

Cite this: *Chem. Sci.*, 2025, 16, 6273

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

Received 13th January 2025  
Accepted 4th March 2025

DOI: 10.1039/d5sc00297d

rsc.li/chemical-science

# Catalytic stereoselective synthesis of all-carbon tetra-substituted alkenes via *Z*-selective alkyne difunctionalization†

Prashant S. Shinde,‡<sup>a</sup> Valmik S. Shinde‡<sup>ab</sup> and Magnus Rueping \*<sup>a</sup>

We report a Ni-catalyzed cascade reaction leading to the arylation of an alkyne-induced acyl migration and the formation of all-carbon tetra-substituted alkenes in good yields with exclusive *Z*-selectivity. This transformation involves the generation of a nucleophilic vinyl-Ni species through regioselective *syn*-arylation nickelation of the alkynes, followed by an intramolecular acyl migration. The steric and electronic properties of the phosphine ligands are crucial for achieving high regio- and stereocontrol in this migratory carbo-acylation process. The synthetic utility of the resulting *Z*-tetra-substituted alkenes is also demonstrated.

All-carbon tetrasubstituted olefins bearing four different carbon-based groups are ubiquitous motifs present in numerous natural products and have various applications from medicinal to materials chemistry (Fig. 1).<sup>1–9</sup> Due to their broad applications, significant research efforts are focused on developing general protocols for the challenging stereoselective synthesis, particularly for acyclic structures.<sup>8,10–16</sup> While strategies exist for synthesizing stereo defined *E*-alkenes, their thermodynamically less stable *Z*-isomers remain considerably more challenging. Achieving *Z*-alkenes with four distinct carbon-based substituents and an adjacent reactive functionality remains a formidable challenge.

Classical methods for forming carbon-carbon double bonds include carbonyl olefinations such as the Wittig reaction and its variants (e.g., Julia, Peterson, McMurry, and Horner-Wadsworth-Emmons reactions), as well as metathesis reactions, elimination processes, and additions to triple bonds (Fig. 2a).<sup>17–20</sup> These methods are effective for producing di- or tri-substituted alkenes; however, they typically yield mixtures of stereoisomers when applied to tetrasubstituted alkenes.<sup>11</sup>

Additionally, their efficiency diminishes when faced with the high steric demands of tetra-substituted alkenes, making the selective synthesis of these structures a key area of research, particularly over the past years. An alternative approach involves the stereoselective insertion of two carbon-based groups across a C-C triple bond, either in a stepwise manner or through

multicomponent strategies, offering a promising route for the synthesis of complex alkenyl products.<sup>21–28</sup> However, a major limitation in these transformations is the challenge of achieving regioselectivity, especially with alkynes that have substituents of similar steric or electronic properties. Therefore, developing a general method that enables the synthesis of highly substituted alkene with precise regio- and stereocontrol is crucial for expanding their synthetic utility. A commonly employed method for synthesizing tetrasubstituted alkenes, particularly those with four distinct functional groups, involves the carbometalation of internal alkynes to generate trisubstituted alkenyl metal

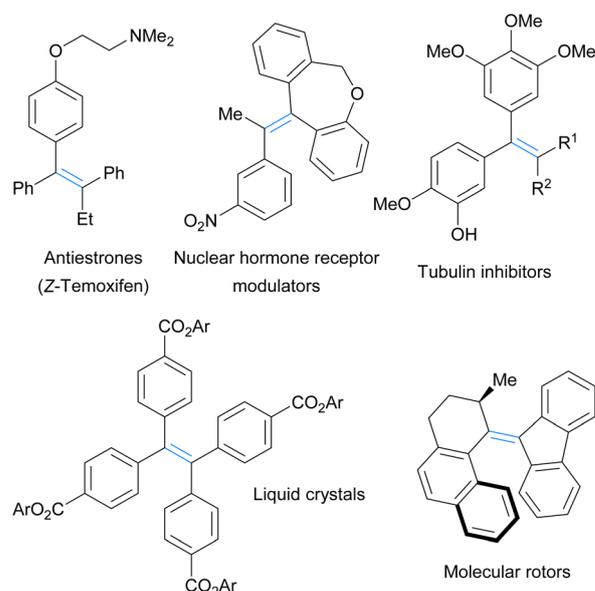


Fig. 1 Current applications for all-carbon tetra-substituted alkenes.

