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Recent progress in transition-metal-free functionalization of allenamides

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With their unique reactivity, selectivity, availability and stability, allenamides are receiving increasing attention, and reports on the functionalization of allenamides are rapidly growing in number. In this review, recent developments in transition-metal-free functionalization of allenamides are highlighted. First, developments based on allenamide reactivity are simply introduced. After presenting the advantages of allenamides, recent progress in transition-metal-free functionalization of allenamides is classified and discussed in detail in four parts: chiral phosphoric-acid-catalyzed asymmetric functionalization, iodine-reagent-mediated functionalization, 1,3-H-shift reaction of allenamides, and other metal-free allenamide functionalizations. For the majority of these transformations, plausible mechanisms are presented in detail. The purpose of this review is to provide illustrations of elegant allenamide chemistry, and thereby elicit further interest from the synthetic community to develop novel allenamide methodology.

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1. Introduction

Regio- and stereo-controlled functionalization of carbon-carbon double bonds has enormous potential in organic synthesis.¹ Allenamides have been widely investigated and utilized as one of the most powerful and versatile building blocks in the field of organic synthesis since the first documentation of their synthesis and characterization in 1968 by Viehe.² The π -donating ability of nitrogen atoms renders allenamides more electron-rich than simple allenes, which predisposes them to electrophilic activation. An electronic bias can be exerted through delocalization of the nitrogen lone pair toward the allenic moiety, as demonstrated in the allenamide resonance form. Accordingly, highly regioselective

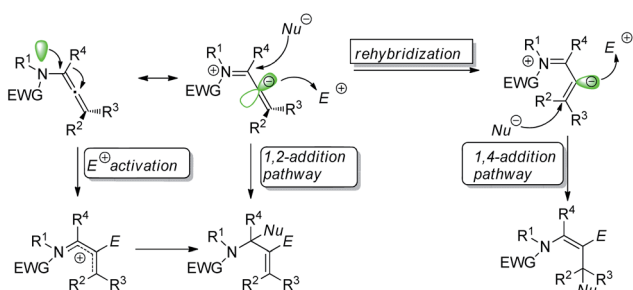
transformations can be achieved by the consecutive addition of electrophiles and nucleophiles (Scheme 1).

With their unique reactivity, selectivity, availability and stability, allenamide functionalization is being increasingly investigated. While a recent review of the flexible reactivity of allenamides in transition-metal-catalyzed functionalization reactions has been published,³ the present review predominantly summarizes progress in transition-metal-free allenamide functionalization in recent years.

2. Chiral phosphoric-acid-catalyzed functionalization of allenamides

The hydrogen bond activation mode is recognized as one of the most powerful strategies in the field of metal-free asymmetric manipulation of heteroatom-based organic functional groups and anions.⁴ Chiral phosphoric acid (CPA)-catalyzed synthesis of value added building blocks, discussed in this section, is continuously expanding within the asymmetric synthesis context.⁵

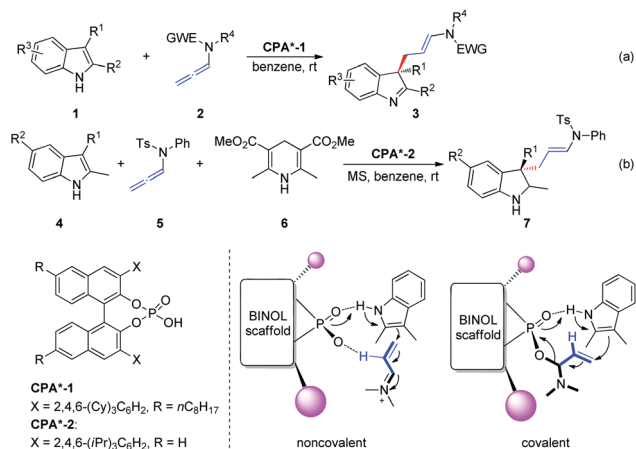
In 2014, Bandini *et al.*⁶ reported the first effective and unprecedented chiral BINOL phosphoric-acid-catalyzed (1–10 mol%) dearomatization of indoles **1** occurring *via* electrophilic activation of allenamides **2** (ee up to 94%). The realization of this transformation resulted in the direct synthesis of densely functionalized enantiomerically enriched 3,3-disubstituted indolenine cores **3** featuring an all-carbon quaternary stereogenic center at the C3 position (Scheme 2a). Moreover, the authors extended this methodology to the preparation of enantiomerically enriched 3,3-disubstituted indolines **7** *via* a Brønsted-acid-catalyzed one-pot dearomatization/



Scheme 1 Reaction model of allenamides.

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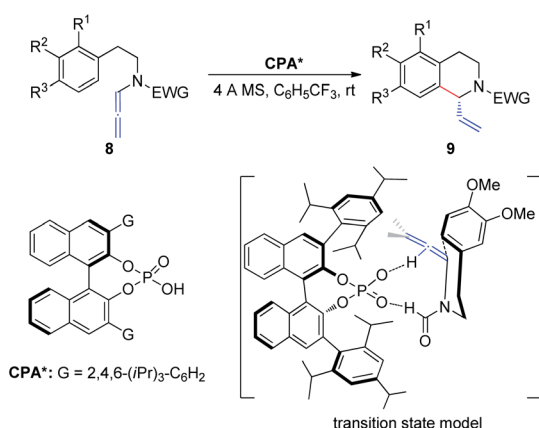




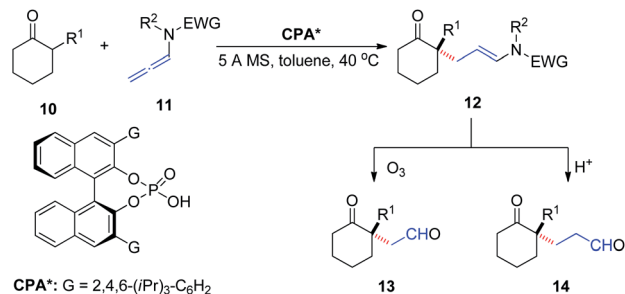
Scheme 2 Chiral phosphoric-acid-catalyzed asymmetric dearomatization of indoles.

hydrogenation transfer sequence entailing a three-component reaction between indole **4**, allenamide **5**, and Hantzsch ester **6** (Scheme 2b). The authors proposed two possible activation modes: non-covalent and covalent CPA-allenamide interactions. Subsequently, the reaction mechanism was investigated by means of density functional theory calculations and electro-spray ionization mass spectrometry analysis.⁷ The first step of the process (rate determining step) was the formation of a covalent adduct between the allenamide and chiral organo-promoter. The resulting chiral α -amino allylic phosphate undergoes dearomative condensation with indoles. In the first step, the indole moiety remains bonded to the catalyst through strong hydrogen bonding.

