

Cite this: *Chem. Sci.*, 2023, 14, 3338

All publication charges for this article have been paid for by the Royal Society of Chemistry

Hypervalent iodine-promoted twofold oxidative coupling of amines with amides and thioamides: chemoselective pathway to oxazoles and thiazoles†

Jiang Nan,^{ID}*^a Xin Ren,^a Qiang Yan,^a Shilei Liu,^a Jing Wang,^a Yangmin Ma^a and Michal Szostak^{ID}*^b

Direct functionalization of the C(O)–N amide bond is one of the most high-profile research directions in the last few decades; however oxidative couplings involving amide bonds and functionalization of thioamide C(S)–N analogues remain an unsolved challenge. Herein, a novel hypervalent iodine-induced twofold oxidative coupling of amines with amides and thioamides has been established. The protocol accomplishes divergent C(O)–N and C(S)–N disconnection by the previously unknown Ar–O and Ar–S oxidative coupling and highly chemoselectively assembles the versatile yet synthetically challenging oxazoles and thiazoles. Employing amides instead of thioamides affords an alternative bond cleavage pattern, which is a result of the higher $n_N \rightarrow \pi_{C=S}^*$ conjugation in thioamides. Mechanistic investigations indicate ureas and thioureas generated in the first oxidation as pivotal intermediates to realize the oxidative coupling. These findings open up new avenues for exploring oxidative amide and thioamide bond chemistry in various synthetic contexts.

Received 17th January 2023
Accepted 25th February 2023

DOI: 10.1039/d3sc00301a

rsc.li/chemical-science

Introduction

The amide bond undoubtedly belongs to one of the most inert chemical bonds owing to the intramolecular $n_N \rightarrow \pi_{C=O}^*$ conjugation and high resonance stabilization (Scheme 1a, left).^{1a–h} Notwithstanding that the amide bond is well-recognized as the most stable carboxylic acid derivative, the highly selective C(O)–N activation of amides that enables us to sequentially perform chemical operations has attracted great attention in organic synthesis over the past few decades (Scheme 1a, right).^{2a–g} This is mostly due to the ubiquitous presence of amide bonds in biochemistry, pharmaceuticals, and diverse bulk and fine chemicals as well as their versatility in synthetic settings.^{3a–f} Indeed, amide bond activation has been experiencing major progress by means of carefully controlled steric repulsion, conformational restriction and electronic effects to successfully activate the N–C(O) bond by ground-state-destabilization of amidic resonance (Scheme 1b, left).^{4,5a–d,6,7} This mode of

activation broadly relies upon disrupting $n_N \rightarrow \pi_{C=O}^*$ conjugation to increase negative charge at the nitrogen atom, while this mode should be contrasted with the tremendously important field of electrophilic activation of amides.⁴ The current well-developed reaction types are predominantly restricted to sterically twisted amides⁸ or electronically activated amides⁹ featuring electron-withdrawing groups (EWGs) that facilitate acyl addition or oxidative addition of the C(O)–N bond to a low-valent metal. Comparatively, formamides are much more broadly available than such activated amides; however, there are few examples of the site-specific C(O)–N activation of non-activated formamides (Scheme 1b, right).¹⁰

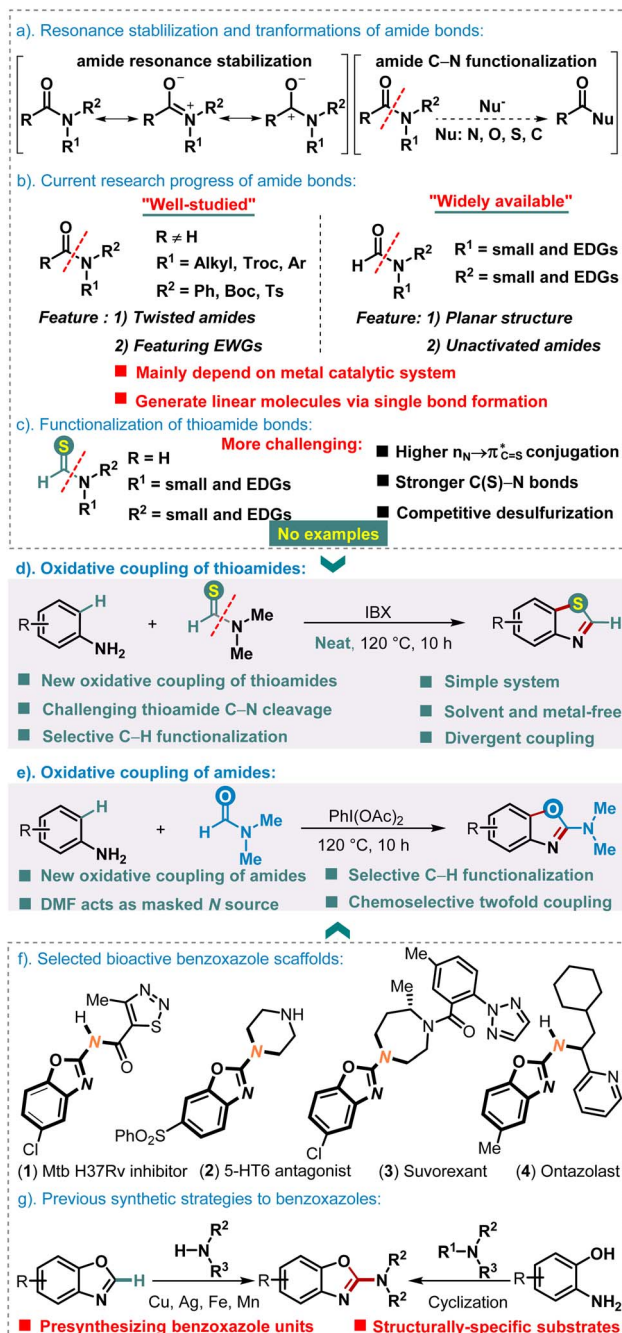
Formamides characterized by planarity and featuring electron-donating groups (EDGs) are not amenable to the ground-state-destabilization pathway. The present amide bond activation has been most successful using metal-catalyzed coupling and only implemented to generate architecturally linear molecules by single bond formation thus far.¹¹