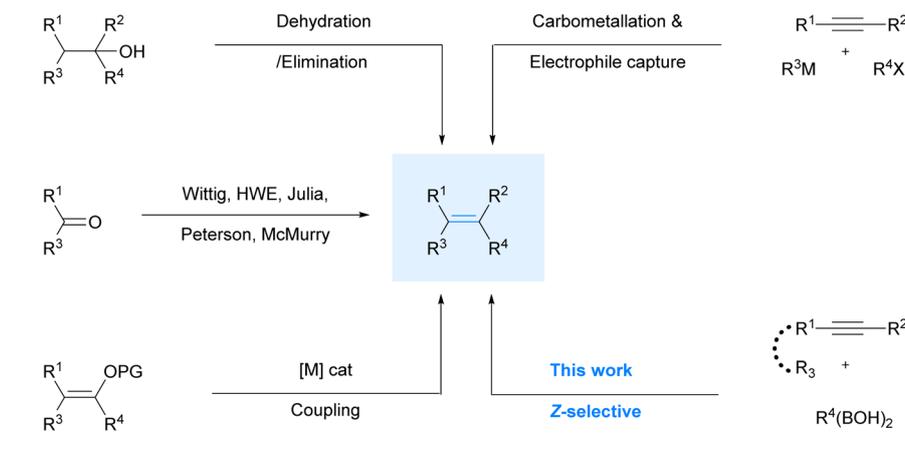
<sup>a</sup>KAUST Catalysis Center (KCC), King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia. E-mail: magnus.rueping@kaust.edu.sa

<sup>b</sup>Medicinal and Process Chemistry Division, CSIR-Central Drug Research Institute, Lucknow 226031, Uttar Pradesh, India

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d5sc00297d>

‡ PSS and VSS contributed equally.

## (a) Synthetic strategies for tetra-substituted alkenes



## (b) This work of tetrasubstituted alkene synthesis from 2-alkynyl phenol ester

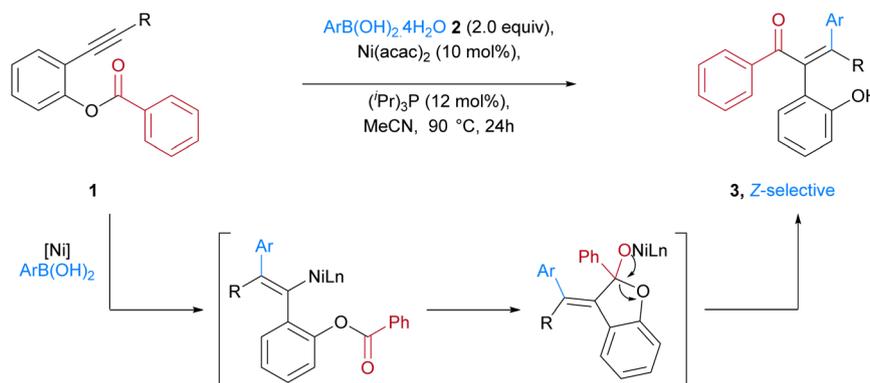


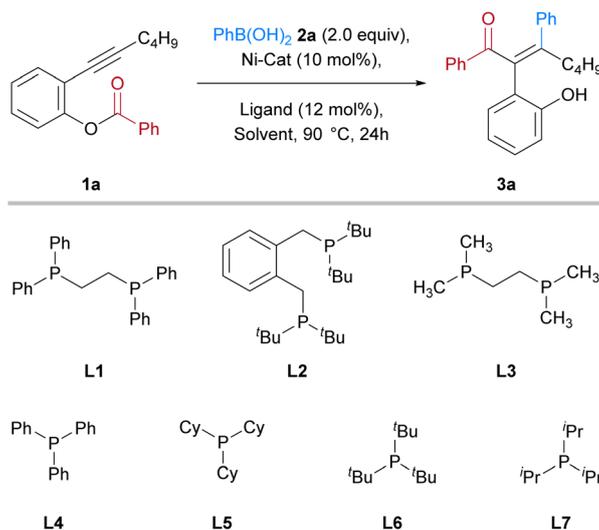
Fig. 2 (a) Synthetic strategies for multi-substituted alkenes; (b) nickel-catalyzed stereoselective synthesis of all-carbon tetra-substituted alkenes via Z-selective alkyne difunctionalization