In 2015, Cozzi *et al.*⁸ reported the cyclization of allenamides **8** to 1-vinyl tetrahydroisoquinolines **9** in the presence of CPAs (Scheme 3). In this reaction, the elusive and relatively unstable iminium ion derived from acrylaldehyde is generated *in situ* and this electrophilic intermediate can engage in stereoselective intramolecular Friedel-Crafts-type allylic alkylation with electron-rich aromatic rings. In particular, given the importance



Scheme 3 Chiral phosphoric-acid-catalyzed asymmetric cyclization of allenamides.

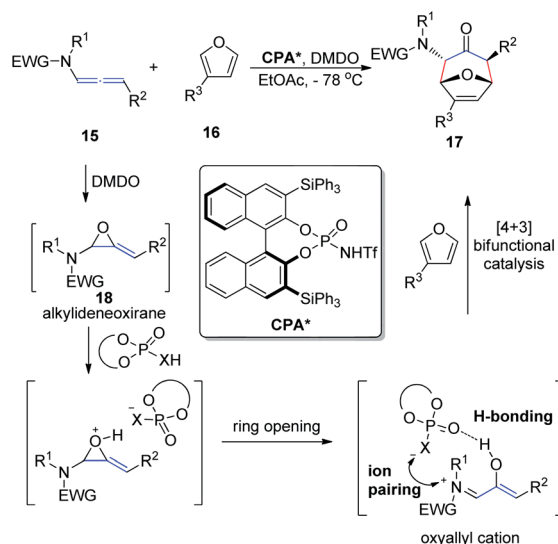


Scheme 4 Chiral phosphoric-acid-catalyzed asymmetric addition of unactivated α -branched cyclic ketones to allenamides.

of the formyl group, the authors assumed that the recognition and high enantiomeric excess obtained in the reaction were governed by the hydrogen bonding between the catalyst and the hydrogen atom of the formyl group.

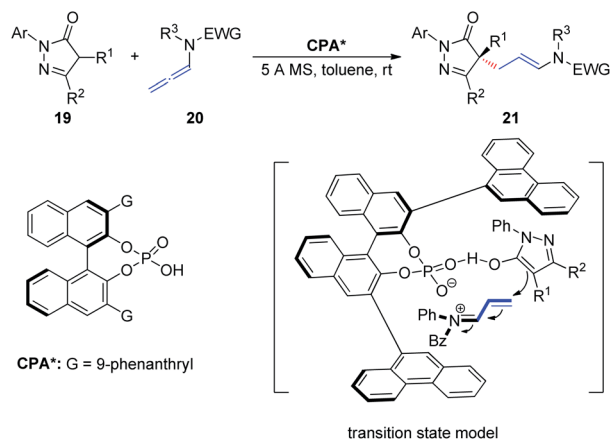
In 2016, Toste *et al.*⁹ reported the asymmetric addition of unactivated α -branched cyclic ketones **10** to allenamides **11** catalyzed by a CPA, to generate an all-carbon quaternary stereocenter **12** with high enantioselectivity (Scheme 4). The reaction exhibited a broad substrate scope, tolerating various aryl, alkenyl, alkynyl, and alkyl substituents as well as cyclohexanone modification. The products could be readily transformed into their corresponding 1,4- and 1,5-ketoaldehyde derivatives **13** and **14**, respectively, both of which are important building blocks in organic synthesis.

In 2017, Vicario *et al.*¹⁰ reported that BINOL-based *N*-tri-fluoromethanesulfonyl phosphoramides catalyze the enantioselective [4 + 3] cycloaddition between furans **16** and oxyallyl cations **18**, the latter being generated *in situ* from allenamide **15** oxidation (Scheme 5). This method provides a direct and facile access to a wide range of potentially valuable seven-membered rings **17** in a highly regio-, diastereo-, and enantioselective



Scheme 5 Enantioselective [4 + 3] cycloaddition catalyzed by chiral *N*-trifluoromethanesulfonyl phosphoramides.



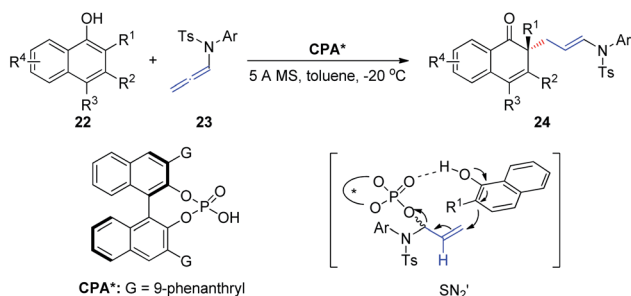


Scheme 6 Chiral phosphoric-acid-catalyzed asymmetric addition of pyrazolones to allenamides.

