsunaga *[a,b]

Received 20th February 2025,
Accepted 3rd April 2025

DOI: 10.1039/d5qo00355e

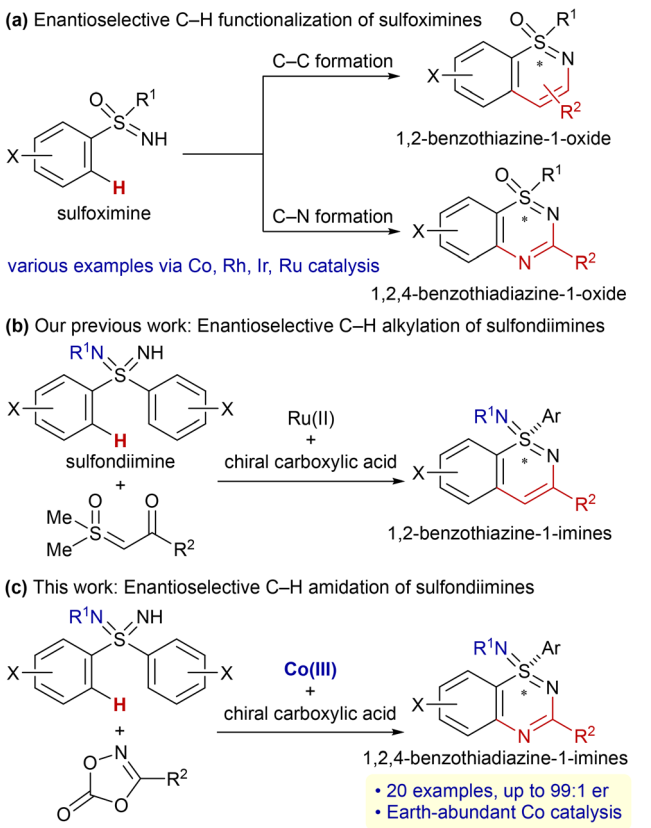
rsc.li/frontiers-organic

In comparison to the notable recent progress in the derivatization of sulfoximines *via* directed C–H activation, the C–H activation/functionalization of sulfondiimines is underdeveloped. Here, we report C–H amidation/cyclization reactions of sulfondiimines with dioxazolones catalyzed by the combination of a cobalt(III) catalyst and a pseudo C_2-symmetric chiral carboxylic acid, leading to the formation of unprecedented 1,2,4-benzothiadiazine-1-imine structures in high enantioselectivity.

Introduction

Sulfur-containing scaffolds, such as sulfones, sulfoxides, and sulfonamides, are fundamental and important motifs in organic chemistry and related research fields.[1] Sulfoximines, *i.e.*, the mono-aza-analogues of sulfones, are less common than the related hexavalent sulfur compounds, but have recently attracted great attention, particularly in medicinal chemistry.[2] This surge in interest has led to the development of synthetic and derivatization methods for sulfoximines; in particular, transition-metal-catalyzed directed C–H functionalization reactions have been examined for the derivatization of sulfoximines.[3–5] Sulfoximines and sulfoximine derivatives that feature different carbon substituents contain a chiral sulfur center, and their stereochemistry can potentially influence their biological properties,[6] which has motivated the investigation of enantioselective methods for the C–H functionalization of sulfoximines (Scheme 1a). Since the pioneering work by Li[5a] and Cramer[5b] using a chiral $Cp^xRh(III)$ catalyst, several catalytic systems have enabled the desymmetrization of diaryl sulfoximines and kinetic resolution to provide chiral 1,2-benzothiazine-1-oxides and 1,2,4-benzothiadiazine-1-oxides in an enantioselective manner.[5]

In contrast to the rapid maturation of the directed C–H functionalization of sulfoximines, sulfondiimines have attracted less attention, despite the fact that they have an additional substituent that increases the structural diversity and provides new potential sites for interaction with biological target molecules.[7,8] In 2019, Bolm and co-workers reported



Scheme 1 Enantioselective directed C–H functionalization of sulfoximines and sulfondiimines.

[a]*Faculty of Pharmaceutical Sciences, Hokkaido University, Sapporo 060-0812, Japan*
[b]*Department of Chemistry, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan. E-mail: yoshino.tatsuhiko.5j@kyoto-u.ac.jp, matsunaga.shigeki.5x@kyoto-u.ac.jp*

†Electronic supplementary information (ESI) available. CCDC 2423806. For ESI and crystallographic data in CIF or other electronic format see DOI: https://doi.org/10.1039/d5qo00355e