Thioamides, the closest O to S isosteres of amides in the strictest sense, have served as highly valuable motifs to accomplish synthetic processes.¹² With respect to the structural and electronic characteristics, thioamides feature a shorter C=S bond than the analogous C=O bond in amides. The weaker electronegativity of sulfur and the higher $n_N \rightarrow \pi_{C=S}^*$ conjugation provide the higher contribution of the polar resonance form. This results in a stronger C(S)–N bond in thioamides, which together with potential side-reactions, such as

^aThe Youth Innovation Team of Shaanxi Universities, Shaanxi Key Laboratory of Chemical Additives for Industry, College of Chemistry and Chemical Engineering, Shaanxi University of Science and Technology, Xi'an 710021, China. E-mail: nanjiang@sust.edu.cn

^bDepartment of Chemistry, Rutgers University, 73 Warren Street, Newark, New Jersey 07102, USA

† Electronic supplementary information (ESI) available. CCDC 2223988 and 2224291. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d3sc00301a>



Scheme 1 Amide functionalization and context of this work.

desulfurization, electrophilic addition, and cyclization, poses a major challenge to chemoselectively cleave the C(S)–N bond (Scheme 1c).¹³ Indeed, studies on the activation of twisted thioamide bonds are exceedingly scarce, and chemoselective C(S)–N bond activation of non-twisted and non-electronically activated thioamides has not been documented to date.

In continuation of our long-standing interest to discover new modes of activation of amide bonds,⁷ herein, we disclose our findings on novel hypervalent iodine-induced twofold oxidative coupling of amines with amides and thioamides (Scheme 1d and e). Of note, the protocol accomplishes divergent C(O)–N

and C(S)–N disconnection by the previously unknown Ar–O and Ar–S oxidative coupling. The method represents the first example of combining the inert C(O)–N/C(S)–N coupling with C–H functionalization in a single operation, providing a powerful platform to assemble the versatile yet synthetically challenging oxazoles and thiazoles that are common in pharmaceuticals and agrochemicals^{14a,b} but currently lack a practical synthetic route.¹⁵ Employing amides instead of thioamides affords an alternative bond cleavage pattern, which is a result of the higher $n_N \rightarrow \pi_{C=S}^*$ conjugation in thioamides, furnishing C2–NR₂-substituted benzoxazoles (Scheme 1f).¹⁶ This oxidative pathway outperforms the current dominant tactic of decorating the benzoxazole scaffold (Scheme 1g).¹⁷ Overall, these findings open up new avenues for exploring oxidative amide and thioamide bond chemistry in various synthetic contexts.