nucleophiles. These intermediates then react with different electrophiles, often through transition metal-catalyzed cross-coupling processes.<sup>21,25–42</sup> Intramolecular capture, particularly in the form of arylyative cyclization, occurs readily, facilitating the formation of cyclic scaffolds with good efficiency.<sup>43–47</sup> Prompted by these reports and by our continuing research interests in nickel-catalyzed transformations,<sup>48–52</sup> we envisioned that by using alkyne-tethered phenolic ester substrate, regioselective *syn*-aryl nickelation of an alkyne would generate nucleophilic vinyl Ni [II] species that may undergo nucleophilic addition to the carbonyl carbon of tethered ester group (Fig. 2b).<sup>47,53,54</sup> We anticipated that the careful choice of bulkier ligands<sup>55–66</sup> could assist in the C–O bond cleavage of the intermediate which would result in subsequent intramolecular acyl group migration<sup>67</sup> and formation of tetrasubstituted alkene products in a stereoselective manner (Fig. 2b). Herein, we describe the successful development of a nickel-catalyzed tandem alkyne hydroarylation acylation strategy, which proceeds with complete Z-selectivity and high regioselectivity to produce a variety of tetra-substituted

alkene products in good-to-excellent yields. The key to the success of this method is the use of Ni-catalysts with bulky monodentate phosphine ligands.

We began our study by reacting 2-hexynyl phenol ester **1a**, synthesized in two steps from 2-iodophenol, with phenyl boronic acid **2a** using various nickel catalysts in acetonitrile at 90 °C (Table 1). Notably, when using Ni(acac)<sub>2</sub>·4H<sub>2</sub>O in combination with the bidentate phosphine ligand 1,2-bis(diphenylphosphino)ethane (**L1**), the desired alkene product **3a** was obtained with high stereoselectivity, achieving a 57% yield (Table 1, entry 1). Analysis of the purified reaction mixture by <sup>1</sup>H NMR spectroscopy confirmed the formation of the expected tetrasubstituted alkene **3a** with excellent Z-selectivity. The choice of the ligand had a significant effect on the reactivity and selectivity of the transformation.<sup>68–71</sup> Systematic studies of various bidentate and monodentate ligands revealed that the use of bulkier monodentate ligands afforded better yield and selectivity (Table 1, entries 1–7). Among the ligands tested, triisopropylphosphine ligand (**L7**) demonstrated the highest



Table 1 Optimization of nickel-catalyzed aryl-acylation of alkynes<sup>a</sup>

Entry	Ni-catalyst	Solvent	L	Yield <sup>b, c</sup> (%)	Z : E
1	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L1</b>	57	99 : 1
2	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L2</b>	52	99 : 1
3	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L3</b>	39	95 : 5
4	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L4</b>	52	96 : 4
5	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L5</b>	80	99 : 1
6	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L6</b>	87	99 : 1
7	<b>Ni(acac)<sub>2</sub>·4H<sub>2</sub>O</b>	<b>MeCN</b>	<b>L7</b>	<b>90<sup>c</sup></b>	<b>99 : 1</b>
8	Ni(OAc) <sub>2</sub> ·4H <sub>2</sub> O	MeCN	<b>L7</b>	84	99 : 1
9	Ni(ClO <sub>4</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	MeCN	<b>L7</b>	57	98 : 2
10	NiBr <sub>2</sub> ·3H <sub>2</sub> O	MeCN	<b>L7</b>	62	98 : 2
11	Ni(COD) <sub>2</sub>	MeCN	<b>L7</b>	86	98 : 2
12	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	Dioxane	<b>L7</b>	66	99 : 1
13	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	THF	<b>L7</b>	62	99 : 1
14	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O	MeCN : 2-Me THF	<b>L7</b>	78	99 : 1
15	Ni(acac) <sub>2</sub> ·4H <sub>2</sub> O, K <sub>2</sub> CO <sub>3</sub> , CsCO <sub>3</sub>	MeCN	<b>L7</b>	0	NA