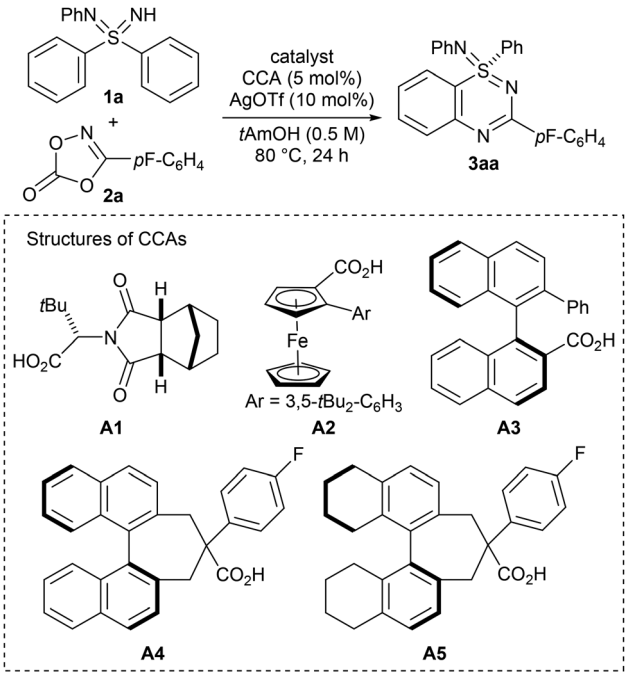
C–H alkylation/cyclization reactions catalyzed by Rh(III) complexes.[9] More recently, our group has reported that the combination of a Ru(II) catalyst and a chiral carboxylic acid enables enantioselective C–H alkylation reactions to provide 1,2-benzothiazine-1-imines in high enantioselectivity (Scheme 1b).[10] Nevertheless, no further studies on the directed C–H functionalization of sulfondiimines have been reported. To expand the chemical space of readily available chiral sulfur-containing structures for medicinal chemistry and other biological studies, we envisioned the extension of our chiral-carboxylic-acid-assisted enantioselective C–H activation/functionalization strategy[11,12] to the synthesis of novel chiral scaffolds from sulfondiimines. Here, we report enantioselective C–H amidation and cyclization reactions of sulfondiimines to furnish 1,2,4-benzothiadiazine-1-imines using a Co(III) catalyst[13] and a chiral carboxylic acid (Scheme 1c). Although the presence of two nitrogen atoms that can potentially act as a directing group in a sulfondiimine makes the stereochemical course of the C–H activation more complicated, the optimal catalytic system achieved high enantioselectivity (up to 99 : 1 er).

Results and discussion

We began our study with an examination of the reaction conditions based on our previous results in the enantioselective C–H amidation of sulfoximines with dioxazolones.[5g] Gratifyingly, the desired C–H amidation/cyclization reaction proceeded to afford a 1,2,4-benzothiadiazine-1-imine using a catalytic amount of Cp*Co(CO)I_2, AgOTf, and a carboxylic acid in *t*AmOH at 80 °C. No C–H amidation product without cyclization was observed at this reaction temperature. We then evaluated several chiral carboxylic acids (CCAs; **A1–A5**) that have previously been investigated in our group[5g,14] under the optimized reaction conditions with sulfondiimine **1a** and dioxazolone **2a** as model substrates (Table 1, entries 1–5). While amino acid derivative **A1**,[14b] ferrocene carboxylic acid **A2**,[14c] and C_1-symmetric binaphthyl carboxylic acid **A3**[14a] resulted in low enantioselectivity (entries 1–3), pseudo C_2-symmetric binaphthyl carboxylic acid **A4**[14d] exhibited good reactivity and enantioselectivity (entry 4). Changing the binaphthyl backbone of **A4** to a partially reduced H_8-binaphthyl structure (**A5**)[5g] further enhanced the reactivity and selectivity, and the desired product was finally obtained in almost quantitative yield and 97 : 3 er (entry 5). The absolute configuration of **3aa** was determined to be *S* by single crystal X-ray diffraction analysis (CCDC 2423806†). With the optimal CCA **A5** in hand, other related piano-stool d^6 metal catalysts, *i.e.*, [Cp*$RhCl_2$]$_2$, [Cp*$IrCl_2$]$_2$, and [Ru(*p*-cymene)Cl_2]$_2$, were also investigated (entries 6–8), but none improved the results relative to Cp*Co(CO)I_2. The combination of a relatively small cobalt catalyst with **A5** was essential for the high enantioselectivity.

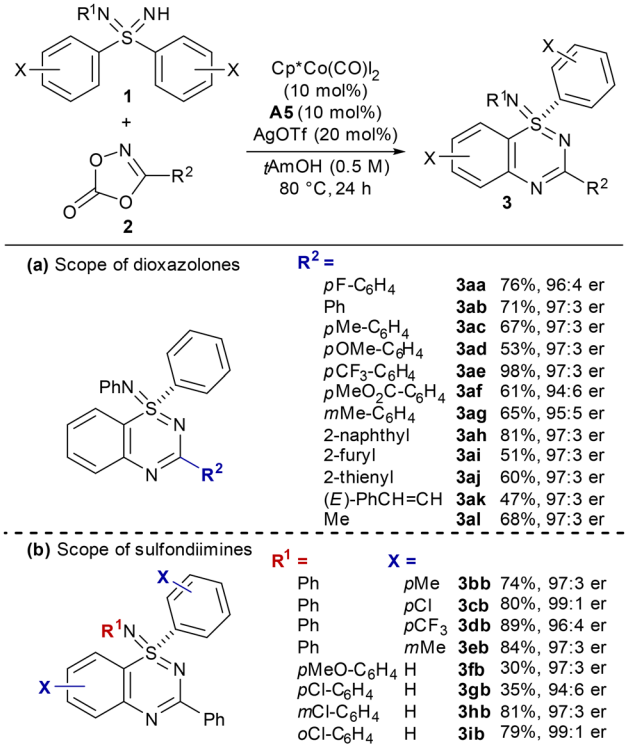
We investigated the substrate scope using the combination of Cp*Co(CO)I_2 and **A5** as the catalyst (Scheme 2). To obtain reproducible results for various substrates, including less reactive ones, we used 10 mol% catalyst under the optimized conditions. We first examined the effects of the structure of dioxazolone **2** (Scheme 2a). A series of *para*-substituted aromatic dioxazolones as well as a *meta*-methyl substituted one resulted in moderate to good product yields with high enantioselectivity (**3aa–3ag**; 94 : 6 to 97 : 3 er), except that a *para*-cyano-substituted dioxazolone exhibited very low reactivity (<20%; not shown in Scheme 2) probably due to the competitive coordination of the cyano group. The extended and heteroaryl group substituents (2-naphthyl, 2-furyl, and 2-thienyl) were well tolerated (**3ah–3aj**; 97 : 3 er). An alkenyl dioxazolone exhibited slightly lower reactivity but furnished the product in high enantioselectivity (**3ak**; 97 : 3 er). We also examined a methyl-substituted dioxazolone, which gratifyingly provided the corresponding product (**3al**) in good yield and selectivity. Next, we investigated the scope of sulfondiimines (Scheme 2b). The introduction of *para*- and *meta*-substituents at the diaryl