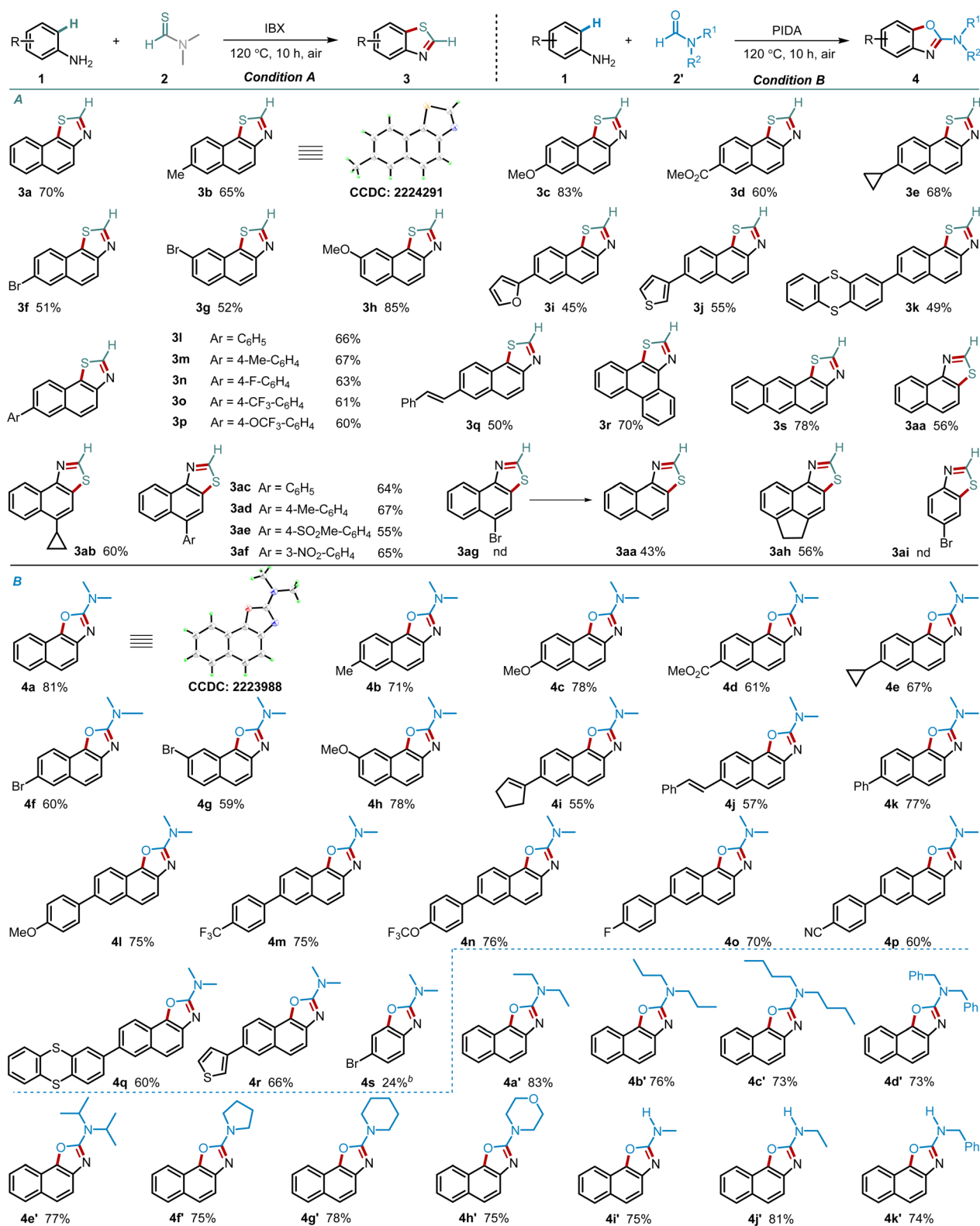
Results and discussion

Initially, we explored the reactivity of commercially available *N,N*-dimethylthioamide **2** with β -naphthylamine **1a** (Table 1). After comprehensive screening of reaction parameters, we were delighted to find that upon treatment with 2-iodoxybenzoic acid (IBX) as an oxidant, these two substrates underwent a formal [3 + 2] cyclization to produce thiazole derivative **3a** in 70% yield under metal-free and solvent-free conditions (entry 1). The reaction accomplished a series of C(S)–N/C–H cleavages and C–N/C–S bond forming events. Control experiments showed that IBX played an indispensable role in simultaneously realizing this novel C(S)–N thioamide conversion with thiazole ring formation in a single operation (entry 2). Other broadly utilized high-valent I³⁺ oxidants, such as PIDA, PIFA or PhIO, were all feasible but afforded lower yields (entries 3–5). Changes in the

Table 1 Optimization of reaction conditions^a

Entry	Variations from the standard conditions	Yield of 3a ^b (%)
1	None	70
2	Without IBX	0
3	PIDA instead of IBX	23
4	PIFA instead of IBX	12
5	PhIO instead of IBX	10
6	At 110 °C	34
7	O ₂ atmosphere	40
8	Reducing loading of IBX to 1.0 equiv.	52
9	Reducing loading of 2 to 2.0 equiv.	45
10	In DCE (0.25 M)	17
11	In 1,4-dioxane (0.25 M)	nd
12	In DMSO (0.25 M)	26

^a Performed on a 0.20 mmol scale. ^b Isolated yields. PIDA = phenyliodine(III) diacetate, PIFA = phenyliodine(III) bis(trifluoroacetate), and PhIO = iodosylbenzene.

Table 2 Substrate scope of synthesizing thiazoles and oxazoles^a

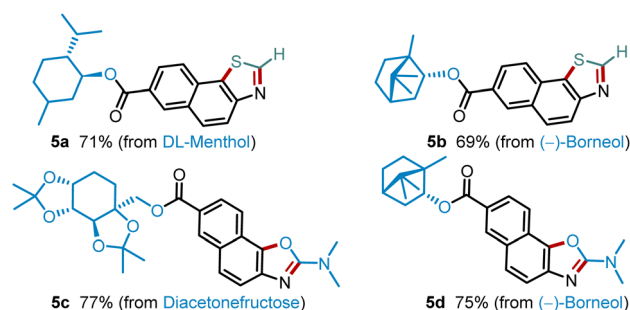
^a Condition A: amine **1** (0.2 mmol), thioamide **2** (1.0 mmol), IBX (0.3 mmol), 120 °C, 10 h, and air. Condition B: amine **1** (0.2 mmol), amide **2'** (5.0 mmol), PIDA (0.3 mmol), 120 °C, 10 h, and air. ^b PIFA instead of PIDA.

reaction temperature (110 °C) or reaction atmosphere were detrimental (entries 6 and 7). Decreasing the amount of IBX or 2 afforded inferior results (entries 8 and 9). Interestingly, employing solvents adversely affected the reaction (entries 10–12). It is noteworthy that solvent-free reactions have recently attracted increasing attention due to low-cost and green chemistry considerations.¹⁸ Most notably, during the screening of all reaction parameters, the side-product **3a'** was not observed, indicating a highly efficient oxidative C(S)–N bond cleavage through breaking $n_N \rightarrow \pi_{C=S}^*$ resonance.

Having identified optimal reaction parameters, we next sought to evaluate the substrate scope of this novel transformation by coupling various naphthylamines with *N,N*-dimethylthioformamide **2** (Table 2). As depicted in Table 2, a range of 2-naphthylamines reacted smoothly with full regioselectivity at the α -site of amine substrates, delivering thiazoles **3a–s** in good yields. The electronically distinct substituents at 6- and 7-positions, such as methyl (**3b**), methoxy (**3c** and **3h**), methoxycarbonyl (**3d**), cyclopropyl (**3e**), bromo (**3f** and **3g**), furyl (**3i**), thienyl (**3j**), thianthrenyl (**3k**), and a series of diverse-substituted arene system (**3l–3p**) moieties, all proved to be competent substrates. The structure of **3b** was unambiguously assigned by X-ray single crystallography. Notably, the high-value but usually challenging in oxidative coupling alkenyl (**3q**) group was retained intact under these conditions, thus providing a versatile handle for downstream modification. Likewise, π -electron-rich phenanthryl- and anthryl-derived thiazoles (**3r–3s**) were equally compatible and prepared in 70% and 78% yields, respectively. Furthermore, the use of 1-naphthylamine to engage in this protocol also furnished the target molecule **3aa** in 56% yield. The naphthyl ring could be diversely decorated with cyclopropyl (**3ab**) or aromatics substituted with alkyl (**3ad**), sulfuryl (**3ae**), or nitro (**3af**) groups. It should be noted that 4-bromo-1-naphthylamine was not tolerated, but delivered the debrominated product **3aa**. However, the readily oxidized dihydro-acenaphthylene unit was well-compatible and generated product **3ah** in 56% yield. At the present stage, the reaction is not compatible with simple anilines (**3ai**) probably because of the more stable aromaticity of than that of naphthylamines.