<sup>a</sup> All reaction were carried out on a 0.2 mmol scale. <sup>b</sup> Yield determined by GC using dodecane as an internal standard. <sup>c</sup> Isolated yield.

reactivity and was selected for further investigation due to its cleaner reaction profile and excellent Z-selectivity (99:1) (Table 1, entry 7). We also evaluated various commercially available Ni-salts in combination with ligand **L7**, which yielded comparable reactivity (entries 8–11). However, using Ni(0) in place of Ni(II) led to slightly reduced reactivity and selectivity (entry 11). Acetonitrile (MeCN) emerged as the optimal solvent among those tested (entries 12–14). Control experiments confirmed that both the Ni complex and ligand were crucial for the reaction's success. Reducing the catalyst loading to 5 mol% had a detrimental effect on the reaction, resulting in lower yields and longer reaction times. The use of bases, typically used for coupling reactions, resulted in no product formation as the substrate is prone to ester hydrolysis (entry 15). Changing the substrate to the corresponding acetylated phenol resulted in the

formation of the corresponding benzofurane product (*vide infra*).

With the optimized conditions established, we next explored the scope of the aryl acylation reaction of alkynes. We began by examining the suitability of various aryl boronic acids (**2**) as coupling partners (Fig. 3). Generally, the steric and electronic properties of the phenyl ring in *para*- and *meta*-substituted aryl boronic acids did not significantly influence the reaction yield. Both electron-rich and electron-deficient aryl boronic acids, featuring substituents such as methyl, *t*-butyl, halogen, trifluoromethyl, *o*-phenoxy, and cyano-groups, successfully reacted with *o*-hexynyl phenol ester **1a**, producing the corresponding rearranged products **3** in good yields (**3a–3l**). In most cases, boronic acids bearing electron-donating groups (*e.g.*, **3j**) resulted in slightly higher yields compared to those