Table 1 Effects of chiral carboxylic acids (CCAs) and metal catalysts under the optimized conditions[a]



Entry	CCA	Catalyst (mol%)	%yield[b]	er[c]
1	**A1**	Cp*Co(CO)I_2 (5)	47	41 : 59
2	**A2**	Cp*Co(CO)I_2 (5)	27	69 : 31
3	**A3**	Cp*Co(CO)I_2 (5)	24	67 : 33
4	**A4**	Cp*Co(CO)I_2 (5)	82	92 : 8
5	**A5**	Cp*Co(CO)I_2 (5)	>95	97 : 3
6	**A5**	[Cp*$RhCl_2$]$_2$ (2.5)	64	72 : 28
7	**A5**	[Cp*$IrCl_2$]$_2$ (2.5)	2	84 : 16
8	**A5**	[Ru(*p*-cymene)Cl_2]$_2$ (2.5)	1	80 : 20

[a] Reaction conditions: **1a** (0.060 mmol), **2a** (0.050 mmol), catalyst, CCA (2.5 μmol, 5 mol%), and AgOTf (5.0 μmol, 10 mol%) in *t*AmOH (0.1 mL) at 80 °C for 24 h. [b] Determined by ^{19}F NMR analysis of the crude reaction mixture using $PhCF_3$ as the internal standard. [c] Determined by chiral HPLC analysis.



Scheme 2 Substrate scope. Reaction conditions: **1** (0.24 mmol), **2** (0.20 mmol), $Cp^*Co(CO)I_2$ (0.02 mmol, 10 mol%), **A5** (0.02 mmol, 10 mol%), and AgOTf (0.04 mol, 20 mol%) in *t*AmOH (0.4 mL) at 80 °C for 24 h.

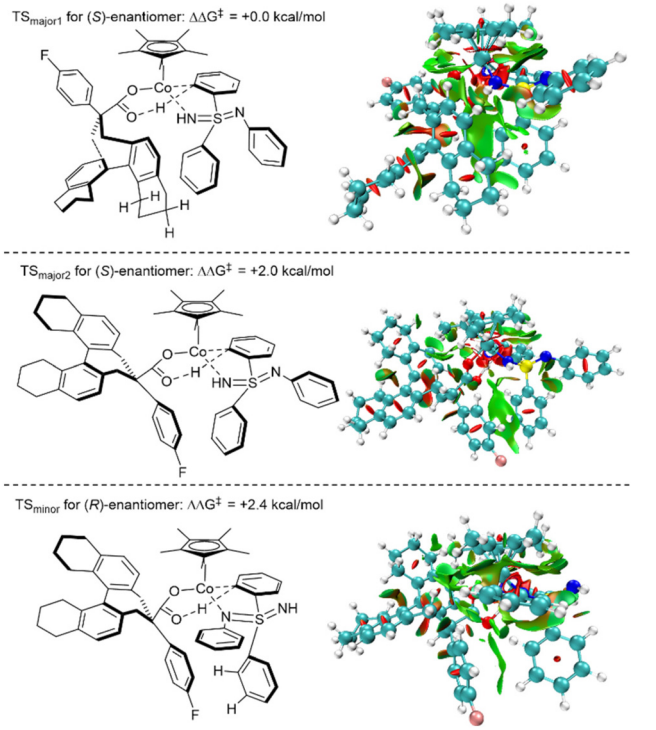


Fig. 1 Transition-state structures and relative Gibbs energies for C–H bond cleavage (left) and non-covalent interaction plots (right) calculated at the M06/def2-TZVPP+SMD(*t*BuOH)//M06L/def2-SVP level of theory.[17–20] The NCI plots were generated with Multiwfn 3.7[21] and visualized by VMD 1.9.4[22] (isosurface = 0.5; color scale from −0.04 to 0.02).

moieties did not interfere with the desired reactions, leading to products in sufficient yield and high enantioselectivity (**3bb–3eb**; 74–89%, 96 : 4–99 : 1 er). Several sulfondiimines with a different aromatic substituent at the nitrogen moiety were also applicable (**3fb–3ib**), although the introduction of a *para*-substituent decreased the reactivity (**3fb** and **3gb**).