We next employed *N,N*-dimethylformamide (DMF) as the structurally closest analog of *N,N*-dimethylthioformamide to participate in this novel methodology (Table 2). To our surprise, reacting 2-naphthylamine **1a** with DMF resulted in the formation of NMe₂-substituted naphthyl-fused oxazole **4a**, wherein the alternative bond cleavage pattern occurred chemoselectively. Considering the unique selectivity with DMF to accomplish the synthesis of 2-amino-substituted benzoxazoles by oxidative coupling, we optimized the reaction conditions (details in the ESI†). By slightly tuning the conditions by replacing IBX with PIDA, the target **4a** was isolated in 81% yield, and its structure was unambiguously confirmed by X-ray crystallography.

With the optimized conditions in hand, the scope of this benzoxazole formation was investigated (Table 2). As shown, various naphthylamine counterparts were amenable to this divergent reaction. Specifically, a collection of functionalized naphthylamines, encompassing methyl, methoxy, ester,



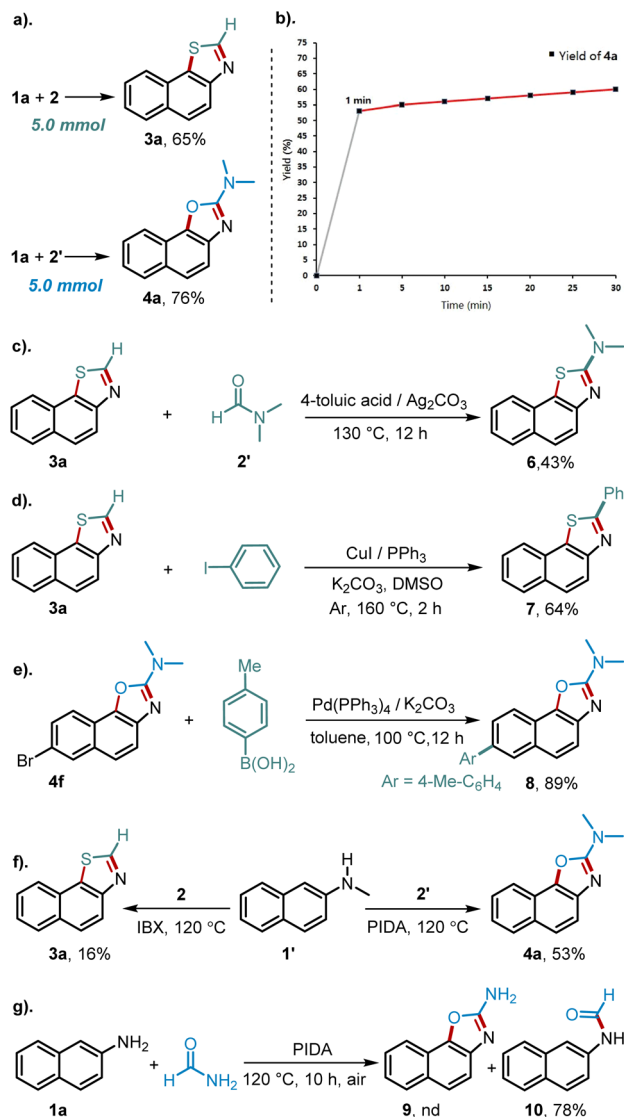
Scheme 2 Further modification of bioactive synthons.

cyclopropyl, and bromo groups, were subjected to this oxidative process to afford the expected products **4b–4h** in 59–81% yields. Importantly, in this variant by-products resulting from C–N dissociation were not observed, indicating the key difference between $n_N \rightarrow \pi_{C=O}^*$ and $n_N \rightarrow \pi_{C=S}^*$ conjugation resonance under oxidative conditions (*vide infra*). Strikingly, the sensitive vinyl fragment (**4i–4j**) was well-compatible. An array of electronically distinct aryl systems (**4k–4p**) and even heterocycles (**4q–4r**) were also feasible while the simple amine behaved unsatisfactorily (**4s**). In addition, the substrate scope of amides was subsequently assessed. The results showed that linear (**4a'–4d'**), sterically bulky (**4e'**), and cyclic (**4f'–4h'**) tertiary amides all underwent smooth cyclization. Notably, this reaction could also be extended to secondary amides, thus resulting in the corresponding NH-secondary amine-tethered heterocycles (**4i'–4k'**) with high value in organic synthesis.

Next, we evaluated further functionalization of several pharmaceutical synthons by these two protocols (Scheme 2). Thus, DL-menthol and (–)-borneol derivatives could be easily converted into the corresponding thiazoles **5a** and **5b** in high yields. Likewise, the industrially important diacetone- β -fructose (DAF) and (–)-borneol synthons also performed well in this transformation to synthesize value-added oxazoles **5c** and **5d** in 77% and 75% yields.

To showcase the versatility and synthetical value of this new methodology, additional experiments were next conducted. First, scaling-up these two reactions to 5.0 mmol proved to be readily feasible, and both thiazole **3a** and oxazole **4a** were obtained in high yields, attesting to the scalability of the protocols (Scheme 3a). Second, shortening the reaction time was feasible to deliver oxazole **4a** in 53% yield after one minute reaction time, which demonstrated exceedingly fast oxidative coupling (Scheme 3b). Next, although the direct synthesis of C2-NR₂ substituted thiazoles was not feasible by this method, the product could be readily obtained through functionalizing the C–H bond of **3a** with DMF as the aminating reagent (Scheme 3c).^{19a} Furthermore, using copper catalysis,^{19b} C–H arylation of **3a** with iodobenzene was feasible to generate C2-arylated **7** in 64% yield (Scheme 3d). Likewise, despite the presence of several coordinating heteroatoms, Suzuki–Miyaura cross-coupling of **4f** proceeded smoothly to deliver **8** in 89% yield (Scheme 3e). Next, the secondary naphthylamine **1'** could be cyclized to generate oxazole product **4a** in 53% yield *via* C–N bond cleavage, ascribed to the *in situ* formed free naphthylamine (Scheme 3f). Finally,