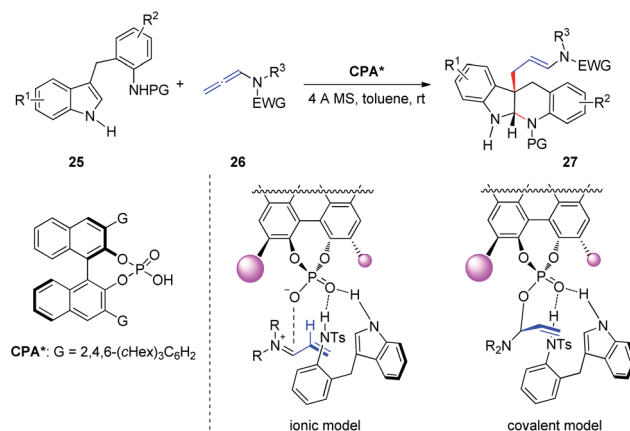
fashion. The reaction relies on the potential of the conjugate base of the *N*-trifluoromethanesulfonyl phosphoramidate catalyst to engage in a bifunctional mode of activation, which combines hydrogen bonding with electrostatic interactions by ion pairing with the oxyallyl cation dienophile. This combination enables efficient chirality transfer to the newly formed stereocenters. Moreover, this catalyst system displays a remarkably wide substrate scope with respect to both the furan and allenamide coupling partners, and the excellent performance of γ -substituted allenamides as oxyallyl cation precursors is highlighted.

In 2018, Wang *et al.*¹¹ described an asymmetric allylic alkylation of pyrazolones *via* CPA-catalyzed asymmetric addition of pyrazolones **19** to allenamides **20** (Scheme 6). The room temperature reaction generates a chiral quaternary stereocenter in high yield and with good enantioselectivity and exhibits a broad substrate scope. Mechanistically, the chiral ion pair generated from protonation of the allenamide by the CPA dictates the enantioinduction of the asymmetric addition process together with an additional hydrogen bonding interaction.

In 2019, Shao *et al.*¹² reported the first chiral phosphoric-acid-catalyzed asymmetric intermolecular C–C bond-forming dearomatization of α -naphthols **22** (Scheme 7). This method is also applicable to β -naphthols. The transformation proceeds



Scheme 7 Chiral phosphoric-acid-catalyzed asymmetric dearomatization of α -naphthols.



Scheme 8 Chiral phosphoric-acid-catalyzed asymmetric dearomative cyclization of homotryptamine derivatives.

with high chemo- and enantioselectivity *via* an allylic substitution reaction and provides enantioenriched α - and β -naphthalenones bearing an all-carbon quaternary center. Notably, two distinct possible reaction mechanisms can be considered; the first involves a concerted asynchronous S_N2 -like displacement, while the second entails participation of an α,β -unsaturated iminium ion formed upon protonation by the allenamide.

Subsequently, Shin *et al.*¹³ reported the CPA-catalyzed asymmetric dearomative cyclization of homotryptamine derivatives, furnishing enantioenriched indolo[2,3-*b*]quinolone scaffolds **27** in up to 99% ee (Scheme 8). The authors proposed two possible stereochemical models: the basic site of the phosphate in CPA activates homotryptamines **25** *via* dual hydrogen bonding with the indole and aniline in **25**, whereas activation of allenamides **26** by protonation at C2 would form an α,β -unsaturated iminium ion, setting the stage for conjugate addition by the indole moiety of **25** (ionic model). Alternatively, basic phosphate may form a covalent adduct with the iminium to generate an allylphosphate aminal (covalent model), followed by S_N2 attack by the indole C3 carbon. The authors indicated that the covalent model is more favorable than the ionic model based on Bandini's report.⁶

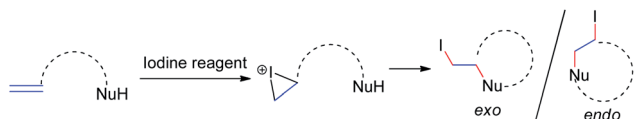
3. Iodine-reagent-mediated functionalization of allenamides

Iodine-containing reagents have received considerable attention as they are inexpensive, nontoxic, and readily available electrophiles that interact with double bonds.¹⁴ The first step in this type of reaction is the interaction between the iodine electrophile and the π -system of the alkene to generate iodonium intermediates, which subsequently undergo an addition or a cyclization reaction, depending on the stereochemistry and ring size formed, in either *exo* or *endo* fashion, as shown in Scheme 9. This segment reviews recent developments in intramolecular cyclizations and intermolecular nucleophilic additions of allenamides mediated by iodine reagents.

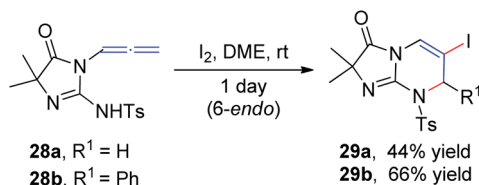
In 1996, Noguchi *et al.*¹⁵ reported the iodine-mediated intramolecular cyclization of *N*-3-allenyl-1-imidazolinones **28**



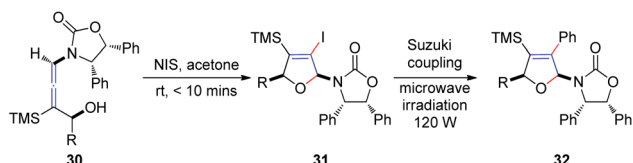
Review



Scheme 9 The reaction model between iodine electrophiles and carbon-carbon double bonds.



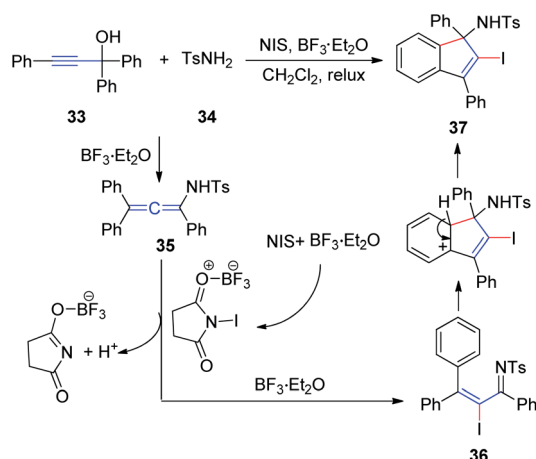
Scheme 10 Iodine-mediated intramolecular cyclization of 3-allyl-1-imidazolinones.