To elucidate the origin of the high enantioselectivity achieved using the optimal chiral carboxylic acid (**A5**), we performed DFT calculations on the transition states for the C–H activation step[15] of **1a**, which is generally considered to be the enantio-determining step in chiral-carboxylate-assisted desymmetrization reactions. The sulfondiimine (**1a**) has two coordinating nitrogen atoms, both of which can potentially act as the directing group (DG) for C–H activation. Thus, we carefully performed conformational searches based on several different initial structures to obtain relevant transition states (for details, see the ESI†). We found two transition states for the major (*S*)-product (TS_{major1} and TS_{major2}) and one for the minor (*R*)-product (TS_{minor}) to be energetically feasible (Fig. 1, left). Among these, TS_{major1} was the most stable structure; the energies of TS_{major2} and TS_{minor} are +2.0 kcal mol^{-1} and +2.4 kcal mol^{-1} higher, respectively, which is in reasonably good agreement with the experimental results. The NH moiety acts as the DG in TS_{major1} and TS_{major2}, while the NPh moiety acts as the DG in TS_{minor} (for other energetically higher transition states, see the ESI†), which indicates that both nitrogen atoms function competitively as DGs, and that the pathway is controlled by the carboxylate ligand. Additionally, a non-covalent interaction (NCI) plot[16] was produced to visualize the weak interactions contributing to the high enantioselectivity (Fig. 1, right). TS_{major1} involves π–π and C–H/π interactions between the H_8-binaphthyl moiety of **A5** and the phenyl group of **1a**, and TS_{major2} involves π–π interactions around the α-aryl group of **A5**. On the other hand, TS_{minor} shows only minor C–H/π interactions between the α-aryl group of **A5** and the phenyl group of **1a**. These DFT calculations suggest that the high selectivity with **A5** might be enhanced by the weak π–π and C–H/π interactions in TS_{major1}. The improvement of the selectivity upon changing the binaphthyl to the H_8-binaphthyl backbone (Table 1, **A4** *vs.* **A5**) might be due to the slight enhancement of such interactions by the increased dihedral angle of the backbone of **A5**.

Conclusions

In summary, we have developed enantioselective C–H amidation/cyclization reactions of sulfondiimines with dioxazolones using an earth-abundant and readily available cobalt catalyst and a chiral carboxylic acid. This catalytic transformation enables convenient and highly enantioselective access to unprecedented chiral 1,2,4-benzothiadiazine-1-imine derivatives,

which would further facilitate biological and medicinal research on chiral-sulfur-containing heterocyclic compounds.

Author contributions

A.M. and T.E. performed the experiments and analyzed the data. A.M. and Y.H. performed the DFT calculations. A.M. and K.H. performed SC-XRD analysis. A.M., T.E., Y.H., and T.Y. prepared, reviewed, and edited the ESI.† T.Y. and S.M. conceptualized and supervised the project. Y.H., K.H., T.Y., and S.M. contributed to the preparation of the manuscript and all authors contributed to reviewing and editing the manuscript.

Data availability

A part of the data supporting this article have been included as part of the ESI.† Crystallographic data for **3aa** has been deposited at the CCDC under deposition number 2423806.†

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Y. H. thanks the JSPS for the Fellowships for Young Scientists program. The authors thank the group of Prof. Dr Hideki Yorimitsu at Kyoto University for their support with the HRMS measurements. This work was supported in part by JSPS KAKENHI grants JP21K05046 (T. Y.), JP23KJ0069 (Y. H.), JP23H00293 (S. M.), and JP24H02209 (S. M.) in Transformative Research Areas (A) JP24A202 Integrated Science of Synthesis by Chemical Structure Reprogramming (SReP).

References

1 (*a*) E. A. Ilardi, E. Vitaku and J. T. Njardarson, Data-Mining for Sulfur and Fluorine: An Evaluation of Pharmaceuticals To Reveal Opportunities for Drug Design and Discovery, *J. Med. Chem.*, 2014, **57**, 2832–2842; (*b*) C. Zhao, K. P. Rakesh, L. Ravidar, W.-Y. Fang and H.-L. Qin, Pharmaceutical and medicinal significance of sulfur (S^{VI})-Containing motifs for drug discovery: A critical review, *Eur. J. Med. Chem.*, 2019, **162**, 679–734.