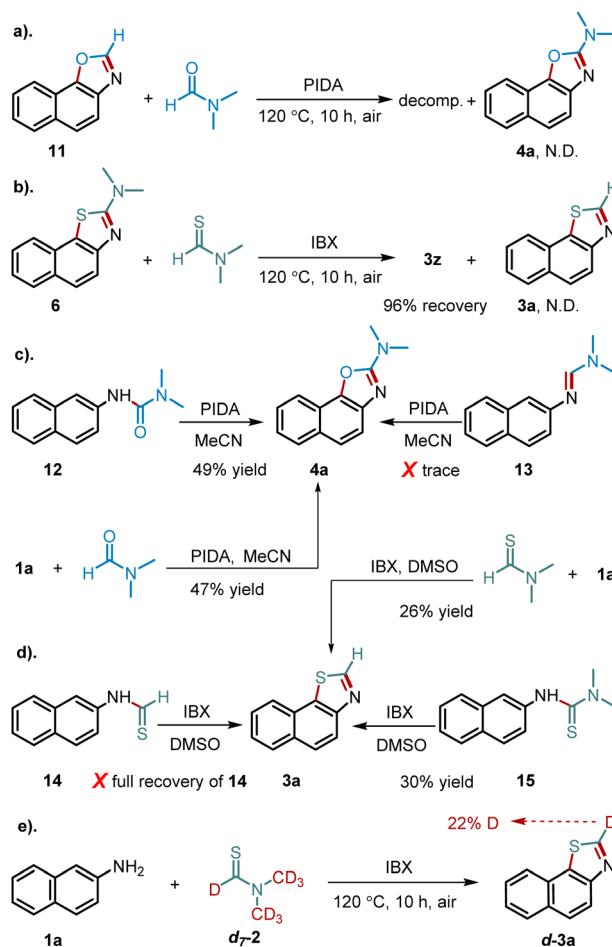




Scheme 3 Applicability of the oxidative methodology.

when formamide was used, the oxazole **9** was not formed, but the reaction produced 78% yield of formylation product **10** (Scheme 3g). This outcome proved the stability of **10** in the presence of hypervalent iodine and provided insights into the reaction mechanism.

To shed light on this highly chemoselective reaction pathway, several sets of control experiments as well as studies with key intermediates were performed (Scheme 4). As depicted in Scheme 4a and b, C2-free oxazole **11** failed to deliver product **4a**, and conversely, C2-NMe₂ thiazole **6** did not undergo the C–N bond cleavage to afford product **12**. These two results clearly illustrate the divergence of oxidative mechanisms to build oxazole and thiazole rings. To further probe the key reaction intermediates, several possible derivatives were prepared and subjected to the reaction conditions. As such, amidine **13** with high-activity²⁰ did not afford the cyclization product, while urea **12** was transformed into the target molecule **4a** with a comparatively high efficiency *cf.* the reaction between **1a** and DMF

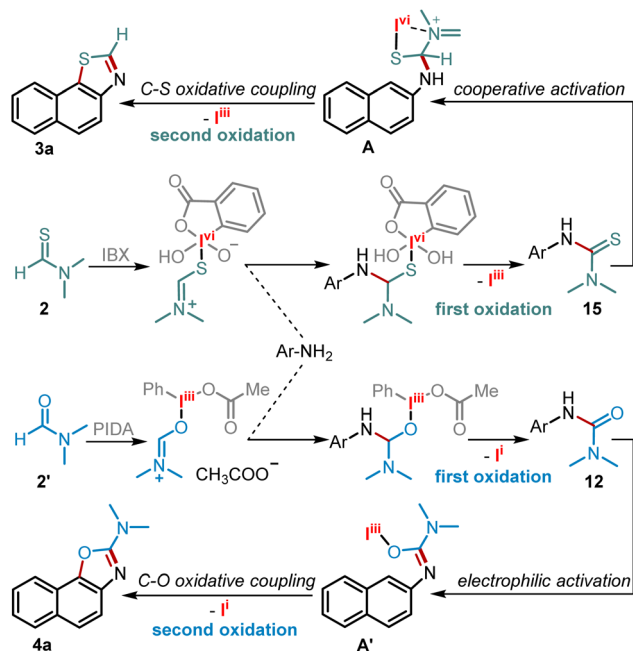


Scheme 4 Studies of the reaction mechanism.

(Scheme 4c). On the other hand, employing amine-derived thioformamide **14** resulted in full recovery, which ruled out the possible intermediacy of thioformamide. However, the use of thiourea **15** resulted in the formation of the target product **3a** with efficiency comparable to the reaction of **1a** and *N,N*-dimethylthioamide (Scheme 4d). Finally, a deuterium labelling study with *d*₇-*N,N*-dimethylthioamide showed in 22% D incorporation in the C2 position (Scheme 4e).