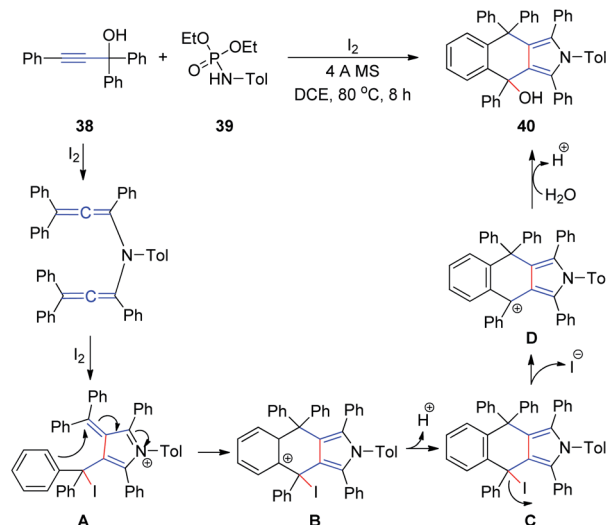
Scheme 11 *N*-Iodosuccinimide-mediated cyclization of chiral γ -substituted allenamides.

to give 6-*endo* cyclization products **29a** and **29b** in 46% and 66% yields, respectively (Scheme 10).

Subsequently, Hegedus *et al.*¹⁶ developed an *N*-iodosuccinimide-mediated cyclization of chiral γ -substituted allenamides **30**, yielding *cis*-iododihydrofurans **31** with retention of stereochemistry, achieved within 10 min (Scheme 11). The vinyl iodide functionality present in dihydrofurans can be further reacted with phenylboronic acid under Suzuki coupling conditions, providing coupling product **32** in 89% yield under microwave irradiation.



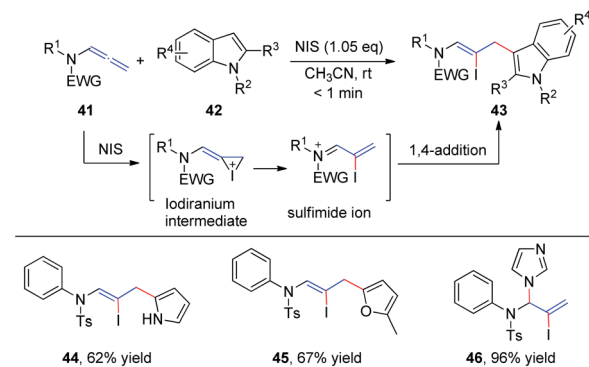
Scheme 12 $\text{BF}_3 \cdot \text{Et}_2\text{O}$ -catalyzed tandem reaction of propargyl alcohol, sulfonamide, and NIS.



Scheme 13 Synthesis of 4,9-dihydro-2*H*-benzo[*f*]isoindoles from propargyl alcohols and phosphoramides in the presence of iodine.

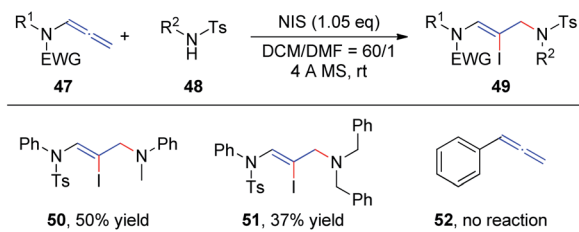
In 2011, Wang *et al.*¹⁷ developed an efficient method to generate *N*-(2-iodoinden-1-yl)arenesulfonamides *via* a $\text{BF}_3 \cdot \text{Et}_2\text{O}$ catalyzed tandem reaction of propargyl alcohol **33**, sulfonamide **34**, and NIS (Scheme 12). Allenesulfonamide **35** is postulated to be a key intermediate for this tandem transformation. Mechanistically, propargyl alcohol and *p*-toluenesulfonamide are first converted to the key allenessulfonamide intermediate under $\text{BF}_3 \cdot \text{Et}_2\text{O}$ catalytic conditions. Meanwhile, in the presence of $\text{BF}_3 \cdot \text{Et}_2\text{O}$, NIS is activated to an iodonium species, which activates the allenessulfonamide *in situ* to afford α -iodo- α,β -unsaturated sulfonamide **36**. Sulfonamide **36** was subsequently transformed into the final product **37** *via* an intramolecular Friedel-Crafts reaction promoted by $\text{BF}_3 \cdot \text{Et}_2\text{O}$.

At a later stage, the same group¹⁸ developed a new method for the synthesis of 4,9-dihydro-2*H*-benzo[*f*]isoindoles from propargyl alcohols **38** and phosphoramides **39** in the presence of iodine in a single step (Scheme 13). First, a diallenamide is formed from propargyl alcohol and phosphoramide in the presence of iodine. Further iodination induces the first



Scheme 14 NIS-mediated intermolecular iodofunctionalization of allenamides with indoles, pyrrole, and furan.



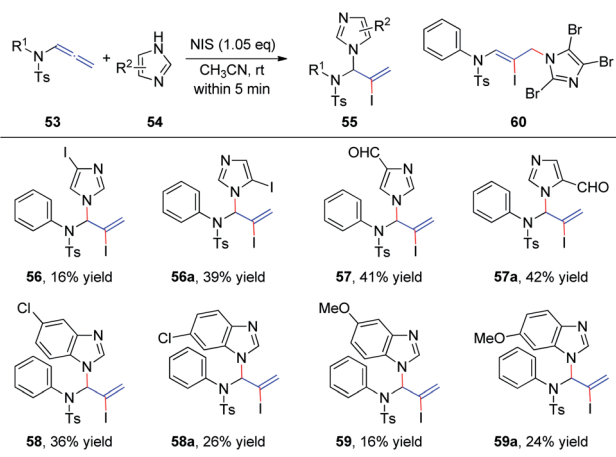


Scheme 15 NIS-mediated iodoamination of allenamides.