2 (*a*) V. Bizet, C. M. M. Hendriks and C. Bolm, Sulfur imidations: access to sulfimides and sulfoximines, *Chem. Soc. Rev.*, 2015, **44**, 3378–3390; (*b*) M. Frings, C. Bolm, A. Blum and C. Gnamm, Sulfoximines from a Medicinal Chemist's Perspective: Physicochemical and in vitro Parameters Relevant for Drug Discovery, *Eur. J. Med. Chem.*, 2017, **126**, 225–245; (*c*) J. A. Bull, L. Degennaro and R. Luisi, Straightforward Strategies for the Preparation of NH-Sulfoximines: A Serendipitous Story, *Synlett*, 2017, 2525–2538; (*d*) P. Mäder and L. Kattner, Sulfoximines as Rising Stars in Modern Drug Discovery? Current Status and Perspective on an Emerging Functional Group in Medicinal Chemistry, *J. Med. Chem.*, 2020, **63**, 14243–14275; (*e*) Y. Han, K. Xing, J. Zhang, T. Tong, Y. Shi, H. Cao, H. Yu, Y. Zhang, D. Liu and L. Zhao, Application of sulfoximines in medicinal chemistry from 2013 to 2020, *Eur. J. Med. Chem.*, 2021, **209**, 112885; (*f*) M. Andresini, A. Tota, L. Degennaro, J. A. Bull and R. Luisi, Synthesis and transformations of NH-sulfoximines, *Chem. – Eur. J.*, 2021, **27**, 17293–17321; (*g*) U. Lücking, New Opportunities for the Utilization of the Sulfoximine Group in Medicinal Chemistry from the Drug Designer's Perspective, *Chem. – Eur. J.*, 2022, **28**, e202201993; (*h*) M.-K. Wei and M. C. Willis, The Catalytic Synthesis of Aza-Sulfur Functional Groups, *Synthesis*, 2025, 1429–1440.

3 (*a*) P. Ghosh, B. Ganguly and S. Das, N–H and C–H Functionalization of Sulfoximine: Recent Advancement and Prospects, *Asian J. Org. Chem.*, 2020, **9**, 2035–2082; (*b*) B. Wang, X. Liang and Q. Zeng, Recent Advances in the Synthesis of Cyclic Sulfoximines via C–H Bond Activation, *Molecules*, 2023, **28**, 1367.

4 For selected examples of non-enantioselective reactions, see: (*a*) W. Dong, L. Wang, K. Parthasarathy, F. Pan and C. Bolm, Rhodium-Catalyzed Oxidative Annulation of Sulfoximines and Alkynes as an Approach to 1,2-Benzothiazines, *Angew. Chem., Int. Ed.*, 2013, **52**, 11573–11576; (*b*) D.-G. Yu, F. de Azambuja and F. Glorius, α-MsO/TsO/Cl Ketones as Oxidized Alkyne Equivalents: Redox-Neutral Rhodium(III)-Catalyzed C–H Activation for the Synthesis of N-Heterocycles, *Angew. Chem., Int. Ed.*, 2014, **53**, 2754–2758; (*c*) R. K. Chinnagolla, A. Vijeta and M. Jeganmohan, Ruthenium- and palladium-catalyzed consecutive coupling and cyclization of aromatic sulfoximines with phenylboronic acids: an efficient route to dibenzothiazines, *Chem. Commun.*, 2015, **51**, 12992–12995; (*d*) Y. Cheng and C. Bolm, Regioselective Syntheses of 1,2-Benzothiazines by Rhodium-Catalyzed Annulation Reactions, *Angew. Chem., Int. Ed.*, 2015, **54**, 12349–12352; (*e*) J. Huang, Y. Huang, T. Wang, Q. Huang, Z. Wang and Z. Chen, Microwave-Assisted Cp^*Co^{III}-Catalyzed C–H Activation/Double C–N Bond Formation Reactions to Thiadiazine 1-Oxides, *Org. Lett.*, 2017, **19**, 1128–1131; (*f*) Y. N. Aher, D. M. Lade and A. B. Pawar, Cp*Ir(III)-catalyzed C–H/N–H functionalization of sulfoximines for the synthesis of 1,2-benzothiazines at room temperature, *Chem. Commun.*, 2018, **54**, 6288–6291; (*g*) H. Xie, J. Lan, J. Gui, F. Chen, H. Jiang and W. Zeng, Ru(II)–Catalyzed Coupling–Cyclization of Sulfoximines with *alpha*–Carbonyl Sulfoxonium Ylides as an Approach to 1,2–Benzothiazines, *Adv. Synth. Catal.*, 2018, **360**, 3534–3543; (*h*) S. Li, L. Liu, R. Wang, Y. Yang, J. Li and J. Wei, Palladium-Catalyzed Oxidative Annulation of Sulfoximines and Arynes by C–H Functionalization as an Approach to Dibenzothiazines, *Org. Lett.*, 2020, **22**, 7470–7474; (*i*) P. Shi, Y. Tu, C. Wang,

D. Kong, D. Ma and C. Bolm, Synthesis of Benzothiadiazine-1-oxides by Rhodium-Catalyzed C–H Amidation/Cyclization, *Org. Lett.*, 2020, **22**, 8842–8845.