Overall, these mechanistic studies indicate that urea and thiourea species act as pivotal intermediates to enable the oxidative assembly of oxazoles and thiazoles. The key mechanistic difference results from the divergent $n_N \rightarrow \pi_{C=O}^*$ and $n_N \rightarrow \pi_{C=S}^*$ conjugation, where the stronger conjugation of the thioamide bond induces N–C cleavage under oxidative conditions. A tentative mechanism is proposed in Scheme 5. The reaction commences with electrophilic activation of the C=S and C=O bonds by the hypervalent iodine reagent,²¹ which is followed by the nucleophilic addition of amine. Subsequently, the first oxidation takes place to give thiourea **15** or urea **12**. At this point, with respect to the generation of thiazoles, the electron-rich intermediate **15** reacts with the hypervalent iodine(vi) to induce a hydride shift to afford **A**, which undergoes the second oxidative coupling by C–H/C–S cyclization. For the generation of oxazoles, the product is





Scheme 5 Possible mechanism.

obtained by electrophilic activation, the second oxidative coupling by C-H/C-O cyclization and isomerization in the presence of hypervalent iodine(III). In the case of thioamides, hypervalent iodine promotes amine dehydrogenation to form iminium.^{22a} The key difference in reactivity between amides and thioamides stems from higher reactivity of thioamides to electrophiles^{22b-d} and high affinity of sulfur towards hypervalent iodine reagents^{23a} with a weaker thiocarbonyl bond that is more susceptible to reduction.^{23b}

Conclusions

In summary, we have developed an unprecedented hypervalent iodine-induced twofold oxidative coupling of amines with amides. This coupling proceeds via a series of C-N/C-O and C-N/C-S forming events enabled by hypervalent iodine oxidants. The previously unknown Ar-O and Ar-S oxidative coupling assembles a collection of versatile yet synthetically challenging oxazoles and thiazoles with high chemoselectivity. Mechanistic studies demonstrated the importance of thiourea and urea species as the key reaction intermediates. This methodology represents the first example of chemoselective divergent oxidative bond functionalization in amides and thioamides to construct valuable heteroarenes. These findings open up new avenues for exploring oxidative amide and thioamide bond chemistry in various synthetic contexts.

Data availability

All experimental and characterization data, as well as NMR spectra are available in the ESI.† Crystallographic data for compound 3b and 4a have been deposited in the Cambridge

Crystallographic Data Centre under accession number CCDC 2224291 and 2223988.

Author contributions

J. N. and Y. M. M. conceived and directed the project. X. R. designed and performed the experiments. Q. Y., S. L. L. and J. W. helped with the collection of some new compounds and data analysis. J. N., and M. S. wrote the paper. All authors discussed the results and commented on the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was financially supported by the NSFC (21801159 and 22171171), the Innovative Talent Promotion Plan-Young Science and Technology Star Project (2022KJXX-15), and the Young Talent Fund of the University Association for Science and Technology in Shaanxi, China (20200605). M.S. thanks Rutgers University and the NSF (CAREER CHE-1650766) for support.

Notes and references

- (a) M. Szostak, *Amide bond activation: concepts and reactions*, Wiley-VCH., New York, 2022; (b) S. Davey, *Nat. Chem.*, 2015, **7**, 682; (c) D. Kaiser, A. Bauer, M. Lemmerer and N. Maulide, *Chem. Soc. Rev.*, 2018, **47**, 7899; (d) G. C. Li and M. Szostak, *Chem. Rec.*, 2019, **20**, 649; (e) G. C. Li, S. Y. Ma and M. Szostak, *Trends Chem.*, 2020, **2**, 914; (f) T. B. Boit, A. S. Bulger, J. E. Dander and N. K. Garg, *ACS Catal.*, 2020, **10**, 12109; (g) G. R. Meng, J. Zhang and M. Szostak, *Chem. Rev.*, 2021, **121**, 12746; (h) M. H. Feng, H. Q. Zhang and N. Maulide, *Angew. Chem., Int. Ed.*, 2022, **61**, e202212213.
- (a) G. Pelletier, W. S. Bechara and A. B. Charette, *J. Am. Chem. Soc.*, 2010, **132**, 12817; (b) J. F. Hu, Y. Zhao, J. J. Liu, Y. M. Zhang and Z. Z. Shi, *Angew. Chem., Int. Ed.*, 2016, **55**, 8718; (c) N. A. Weires, E. L. Baker and N. K. Garg, *Nat. Chem.*, 2016, **8**, 75; (d) J. A. Walker Jr., K. L. Vickerman, J. N. Humke and L. M. Stanley, *J. Am. Chem. Soc.*, 2017, **139**, 10228; (e) C.-L. Ji and X. Hong, *J. Am. Chem. Soc.*, 2017, **139**, 15522; (f) A. A. Kadam, T. L. Metz, Y. Q. Qian and L. M. Stanley, *ACS Catal.*, 2019, **9**, 5651; (g) G. J. Wang, Q. Q. Shi, W. Y. Hu, T. Chen, Y. Y. Guo, Z. L. Hu, M. H. Gong, J. C. Guo, D. H. Wei, Z. Q. Fu and W. Huang, *Nat. Commun.*, 2020, **11**, 946.
- (a) A. Greenberg, C. M. Breneman and J. F. Liebman, *The amide linkage: Structural significance in chemistry, biochemistry and materials science*, Wiley-VCH., New York, 2000; (b) A. B. Hughes, *Amino acids, peptides and proteins in organic chemistry*, Wiley, Weinheim, 2011; (c) K. Brix and W. Stocker, *Proteases: structure and function*, Springer, Verlag, Wien, 2013; (d) B. J. Burkhart, C. J. Schwalen, G. Mann, J. H. Naismith and D. A. Mitchell, *Chem. Rev.*, 2017, **117**, 5389; (e) A. Karmakar and A. J. L. Pombeiro,