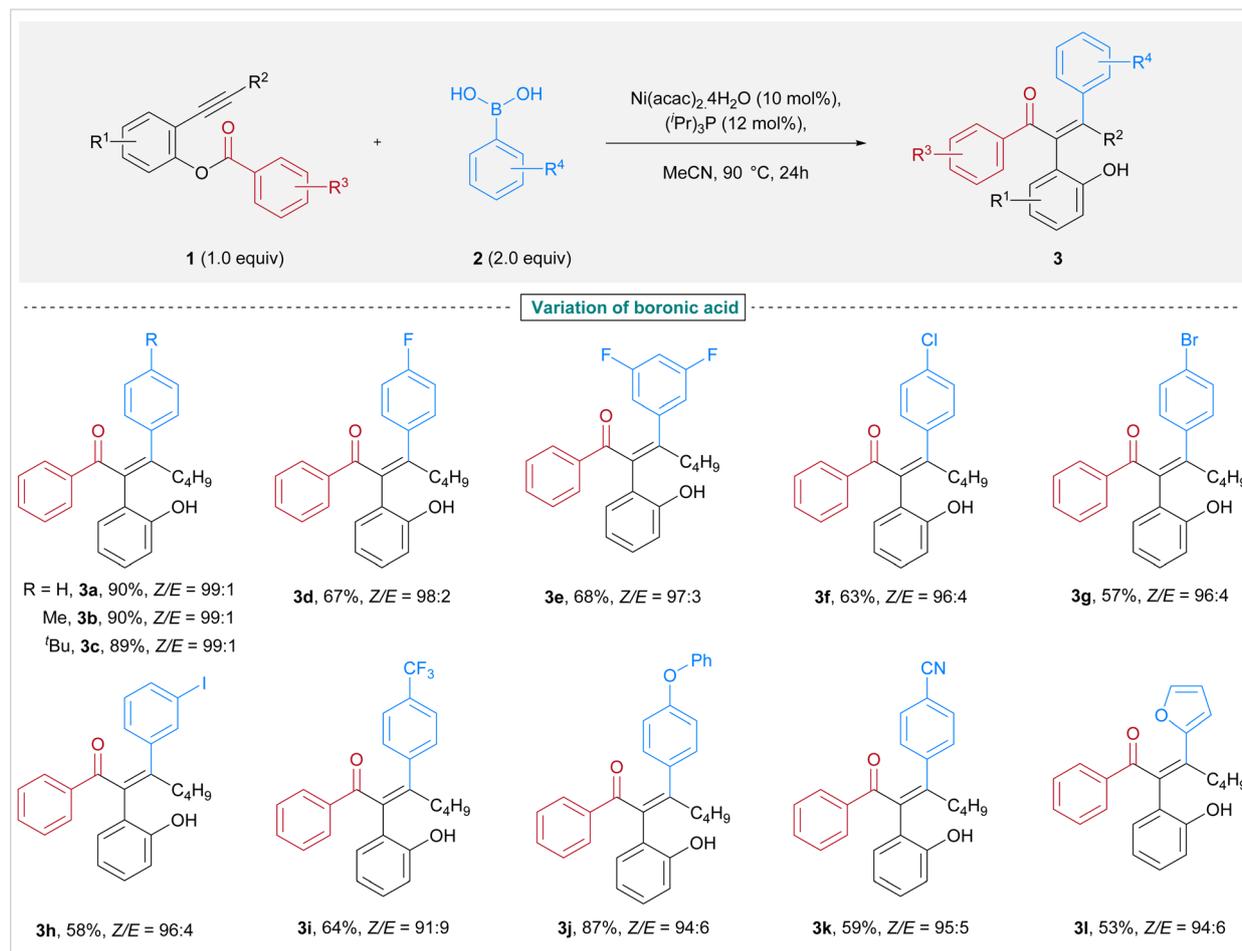


Fig. 3 Scope of Ni-catalyzed aryl-acylation of alkynes using boronic acids.

with electron-withdrawing groups (e.g., **3k**). Additionally, hetero-aromatic boronic acids proved compatible with this reaction, delivering a lower yield of the desired product (**3l**). We then explored the generality of this Ni-catalyzed aryl acylation reaction with 2-alkynyl phenol esters **1**, featuring various ester groups in (Fig. 4). Variations in the ester group on the phenol did not significantly impact the reaction efficiency. The reaction conditions were well-tolerated with a range of ester groups, including strained cyclopropyl (**3n**), 4-methyl (**3m**), naphthyl (**3o**), *p*-chloro (**3p**), *o*-bromo (**3q**), pentafluoro (**3r**), electron-donating groups such as methoxy (**3s**) and *N,N*-dimethylamine (**3t**), as well as electron-withdrawing groups like nitro (**3v**). Additionally, heteroatomic thiophene-containing esters (**3w**) were also compatible. Notably, the reaction was not restricted to simple esters; phosphoryl esters also yielded the desired product, albeit as a *Z/E* mixture (77 : 23) (**3x**). Next, we investigated the reaction scope with variations in the alkyne side chain ( $R^2$ ). When 2-alkynyl phenol ester **1** containing a shorter alkyl chain substituent on the alkynyl moiety was employed, the reaction afforded a single isomer, yielding 76% of the corresponding tetrasubstituted alkene (**3y**) as a white solid. The

structure of (**3y**) was unambiguously confirmed through X-ray crystallographic analysis (CCDC: 2110836).

Reactions of **1**, bearing longer alkyl chain, heteroatomic, and phenyl group substituents on the alkyne moiety, also resulted in the formation of the corresponding tetra-substituted alkenes (**3z–3ac**) in high yields. We also examined substrates with various substituents on the phenol ring, including phenyl, methyl ester, fluoro, and chloro groups. In all cases, the expected products were obtained in good to excellent yields (**3ad–3ag**).