5 For enantioselective reactions, see: (*a*) B. Shen, B. Wan and X. Li, Enantiodivergent Desymmetrization in the Rhodium (III)-Catalyzed Annulation of Sulfoximines with Diazo Compounds, *Angew. Chem., Int. Ed.*, 2018, **57**, 15534–15538; (*b*) Y. Sun and N. Cramer, Enantioselective Synthesis of Chiral-at-Sulfur 1,2-Benzothiazines by Cp^xRh^{III}-Catalyzed C–H Functionalization of Sulfoximines, *Angew. Chem., Int. Ed.*, 2018, **57**, 15539–15543; (*c*) M. Brauns and N. Cramer, Efficient Kinetic Resolution of Sulfur-Stereogenic Sulfoximines by Exploiting Cp^XRh^{III}-Catalyzed C–H Functionalization, *Angew. Chem., Int. Ed.*, 2019, **58**, 8902–8906; (*d*) T. Zhou, P.-F. Qian, J.-Y. Li, Y.-B. Zhou, H.-C. Li, H.-Y. Chen and B.-F. Shi, Efficient Synthesis of Sulfur-Stereogenic Sulfoximines via Ru(II)-Catalyzed Enantioselective C–H Functionalization Enabled by Chiral Carboxylic Acid, *J. Am. Chem. Soc.*, 2021, **143**, 6810–6816; (*e*) K. Mukherjee, N. Grimblat, S. Sau, K. Ghosh, M. Shankar, V. Gandon and A. K. Sahoo, Kinetic resolution of sulfur-stereogenic sulfoximines by Pd(II)-MPAA catalyzed C–H arylation and olefination, *Chem. Sci.*, 2021, **12**, 14863–14870; (*f*) J.-Y. Li, P.-P. Xie, T. Zhou, P.-F. Qian, Y.-B. Zhou, H.-C. Li, X. Hong and B.-F. Shi, Ir(III)-Catalyzed Asymmetric C–H Activation/Annulation of Sulfoximines Assisted by the Hydrogen-Bonding Interaction, *ACS Catal.*, 2022, **12**, 9083–9091; (*g*) Y. Hirata, D. Sekine, Y. Kato, L. Lin, M. Kojima, T. Yoshino and S. Matsunaga, Cobalt(III)/Chiral Carboxylic Acid-Catalyzed Enantioselective Synthesis of Benzothiadiazine-1-oxides via C–H Activation, *Angew. Chem., Int. Ed.*, 2022, **61**, e202205341; (*h*) Y.-B. Zhou, T. Zhou, P.-F. Qian, J.-Y. Li and B.-F. Shi, Synthesis of Sulfur-Stereogenic Sulfoximines via Co(III)/Chiral Carboxylic Acid-Catalyzed Enantioselective C–H Amidation, *ACS Catal.*, 2022, **12**, 9806–9811; (*i*) L.-T. Huang, Y. Hirata, Y. Kato, L. Lin, M. Kojima, T. Yoshino and S. Matsunaga, Ruthenium(II)/Chiral Carboxylic Acid Catalyzed Enantioselective C–H Functionalization of Sulfoximines, *Synthesis*, 2022, 4703–4710; (*j*) P.-F. Qian, T. Zhou, J.-Y. Li, Y.-B. Zhou and B.-F. Shi, Ru(II)/Chiral Carboxylic Acid-Catalyzed Asymmetric [4 + 3] Annulation of Sulfoximines with α,β-Unsaturated Ketones, *ACS Catal.*, 2022, **12**, 13876–13883; (*k*) S.-Y. Song, X. Zhou, Z. Ke and S. Xu, Synthesis of Chiral Sulfoximines via Iridium-Catalyzed Regio- and Enantioselective C–H Borylation: A Remarkable Sidearm Effect of Ligand, *Angew. Chem., Int. Ed.*, 2023, **62**, e202217130; (*l*) G. Zhou, T. Zhou, A.-L. Jiang, P.-F. Qian, J.-Y. Li, B.-Y. Jiang, Z.-J. Chen and B.-F. Shi, Electrooxidative Rhodium(III)/Chiral Carboxylic Acid-Catalyzed Enantioselective C–H Annulation of Sulfoximines with Alkynes, *Angew. Chem., Int. Ed.*, 2024, **63**, e202319871; (*m*) Q. Song, W. Wu, W. Chen, H. Gao, Z. Zhou, Z. Zeng and W. Yi, α-Chloroketones enabled Rh(III)-catalyzed enantioselective C–H [4 + 2] annulation of sulfoximines under mild and redox-neutral conditions, *Green Synth. Catal.*, DOI: 10.1016/j.gresc.2024.05.004; (*n*) H. Liu, J.-J. Jiang and J. Wang, Catalytic Asymmetric C–H Activation/Cyclization of Sulfoximines with Sulfoxonium Ylides by a Chiral η^6-Benzene Ruthenium(II) Catalyst, *ACS Catal.*, 2024, **14**, 17398–17404; (*o*) Y. Xiong, M. Suleman, S. Xu and Z. Chen, Chiral Cp^xRh^{III}-catalyzed enantioselective C–H annulation to access fused tricyclic sulfur-stereogenic and medium-sized aza-heterocycles, *Org. Chem. Front.*, 2025, **12**, 614–622.

6 (*a*) R. Bentley, Role of sulfur chirality in the chemical processes of biology, *Chem. Soc. Rev.*, 2005, **34**, 609–624; (*b*) W. Liu, J. Ke and C. He, Sulfur stereogenic centers in transition-metal-catalyzed asymmetric C–H functionalization: generation and utilization, *Chem. Sci.*, 2021, **12**, 10972–10984; (*c*) P.-F. Qian, J.-Y. Li, T. Zhou and B.-F. Shi, Synthesis of *P*- and *S*-Stereogenic Compounds via Enantioselective C–H Functionalization, *Synthesis*, 2022, 4784–4794; (*d*) X. Zhang, F. Wang and C.-H. Tan, Asymmetric Synthesis of S(IV) and S(VI) Stereogenic Centers, *JACS Au*, 2023, **3**, 700–714.