- Coord. Chem. Rev.*, 2019, **39**, 86; (f) V. Pattabiraman and J. Bode, *Nature*, 2011, **480**, 471.
- 4 (a) S. A. Ruider and N. Maulide, *Angew. Chem., Int. Ed.*, 2015, **54**, 13856; (b) D. Kaiser, C. J. Teskey, P. Adler and N. Maulide, *J. Am. Chem. Soc.*, 2017, **139**, 16040; (c) H. Takezawa, K. Shitozawa and M. Fujita, *Nat. Chem.*, 2020, **12**, 574.
- 5 (a) C. P. Chen, P. Liu, M. M. Luo and X. M. Zeng, *ACS Catal.*, 2018, **8**, 5864; (b) C. C. D. Wybon, C. Mensch, C. Hollanders, C. Gadais, W. A. Herrebout, S. Ballet and B. U. W. Maes, *ACS Catal.*, 2018, **8**, 203; (c) C. Hollanders, E. Renders, C. Gadais, D. Masullo, L. V. Raemdonck, C. C. D. Wybon, C. Martin, W. A. Herrebout, B. U. W. Maes and S. Ballet, *ACS Catal.*, 2020, **10**, 4280; (d) Y. Long, Y. L. Zheng, Y. Xia, L. Qu, Y. H. Yang, H. F. Xiang and X. G. Zhou, *ACS Catal.*, 2022, **12**, 4688.
- 6 (a) K. Tani and B. M. Stoltz, *Nature*, 2006, **441**, 731; (b) B. Sliter, J. Morgan and A. Greenberg, *J. Org. Chem.*, 2011, **76**, 2770; (c) S. A. Glover and A. A. Rosser, *J. Org. Chem.*, 2012, **77**, 5492; (d) T. Shiba, T. Kurahashi and S. Matsubara, *J. Am. Chem. Soc.*, 2013, **135**, 13636; (e) H. Nagae, T. Hirai, D. Kato, S. Soma, S. Akebi and K. Mashima, *Chem. Sci.*, 2019, **10**, 2860.
- 7 (a) S. C. Shi, G. R. Meng and M. Szostak, *Angew. Chem., Int. Ed.*, 2016, **55**, 6959; (b) F. Hu, R. Lalancette and M. Szostak, *Angew. Chem., Int. Ed.*, 2016, **55**, 5062; (c) C. W. Liu and M. Szostak, *Angew. Chem., Int. Ed.*, 2017, **56**, 12718; (d) G. R. Meng, S. C. Shi, R. Lalancette, R. Szostak and M. Szostak, *J. Am. Chem. Soc.*, 2018, **140**, 727; (e) T. L. Zhou, C.-L. Ji, X. Hong and M. Szostak, *Chem. Sci.*, 2019, **10**, 9865; (f) G. C. Li, C.-L. Ji, X. Hong and M. Szostak, *J. Am. Chem. Soc.*, 2019, **141**, 11161; (g) C.-A. Wang, M. M. Rahman, E. Bisz, B. Dziuk, R. Szostak and M. Szostak, *ACS Catal.*, 2022, **12**, 2426; (h) D. X. Zuo, Q. Wang, L. Liu, T. Z. Huang, M. Szostak and T. Q. Chen, *Angew. Chem., Int. Ed.*, 2022, **61**, e202202794.
- 8 (a) J. Aubé, *Angew. Chem., Int. Ed.*, 2012, **51**, 3063; (b) P. Lei, G. R. Meng and M. Szostak, *ACS Catal.*, 2017, **7**, 1960; (c) L. B. Fu, M. Z. Xu, J. Y. Yu and W. R. Gutekunst, *J. Am. Chem. Soc.*, 2019, **141**, 2906; (d) H. Takezawa, K. Shitozawa and M. Fujita, *Nat. Chem.*, 2020, **12**, 574–578.
- 9 (a) G. R. Meng, P. Lei and M. Szostak, *Org. Lett.*, 2017, **19**, 2158; (b) Y. M. Liu, S. C. Shi, M. Achtenhagen, R. Z. Liu and M. Szostak, *Org. Lett.*, 2017, **19**, 1614; (c) S. Yu, T. Shin, M. S. Zhang, Y. Z. Xia, H. Kim and S. Lee, *Org. Lett.*, 2018, **20**, 7563; (d) J. J. Chen, Y. Z. Xia and S. Lee, *Org. Lett.*, 2020, **22**, 3504; (e) Y. Long, Y. L. Zheng, Y. Xia, L. Qu, Y. H. Yang, H. F. Xiang and X. G. Zhou, *ACS Catal.*, 2022, **12**, 4688.
- 10 (a) C. Liana Allen, B. N. Atkinson and J. M. J. Williams, *Angew. Chem., Int. Ed.*, 2011, **51**, 1383; (b) T. M. E. Dine, D. Evans, J. Rouden and J. Blanchet, *Chem. - Eur. J.*, 2016, **22**, 5894; (c) R. B. Sonawane, N. K. Rasal and S. V. Jagtap, *Org. Lett.*, 2017, **19**, 2078; (d) T. Ghosh, S. Jana and J. Dash, *Org. Lett.*, 2019, **21**, 6690; (e) J. W. Yin, J. Y. Zhang, C. Q. Cai, G.-J. Deng and H. Gong, *Org. Lett.*, 2019, **21**, 387; (f) M.-H. Zhu, Z. R. Cheng, J. L. Wei, H. Tan and N. Jiao, *CCS Chem.*, 2022, DOI: [10.31635/ccschem.022.202202585](https://doi.org/10.31635/ccschem.022.202202585).
- 11 (a) W. S. Bechara, G. Pelletier and A. B. Charette, *Nat. Chem.*, 2012, **4**, 228; (b) H. Yue, L. Guo, S.-C. Lee, X. Liu and M. Rueping, *Angew. Chem., Int. Ed.*, 2017, **56**, 3972; (c) J. Zhuo, Y. Zhang, Z. J. Li and C. Li, *ACS Catal.*, 2020, **10**, 3895; (d) G. S. Lee, J. Won, S. Choi, M.-H. Baik and S. H. Hong, *Angew. Chem., Int. Ed.*, 2020, **59**, 16933.
- 12 (a) T. Murai, *The Chemistry of Thioamides*, Springer, Singapore, 2019; (b) T. S. Jagodziński, *Chem. Rev.*, 2003, **103**, 197; (c) S. Fukagawa, Y. Kato, R. Tanaka, M. Kojima, T. Yoshino and S. Matsunaga, *Angew. Chem., Int. Ed.*, 2018, **58**, 1153; (d) J. Zhang, Z. L. Liu, Z. Yin, X. F. Yang, Y. M. Ma, R. Szostak and M. Szostak, *Org. Lett.*, 2020, **22**, 9500; (e) M. Saito, S. Murakami, T. Nanjo, Y. Kobayashi and Y. Takemoto, *J. Am. Chem. Soc.*, 2020, **142**, 8130.
- 13 (a) A. N. Desnoyer and J. A. Love, *Chem. Soc. Rev.*, 2017, **46**, 197; (b) J. Lou, Q. Wang, P. Wu, H. Wang, Y.-G. Zhou and Z. Yu, *Chem. Soc. Rev.*, 2020, **49**, 4307; (c) R. W. Newberry, B. VanVeller, I. A. Guzei and R. T. Raines, *J. Am. Chem. Soc.*, 2013, **135**, 7843; (d) J. Luo, M. Rauch, L. Avram, Y. Ben-David and D. Milstein, *J. Am. Chem. Soc.*, 2020, **142**, 21628.
- 14 (a) E. Vitaku, D. T. Smith and J. T. Njardarson, *J. Med. Chem.*, 2014, **57**, 10257; (b) C. A. Grice, K. L. Tays, B. M. Savall, J. M. Wei, C. R. Butler, F. U. Axe, S. D. Bembenek, A. M. Fourie, P. J. Dunford, K. Lundeen, F. Coles, X. H. Xue, J. P. Riley, K. N. Williams, L. Karlsson and J. P. Edwards, *J. Med. Chem.*, 2008, **51**, 4150.
- 15 (a) D. Ma, X. Lu, L. Shi, H. Zhang, Y. Jiang and X. Liu, *Angew. Chem., Int. Ed.*, 2010, **50**, 1118; (b) Y. Sun, H. Jiang, W. Wu, W. Zeng and X. Wu, *Org. Lett.*, 2013, **15**, 1598; (c) P. Dang, W. L. Zeng and Y. Liang, *Org. Lett.*, 2015, **17**, 34.
- 16 (a) K. G. Liu, J. R. Lo, T. A. Comery, G. M. Zhang, J. Y. Zhang, D. M. Kowal, D. L. Smith, L. Di, E. H. Kerns, L. E. Schechter and A. J. Robichaud, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 1115; (b) G. Pochetti, N. Mitro, A. Lavecchia, F. Gilardi, N. Besker, E. Scotti, M. Aschi, N. Re, G. Fracchiolla, A. Laghezza, P. Tortorella, R. Montanari, E. Novellino, F. Mazza, M. Crestani and F. Liodice, *J. Med. Chem.*, 2010, **53**, 4354.
- 17 (a) J. Y. Kim, S. H. Cho, J. Joseph and S. Chang, *Angew. Chem., Int. Ed.*, 2010, **49**, 9899; (b) S. Wertz, S. Kodama and A. Studer, *Angew. Chem., Int. Ed.*, 2011, **50**, 11511; (c) J. Liu and J. M. Hoover, *Org. Lett.*, 2019, **21**, 4510.
- 18 (a) C. Villa, E. Mariani, A. Loupy, C. Grippo, G. C. Grossia and A. Bargagna, *Green Chem.*, 2003, **5**, 623; (b) V. Polshettiwar and R. S. Varma, *Acc. Chem. Res.*, 2008, **41**, 629; (c) A. Sarkar, S. Santra, S. K. Kundu, A. Hajra, G. V. Zyryanov, O. N. Chupakhin, V. N. Charushinb and A. Majee, *Green Chem.*, 2016, **18**, 4475.
- 19 (a) Q. Sun and X. G. Bao, *Chem. Commun.*, 2022, **58**, 2216; (b) L. M. Bouchet, A. A. Heredia, J. E. Argüello and L. C. Schmidt, *Org. Lett.*, 2020, **22**, 610.
- 20 (a) P. Debnath, M. Baeten, N. Lefèvre, S. V. Daele and B. U. W. Maes, *Adv. Synth. Catal.*, 2015, **357**, 197; (b)