Notably, expanding the scope of the *syn*-arylation rearrangement to include an amide moiety in place of the ester also proved successful under standard conditions, yielding the corresponding alkene derivative (**3ah**) in 52%. Furthermore, the scalability of our protocol was exemplified by the aryl-acylation of 2-hexynyl phenol ester **1a** on a 1.2-gram scale affording 84% of *Z*-alkene **3b**. We next showcased the synthetic utility of the products through a series of post-functionalization reactions (Fig. 5). PTSA-catalyzed dehydrative cyclization of (**3b**) yielded the corresponding 2,3-difunctionalized benzofuran<sup>47,72,73</sup> **4** in good yield. Treatment of **3b** with  $\text{LiAlH}_4$  led to the selective reduction of the ketone moiety, providing the reduced product



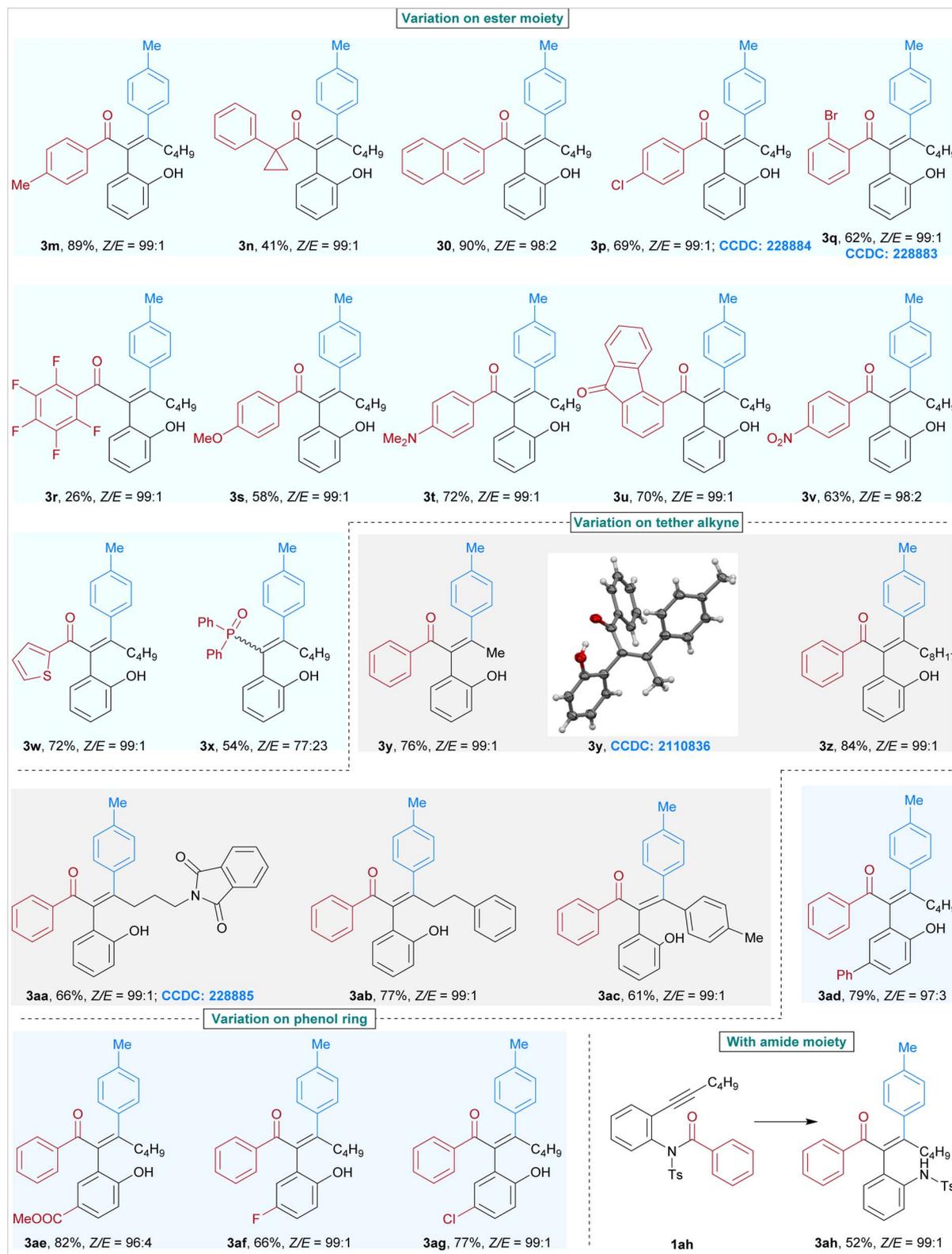


Fig. 4 Scope of variation in esters, tethered alkynes, and phenolic groups.