7 M. T. Passia, J.-H. Schöbel and C. Bolm, Sulfondiimines: synthesis, derivatisation and application, *Chem. Soc. Rev.*, 2022, **51**, 4890–4901.

8 For selected recent synthetic methods of sulfondiimines, see: (*a*) T. Yoshimura, H. Ishikawa, T. Fujie, E. Takata, R. Miyatake, H. Kita and E. Tsukurimichi, Convenient Preparation of N-Monosubstituted *S*,*S*-Diarylsulfodiimides Using Fluoro-λ^6-sulfanenitriles, *Synthesis*, 2008, 1835–1840; (*b*) M. Candy, C. Guyon, S. Mersmann, J.-R. Chen and C. Bolm, Synthesis of Sulfondiimines by *N*-Chlorosuccinimide-Mediated Oxidative Imination of Sulfiliminium Salts, *Angew. Chem., Int. Ed.*, 2012, **51**, 4440–4443; (*c*) Z.-X. Zhang, T. Q. Davies and M. C. Willis, Modular Sulfondiimine Synthesis Using a Stable Sulfinylamine Reagent, *J. Am. Chem. Soc.*, 2019, **141**, 13022–13027; (*d*) M. Ding, C. Bell and M. C. Willis, The Modular Synthesis of Sulfondiimidoyl Fluorides and their Application to Sulfondiimidamide and sulfondiimine synthesis, *Angew. Chem., Int. Ed.*, 2024, **63**, e202409240.

9 R. A. Bohmann, J.-H. Schöbel, Y. Unoh, M. Miura and C. Bolm, Regioselective Syntheses of 1,2−Benzothiazine 1−Imines by Rhodium−Catalyzed Annulation Reactions of Sulfondiimines, *Adv. Synth. Catal.*, 2019, **361**, 2000–2003.

10 L.-T. Huang, Y. Kitakawa, K. Yamada, F. Kamiyama, M. Kojima, T. Yoshino and S. Matsunaga, Enantioselective Synthesis of 1,2-Benzothiazine 1-Imines via RuII/Chiral Carboxylic Acid-Catalyzed C–H Alkylation/Cyclization, *Angew. Chem., Int. Ed.*, 2023, **62**, e202305480.

11 (*a*) T. Yoshino and S. Matsunaga, Chiral Carboxylic Acid Assisted Enantioselective C–H Activation with Achiral Cp^xM^{III} (M = Co, Rh, Ir) Catalysts, *ACS Catal.*, 2021, **11**, 6455–6466; (*b*) T. Yoshino, Enantioselective C–H Functionalization Using High-Valent Group 9 Metal Catalysts, *Bull. Chem. Soc. Jpn.*, 2022, **95**, 1280–1288.

12 For related reviews on enantioselective C–H activation/functionalization, see: (*a*) Q. Shao, K. Wu, Z. Zhuang, S. Qian and J.-Q. Yu, From $Pd(OAc)_2$ to Chiral Catalysts:

The Discovery and Development of Bifunctional Mono-N-Protected Amino Acid Ligands for Diverse C–H Functionalization Reactions, *Acc. Chem. Res.*, 2020, **53**, 833–851; (*b*) T. Yoshino, S. Satake and S. Matsunaga, Diverse Approaches for Enantioselective C–H Functionalization Reactions Using Group 9 Cp^xM^{III} Catalysts, *Chem. – Eur. J.*, 2020, **26**, 7346–7357; (*c*) J. Mas-Roselló, A. G. Herraiz, B. Audic, A. Laverny and N. Cramer, Chiral Cyclopentadienyl Ligands: Design, Syntheses, and Applications in Asymmetric Catalysis, *Angew. Chem., Int. Ed.*, 2021, **60**, 13198–13224; (*d*) H. Liang and J. Wang, Enantioselective C–H Bond Functionalization Involving Arene Ruthenium(II) Catalysis, *Chem. – Eur. J.*, 2023, **29**, e202202461; (*e*) E. L. Lucas, N. Y. S. Lam, Z. Zhuang, H. S. S. Chan, D. A. Strassfeld and J.-Q. Yu, Palladium-Catalyzed Enantioselective β-C(sp^3)–H Activation Reactions of Aliphatic Acids: A Retrosynthetic Surrogate for Enolate Alkylation and Conjugate Addition, *Acc. Chem. Res.*, 2022, **55**, 537–550; (*f*) P.-F. Qian, J.-Y. Li, Y.-B. Zhou, T. Zhou and B.-F. Shi, Half-Sandwich d^6-Metal (Co^{III}, Rh^{III}, Ir^{III}, Ru^{II})-Catalyzed Enantioselective C–H Activation, *SynOpen*, 2023, **7**, 466–485; (*g*) B.-B. Gou, W.-J. Shen, Q. Gu and S.-L. You, Synthesis of Chiral Cyclopentadienyl Rhodium Complexes and Their Application in Enantioselective C–H Functionalization Reactions, *Synlett*, 2025, **36**, 651–660.