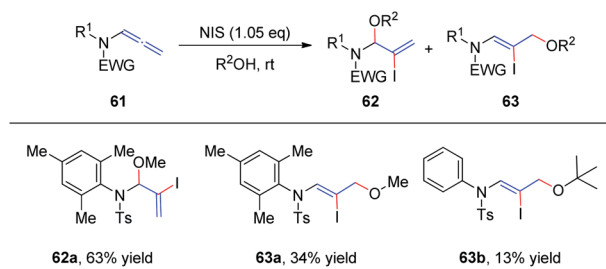
cyclization to give compound **A**. The phenyl ring of **A** then immediately attacks the α,β -unsaturated iminium intramolecularly to execute the second cyclization and deliver **B**. Aromatization of the resulting **C** generates **D**, which is hydrated to afford **40**.

In 2016, our group¹⁹ reported the first *N*-iodosuccinimide-mediated intermolecular iodofunctionalization of allenamides **41** with indoles, pyrroles, and furans, affording the desired 1,4-addition products **43**, **44**, and **45**, respectively, in good yields under mild conditions (Scheme 14). Moreover, when imidazole was used as the nucleophile, the corresponding 1,2-addition product **46** was obtained in good yield. The reaction mechanism involves an iodonium intermediate, which undergoes a decyclization reaction through the delocalization of the nitrogen lone pair toward the alkene to form the key conjugated sulfimide ion species intermediate. Subsequently, the conjugated sulfimide ion undergoes regioselective addition to give the desired product **43**.

In our preceding report, we found that the degradation product 4-methyl-*N*-phenylbenzenesulfonamide **48** could also be used as a nucleophile to obtain 1,4-addition products, iodine-substituted allylamino *Z*-enamides **49** (Scheme 15). Therefore, we further studied the NIS-mediated iodoamination of allenamides **47** with sulfonamides **48**.²⁰ These reactions proceed rapidly and tolerate a broad range of substrates. Moreover, *N*-methylaniline and dibenzylamine likewise reacted efficiently with allenamides to obtain the desired products **50**



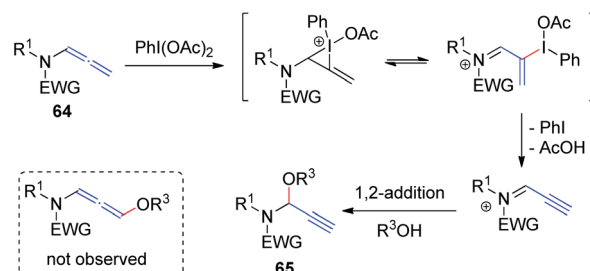
Scheme 16 Regioselective iodoamination of allenamides to generate imidazole heterocycles.

Scheme 17 *N*-Iodosuccinimide-mediated regioselective 1,2-additions of alcohols to allenamides.

and **51**, respectively, in moderate yields, while unfunctionalized allene **52** could not afford the iodoamination product.

Subsequently, we further extended this regioselective iodoamination of allenamides **53** to imidazole heterocycles **54** (Scheme 16).²¹ It is noteworthy that the regioselectivity of this iodoamination appears to differ from that observed in our earlier report¹⁹ involving sulfonamides, to obtain the 1,2-adduct. The facile reaction is regioselective and tolerant of a broad range of imidazole and benzimidazole derivatives. The key intermediate is a conjugated sulfimide ion species that undergoes nucleophilic attack by imidazole to form the 1,2-adduct **55**. Moreover, mixtures of *N*¹- and *N*³-substituted isomers **56/56a–59/59a** were obtained using asymmetrically substituted imidazoles, such as 4-iodoimidazole, imidazole-3-carbaldehyde, 5-chloro-1*H*-benzimidazole, and 5-methoxy-1*H*-benzimidazole. In addition, trisubstituted imidazole produced the 1,4-adduct **60** exclusively, because of steric hindrance.

In 2018, we reported the *N*-iodosuccinimide-mediated regioselective 1,2-addition of alcohols to allenamides **61** for the assembly of a series of *N*, *O*-acetals **62** (Scheme 17).²² These novel reactions proceed rapidly and exhibit a broad substrate scope for a variety of allenamides. It is noteworthy that the alcohol serves as both the solvent and nucleophile in this transformation. Moreover, when trimethylphenyl allenamide was used as the reactant, the 1,2-adduct **62** was obtained in 63% yield, together with the 1,4-adduct **63a** (34% yield); and when *tert*-butanol was employed as the nucleophile and solvent, 1,4-addition product **63b** was isolated in 13% yield as the major product, with both of these experimental results possibly arising from increased steric hindrance.

Scheme 18 Synthesis of propargylic *N*, *O*-acetals via hypervalent iodine-mediated activation of allenamides in alcohols.

Reaction scheme showing the synthesis of 74 from 72 and 73, and the synthesis of 76 and 77 from 75.

Reaction 1: 72 + 73 $\xrightarrow{\text{NIS}}$ [ion pair and hydrogen bond] $\rightarrow$ 74

Reaction 2: 75 $\xrightarrow[\text{Et}_3\text{N}/\text{CH}_3\text{CN} = 1:1, 70^\circ\text{C}, 7\text{ h}]{\text{Pd}(\text{PPh}_3)_2\text{Cl}_2 (5\text{ mol\%}), \text{phenylacetylene} (2\text{ equiv.})}$ 76, 82% yield

Reaction 3: 75 $\xrightarrow[\text{Pd}(\text{PPh}_3)_4 (10\text{ mol\%}), \text{toluene}, 80^\circ\text{C}, 3\text{ h}]{\text{SnBu}_3 (1.2\text{ equiv.})}$ 77, 55% yield

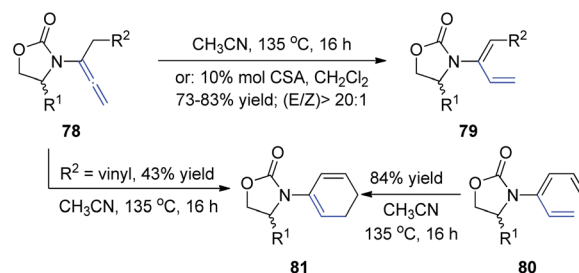
Yu *et al.*²³ recently demonstrated hypervalent iodine-mediated activation of allenamides **64** in alcohols to obtain propargylic N, O-acetals **65** in high yields with excellent regioselectivity (Scheme 18). By using PhI(OAc)₂ as the oxidant and an alcohol as both nucleophile and solvent, allenamides were converted to propargylic N, O-acetals **65** *via* 1,2-addition of alcohol to the sulfinide ion intermediate; 1,4-adducts were not detected.