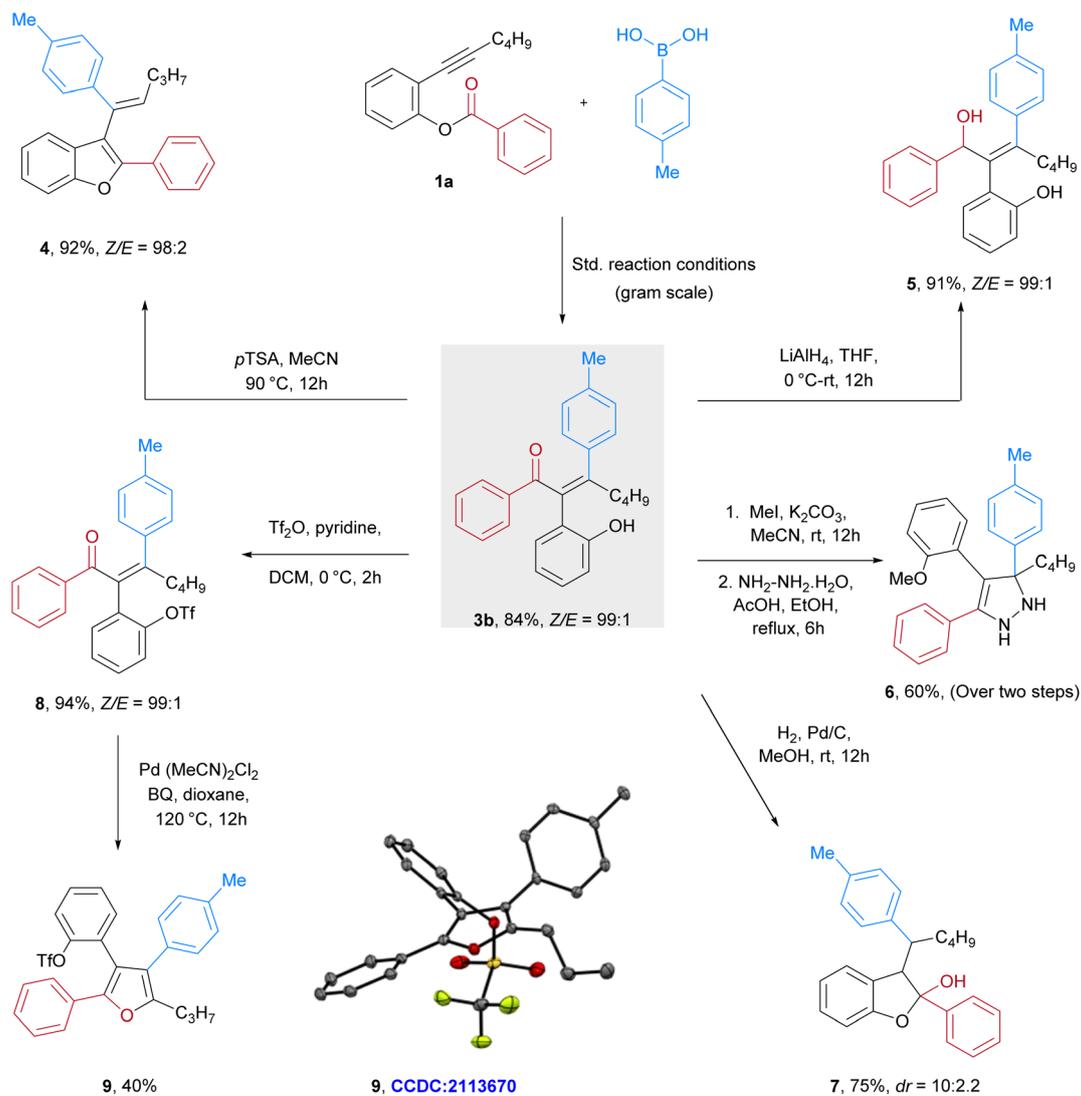


Fig. 5 Chemical transformations of **3b** to synthetically valuable building blocks.