- M. Baeten and B. U. W. Maes, *Adv. Synth. Catal.*, 2016, **358**, 826.
- 21 (a) C. Zhu, Y. Liang, X. Hong, H. Sun, W.-Y. Sun, K. N. Houk and Z. Shi, *J. Am. Chem. Soc.*, 2015, **137**, 7564; (b) T. Otani, A. Tsuyuki, T. Iwachi, S. Someya, K. Tateno, H. Kawai, T. Saito, K. S. Kanyiva and T. Shibata, *Angew. Chem., Int. Ed.*, 2017, **56**, 3906; (c) L. Habert and K. Cariou, *Angew. Chem., Int. Ed.*, 2020, **60**, 171; (d) Y. Wang, M. Yang, Y.-Y. Sun, Z.-G. Wu, H. Dai and S. H. Li, *Org. Lett.*, 2021, **23**, 8750.
- 22 (a) K. C. Nicolaou, C. J. N. Mathison and T. Montagnon, *J. Am. Chem. Soc.*, 2004, **126**, 5192; (b) N. Mahanta, D. M. Szantai-Kis, E. J. Petersson and D. A. Mitchell, *ACS Chem. Biol.*, 2019, **14**, 142; (c) H. J. Kim, D. W. Graham, A. A. DiSpirito, M. A. Alterman, N. Galeva, C. K. Larive, D. Asunskis and P. M. A. Sherwood, *Science*, 2004, **305**, 1612; (d) A. Okano, R. C. James, J. G. Pierce, J. Xie and D. L. Boger, *J. Am. Chem. Soc.*, 2012, **134**, 8790.
- 23 (a) D. Kaiser, A. Bauer, M. Lemmerer and N. Maulide, *Chem. Soc. Rev.*, 2018, **47**, 7899; (b) K. B. Wiberg and D. J. Rush, *J. Am. Chem. Soc.*, 2001, **123**, 2038.