Subsequently, we developed a new method for the synthesis of *N*²-allyl-1,2,3-triazoles *via* NIS-mediated allylation of allenamides **72** with mono- and unsubstituted NH-1,2,3-triazoles and

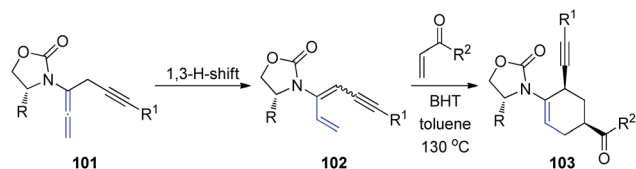
4. 1,3-H-shift reaction of allenamides

Hsung *et al.*²⁹ subsequently expanded the substrate scope of the 1,3-H shift reaction for the preparation of 3-amido-trienes **83**. Such 1,3-hydrogen shifts could be achieved thermally or *via* Brønsted acid promotion (Scheme 22). Under either condition, these processes are highly regioselective for the α -position, and highly stereoselective for the *E*-configuration. For example, when allenamides with both α - and γ -substitutions were examined, the 1,3-H shift in this case was found to be completely regioselective occurring exclusively from the α -position to afford highly substituted (*E*)-3-amido-trienes **83a–83c** in good yields.

Hsung *et al.*³⁰ then described a new torquoselective ring closure of chiral amide-substituted 1,3,5-hexatrienes and its application in tandem with [4 + 2] cycloaddition. They found that the reactions of allenamides **84-Z** and **85-Z** led to tricycles **87a** and **87b** as single isomers *via* the highly stereoselective [4 + 2] cycloaddition of cyclic amido dienes **86a** and **86b**, respectively, thereby constituting a quadruple tandem process



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Scheme 27 The tandem propargylation-1,3-H-shift sequence of chiral allenamides.

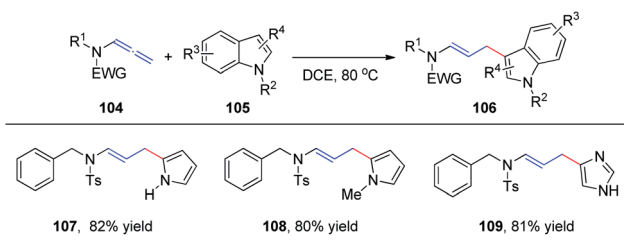
state, as shown in Scheme 26, leading to complex nitrogen heterocycles **100** in a highly stereoselective manner.

Recently, the same group described a tandem propargylation-1,3-H-shift sequence of chiral allenamides **101** to access both *E* and *Z* isomers of chiral 3-amidodienynes **102** in Diels-Alder cycloadditions gave *endo-II* products **103** in good yields and excellent selectivity, while the reactivity of the corresponding (*E*)-3-amidodienynes toward electrocyclization was inadequate.

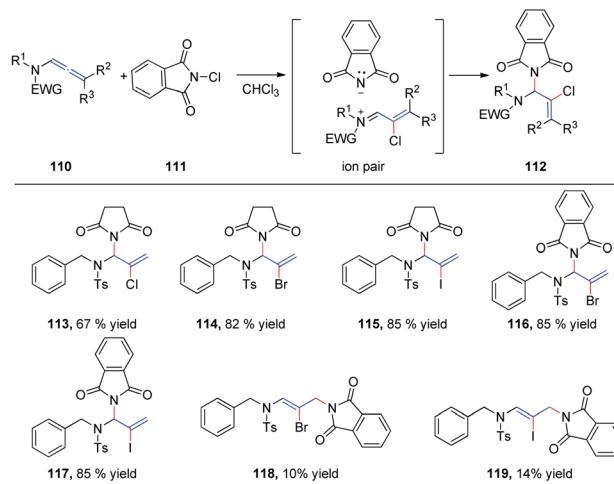
5. Other metal-free allenamide functionalization

In 2015, we reported the first catalyst-free intermolecular addition of indoles **105** to the distal double bond of allenamides **104** (Scheme 28).³⁵ The reaction proceeds smoothly at 80 °C to provide a series of (*E*)-enesulfonamide/enamide derivatives **106** in high yields with excellent regioselectivity. Interestingly, pyrrole, methylpyrrole, and imidazole were likewise efficient nucleophiles, affording the desired products **107**, **108**, and **109** in 82%, 80%, and 81% yields, respectively.

We subsequently reported the regioselective 1,2-addition of allenamides **110** to *N*-chlorophthalimide **111** for the synthesis of 2-chloro allylic amination derivatives **112** via an ion pair composed of a σ -complex and the imide conjugate base (Scheme 29).³⁶ This reaction was conducted under very mild conditions and afforded yields of up to 99%. *N*-Haloimides served as both electrophiles and nucleophiles in this reaction. Moreover, *N*-chlorosuccinimide, *N*-bromosuccinimide, *N*-iodosuccinimide, *N*-bromophthalimide, and *N*-iodophthalimide were all efficient substrates for the reaction, affording the desired 1,2-adducts **113–117** in moderate to good yields. In addition, 1,4-adducts, **118** and **119**, were also isolated when *N*-



Scheme 28 Intermolecular addition of indoles to allenamides under thermal conditions.