13 For selected reviews on high-valent cobalt-catalyzed C–H activation/functionalization reactions, see: (*a*) M. Moselage, J. Li and L. Ackermann, Cobalt-Catalyzed C–H Activation, *ACS Catal.*, 2016, **6**, 498–525; (*b*) T. Yoshino and S. Matsunaga, (Pentamethylcyclopentadienyl)cobalt(III)-Catalyzed C–H Bond Functionalization: From Discovery to Unique Reactivity and Selectivity, *Adv. Synth. Catal.*, 2017, **359**, 1245–1262; (*c*) R. Mei, U. Dhawa, R. C. Samanta, W. Ma, J. Wencel-Delord and L. Ackermann, Cobalt-Catalyzed Oxidative C–H Activation: Strategies and Concepts, *ChemSusChem*, 2020, **13**, 3306–3356; (*d*) B. Garai, A. Das, D. V. Kumar and B. Sundararaju, Enantioselective C–H bond functionalization under Co(III)-catalysis, *Chem. Commun.*, 2024, **60**, 3354–3369.

14 (*a*) L. Lin, S. Fukagawa, D. Sekine, E. Tomita, T. Yoshino and S. Matsunaga, Chiral Carboxylic Acid Enabled Achiral Rhodium(III)–Catalyzed Enantioselective C–H Functionalization, *Angew. Chem., Int. Ed.*, 2018, **57**, 12048–12052; (*b*) S. Fukagawa, Y. Kato, R. Tanaka, M. Kojima, T. Yoshino and S. Matsunaga, Enantioselective C(sp^3)–H Amidation of Thioamides Catalyzed by a $Cobalt^{III}$/Chiral Carboxylic Acid Hybrid System, *Angew. Chem., Int. Ed.*, 2019, **58**, 1153–1157; (*c*) D. Sekine, K. Ikeda, S. Fukagawa, M. Kojima, T. Yoshino and S. Matsunaga, Chiral 2-Aryl Ferrocene Carboxylic Acids for the Catalytic Asymmetric C(sp^3)–H Activation of Thioamides, *Organometallics*, 2019, **38**, 3921–3926; (*d*) Y. Kato, L. Lin, M. Kojima, T. Yoshino and S. Matsunaga, Development of Pseudo-C_2-symmetric Chiral Binaphthyl Monocarboxylic Acids for Enantioselective C(sp^3)–H functionalization Reactions under Rh(III) Catalysis, *ACS Catal.*, 2021, **11**, 4271–4277.

15 (*a*) L. Ackermann, Carboxylate-Assisted Transition-Metal-Catalyzed C–H Bond Functionalizations: Mechanism and Scope, *Chem. Rev.*, 2011, **111**, 1315–1345; (*b*) D. L. Davies, S. A. Macgregor and C. L. McMullin, Computational Studies of Carboxylate-Assisted C–H Activation and Functionalization at Group 8–10 Transition Metal Centers, *Chem. Rev.*, 2017, **117**, 8649–8709.

16 E. R. Johnson, S. Keinan, P. Mori-Sánchez, J. Contreras-García, A. J. Cohen and W. Yang, Revealing Noncovalent Interactions, *J. Am. Chem. Soc.*, 2010, **132**, 6498–6506.

17 (*a*) Y. Zhao and D. G. Truhlar, A new local density functional for main-group thermochemistry, transition metal bonding, thermochemical kinetics, and noncovalent interactions, *J. Chem. Phys.*, 2006, **125**, 194101; (*b*) Y. Zhao and D. G. Truhlar, The M06 suite of density functionals for main group thermochemistry, thermochemical kinetics, noncovalent interactions, excited states, and transition elements: two new functionals and systematic testing of four M06-class functionals and 12 other functionals, *Theor. Chem. Acc.*, 2008, **120**, 215–241.

18 F. Weigend and R. Ahlrichs, Balanced basis sets of split valence, triple zeta valence and quadruple zeta valence quality for H to Rn: Design and assessment of accuracy, *Phys. Chem. Chem. Phys.*, 2005, **7**, 3297–3305.

19 A. V. Marenich, C. J. Cramer and D. G. Truhlar, Universal Solvation Model Based on Solute Electron Density and on a Continuum Model of the Solvent Defined by the Bulk Dielectric Constant and Atomic Surface Tensions, *J. Phys. Chem. B*, 2009, **113**, 6378–6396.

20 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. J. Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin, V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman and D. J. Fox, *All the DFT calculations were performed using Gaussian 16, Revision C.02*, Gaussian, Inc., Wallingford CT, 2016.

21 (*a*) T. Lu and F. Chen, Multiwfn: A Multifunctional Wavefunction Analyzer, *J. Comput. Chem.*, 2012, **33**, 580–592; (*b*) T. Lu, A comprehensive electron wavefunction analysis toolbox for chemists, Multiwfn, *J. Chem. Phys.*, 2024, **161**, 082503.

22 W. Humphrey, A. Dalke and K. Schulten, VMD: Visual Molecular Dynamics, *J. Mol. Graphics*, 1996, **14**, 33–38.