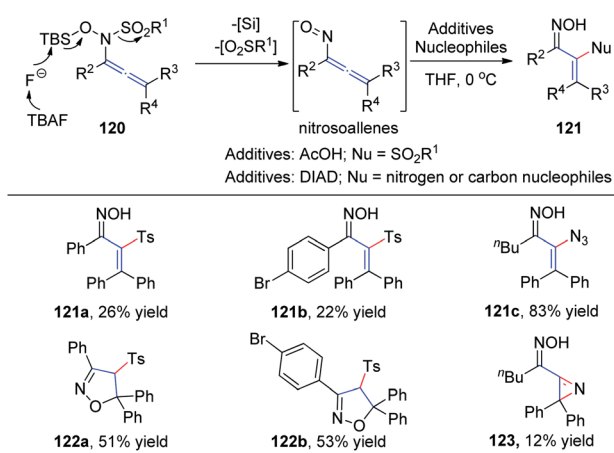


Scheme 29 Intermolecular addition of *N*-chlorophthalimide to allenamides.

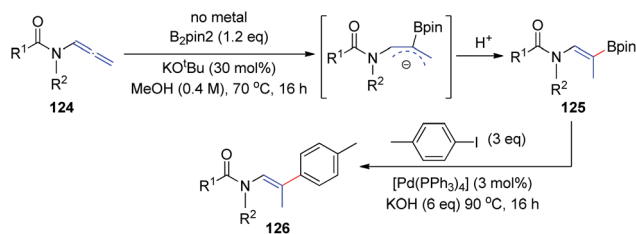
bromophthalimide and *N*-iodophthalimide were used as the reactants.

In 2015, Tanimoto *et al.*³⁷ developed a synthesis of α -functionalized enoximes **121** via nucleophilic substitution of nitrosoallenes, a novel chemical species prepared from allenyl *N*-hydroxysulfonamides **120** (Scheme 30). Introduction of various nucleophiles proceeded smoothly to create C–N, C–O, C–S, C–F, and C–C bonds in the presence of azodicarboxylates. Interestingly, α -sulfonyl enoximes **121a** and **121b** were generated via sulfone transfer in the presence of AcOH. Moreover, when all the substituents on the allenylamides were aryl groups, 2-isoxazolines **122a** and **122b** were afforded as major products, derived from the cyclocondensation of the initially generated vinylsulfones, likely because of their steric bulkiness. Vinyl azide **121c** was produced in excellent yield as an inseparable mixture with 2*H*-azirine **123**.

In 2018, the Fernández and Vicario group³⁸ described a high-yielding transition-metal-free borylation of the distal double



Scheme 30 The synthesis of α -functionalized enoximes via nucleophilic substitution of nitrosoallenes.



Scheme 31 Transition-metal-free borylation of electron-deficient allenamide variants.

bond of electron-deficient variants of allenamides **124**, proceeding with complete stereocontrol to provide *Z* isomers exclusively (Scheme 31). The acyl groups on the amine moiety were crucial for obtaining complete stereoselectivity, owing to the formation of a stable allylic anion intermediate, which is further regioselectively protonated to give the final product **125**. This transition-metal-free borylation can be followed by Pd-catalyzed cross coupling with aryl iodides, to generate trisubstituted olefins **126** in a stereoselective manner.

6. Conclusions

Recent advances in transition-metal-free functionalization of allenamides are summarized herein. These innovative transformations have rendered allenamides highly versatile building blocks in organic synthesis, enabling the assembly of a diverse array of carbo- and heterocyclic structures that can serve as platforms for further transformations. Undoubtedly, the level of interest in allenamides from the synthetic community is immensely high, and there is a tremendous momentum to continue developing allenamide methodology and hence expand their synthetic utility.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- (a) X. Wu and L. Z. Gong, *Synthesis*, 2019, **51**, 122–134; (b) D. G. Geng, *Chin. J. Org. Chem.*, 2019, **39**, 301–317; (c) R. Santhoshkumar and C. H. Cheng, *Asian J. Org. Chem.*, 2018, **7**, 1151–1163; (d) H. Hori, S. Arai and A. Nishida, *Adv. Synth. Catal.*, 2017, **359**, 1170–1176; (e) T. Lu, Z. J. Lu, Z. X. Ma, Y. Zhang and R. P. Hsung, *Chem. Rev.*, 2013, **113**, 4862–4904; (f) P. E. Standen and M. C. Kimber, *Curr. Opin. Drug Discovery Dev.*, 2010, **13**, 645–657.
- A. J. Hubert and H. G. Viehe, *J. Chem. Soc. C*, 1968, 228–230.
- (a) C. Praveen, *Coord. Chem. Rev.*, 2019, **392**, 1–34; (b) J. L. Mascarenas, I. Varela and F. Lopez, *Acc. Chem. Res.*, 2019, **52**, 465–479; (c) E. Manoni and M. Bandini, *Eur. J. Org. Chem.*, 2016, **2016**, 3135–3142; (d) M. E. Muratore, A. Homs, C. Obradors and A. M. Echavarren, *Chem.-Asian J.*, 2014, **9**, 3066–3082; (e) F. Lopez and J. L. Mascarenas, *Beilstein J. Org. Chem.*, 2013, **9**, 2250–2264.
- (a) *Asymmetric Brønsted Acid Catalysis*, ed. M. Rueping, D. Parmar and E. Sugiono, Wiley-VCH, Weinheim, 2016; (b) Y. L. Yin, X. W. Zhao, B. K. Qiao and Z. Y. Jiang, *Org. Chem. Front.*, 2020, **7**, 1283–1296; (c) M. C. Gimeno and R. P. Herrera, *Eur. J. Org. Chem.*, 2020, **2020**, 1057–1068.
- (a) V. T. Tran, S. K. Nimmagadda, M. Y. Liu and K. M. Engle, *Org. Biomol. Chem.*, 2020, **18**, 618–637; (b) A. Rahman and X. F. Lin, *Org. Biomol. Chem.*, 2018, **16**, 4753–4777; (c) Y. Kuroda, S. Harada, K. Yamada and K. Takasu, *J. Synth. Org. Chem., Jpn.*, 2018, **76**, 325–335; (d) A. Gualandi, G. Rodeghiero and P. G. Cozzi, *Asian J. Org. Chem.*, 2018, **7**, 1957–1981.
- C. Romano, M. Q. Jia, M. Monari, E. Manoni and M. Bandini, *Angew. Chem., Int. Ed.*, 2014, **53**, 13854–13857.
- P. Giacinto, A. Bottoni, A. Garelli, G. P. Miscione and M. Bandini, *ChemCatChem*, 2018, **10**, 2442–2449.
- E. Manoni, A. Gualandi, L. Mengozzi, M. Bandini and P. G. Cozzi, *RSC Adv.*, 2015, **5**, 10546–10550.
- X. Y. Yang and F. D. Toste, *Chem. Sci.*, 2016, **7**, 2653–2656.
- L. Villar, U. Uria, J. I. Martinez, L. Prieto, E. Reyes, L. Carrillo and J. L. Vicario, *Angew. Chem., Int. Ed.*, 2017, **56**, 10535–10538.
- K. Yang, X. Z. Bao, S. Y. Liu, J. N. Xu, J. P. Qu and B. M. Wang, *Eur. J. Org. Chem.*, 2018, **2018**, 6469–6473.
- B. M. Yang, X. J. Zhai, S. B. Feng, D. Y. Hu, Y. H. Deng and Z. H. Shao, *Org. Lett.*, 2019, **21**, 330–334.
- S. Biswas, H. Kim, K. L. Cao and S. Shin, *Adv. Synth. Catal.*, 2020, **362**, 1841–1845.
- (a) S. Hummel and S. F. Kirsch, *Beilstein J. Org. Chem.*, 2011, **7**, 847–859; (b) Y. Yamamoto, I. D. Gridnev, N. T. Patil and T. Jin, *Chem. Commun.*, 2009, **34**, 5075–5087; (c) M. J. Mphahlele, *Molecules*, 2009, **14**, 4814–4837; (d) A. N. French, S. Bissmire and T. Wirth, *Chem. Soc. Rev.*, 2004, **33**, 354–362.
- M. Noguchi, H. Okada, M. Watanabe, K. Okuda and O. Nakamura, *Tetrahedron*, 1996, **52**, 6581–6590.
- C. J. T. Hyland and L. S. Hegedus, *J. Org. Chem.*, 2006, **71**, 8658–8660.
- Y. X. Zhu, G. W. Yin, D. Hong, P. Lu and Y. G. Wang, *Org. Lett.*, 2011, **13**, 1024–1027.
- G. W. Yin, Y. X. Zhu, L. Zhang, P. Lu and Y. G. Wang, *Org. Lett.*, 2011, **13**, 940–943.
- H. H. Li, X. X. Li, Z. G. Zhao, T. Ma, C. Y. Sun and B. W. Yang, *Chem. Commun.*, 2016, **52**, 10167–10170.
- H. H. Li, X. X. Li, Z. G. Zhao, C. B. Lin, T. Ma, C. Y. Sun, B. W. Yang and X. L. Fu, *Tetrahedron Lett.*, 2016, **57**, 4640–4644.
- Y. Li, G. L. Luo, X. X. Li and Z. G. Zhao, *New J. Chem.*, 2018, **42**, 16940–16947.



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- 22 X. Yuan, X. Man, X. X. Li and Z. G. Zhao, *Tetrahedron*, 2018, **74**, 5674–5682.
- 23 R. H. Huang, P. Y. Xu, W. X. Wang, G. Peng and H. Yu, *Tetrahedron Lett.*, 2020, **61**, 151753.
- 24 G. L. Luo, Y. C. Liu, N. Ding, X. X. Li and Z. G. Zhao, *ACS Omega*, 2019, **4**, 15312–15322.
- 25 X. Man, Y. C. Liu, X. X. Li and Z. G. Zhao, *New J. Chem.*, 2019, **43**, 14739–14746.
- 26 S. F. Chen, Q. Yan, H. Y. Zhao and B. G. Li, *J. Org. Chem.*, 2013, **78**, 5085–5089.
- 27 J. L. Stille, *Angew. Chem., Int. Ed.*, 1986, **25**, 508–524.
- 28 R. Hayashi, R. P. Hsung, J. B. Feltenberger and A. G. Lohse, *Org. Lett.*, 2009, **11**, 2125–2128.
- 29 R. Hayashi, J. B. Feltenberger, A. G. Lohse, M. C. Walton and R. P. Hsung, *Beilstein J. Org. Chem.*, 2011, **7**, 410–420.
- 30 R. Hayashi, J. B. Feltenberger and R. P. Hsung, *Org. Lett.*, 2010, **12**, 1152–1155.
- 31 R. Hayashi, M. C. Walton, R. P. Hsung, J. H. Schwab and X. L. Yu, *Org. Lett.*, 2010, **12**, 5768–5771.
- 32 R. Hayashi, Z. X. Ma and R. P. Hsung, *Org. Lett.*, 2012, **14**, 252–255.
- 33 J. B. Feltenberger and R. P. Hsung, *Org. Lett.*, 2011, **13**, 3114–3117.
- 34 Z. X. Ma, L. C. Fang, B. J. Haugen, D. Bruckbauer, J. B. Feltenberger and R. P. Hsung, *Synlett*, 2017, **28**, 2906–2912.
- 35 H. H. Li, T. Ma, X. X. Li and Z. G. Zhao, *RSC Adv.*, 2015, **5**, 84044–84047.
- 36 H. H. Li, X. X. Li, Z. G. Zhao, X. Yuan and C. Y. Sun, *Org. Biomol. Chem.*, 2017, **15**, 4005–4013.
- 37 H. Tanimoto, K. Yokoyama, Y. Mizutani, T. Shitaoka, T. Morimoto, Y. Nishiyama and K. Kakiuchi, *J. Org. Chem.*, 2016, **81**, 559–574.
- 38 L. Garcia, J. Sendra, N. Miralles, E. Reyes, J. J. Carbo, J. L. Vicario and E. Fernández, *Chem.–Eur. J.*, 2018, **24**, 14059–14063.