in excellent yield. We then aimed to transform **3b** into the highly functionalized pyrazole structure **6** through a selective five-membered ring cyclization using hydrazine hydrate. Additionally, Pd/C-catalyzed hydrogenation of **3b** produced substituted benzofuran-2-ol **7** in 75% yield. Additionally, we leveraged the phenol group on **3b** as a functional handle, converting it into the corresponding triflate **8** in 94% yield. This triflate was subsequently subjected to a Pd-catalyzed oxidative coupling reaction. Interestingly, an unexpected transformation occurred and yielded a tetrasubstituted furan **9**. The structure of the furan **9** was confirmed by X-ray crystallographic analysis (CCDC: 2113670). On the basis of the literature reports<sup>47,53,54,57,74,75</sup> and the experimental results we propose a catalytic cycle (Fig. 6). Initially, the nickel complex undergoes a transmetalation with boronic acids **2a** to form the aryl-Ni intermediate **A**, which regioselectively adds in *syn* fashion across the alkyne in **1a** to form the alkenyl-Ni species **B**. The organo-nickel intermediate **B** subsequently adds to the carbonyl carbon of the ester moiety that results in cyclic intermediate **C**.

Finally, the C–O bond cleavage with ring opening leads to the formation of alkene product **3a** with acyl group migration along with the regeneration of the Ni complex.

In summary, we have developed an unconventional Ni-catalyzed approach for the synthesis of tetrasubstituted alkenes from alkynes and boronic acids. This method enables a one-step difunctionalization of internal alkynes through the simultaneous addition of both aryl and acyl groups across triple bonds, providing streamlined access to tetrasubstituted alkenes with high regio- and stereocontrol; challenging to achieve with conventional methods. The process exhibits excellent functional group compatibility and broad synthetic applicability, even in complex molecular settings. Its practicality is further demonstrated by gram-scale synthesis and diverse post-functionalization of complex molecules. This straightforward protocol opens new avenues in multi-substitution chemistry for acyclic, all-carbon tetrasubstituted Z-olefinic products.



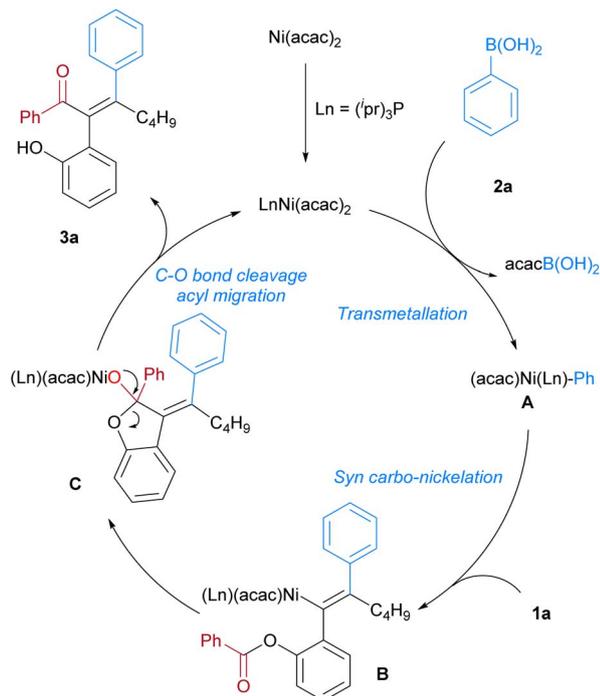


Fig. 6 Plausible mechanism of the Ni-catalyzed aryl-acylation of alkynes.

## Data availability

Experiment procedures, characterization of the new compounds are available in the ESI.†

## Author contributions

P. S. S., V. S. S., and M. R. conceived and designed the experiments. P. S. S., V. S. S. conducted the experiments, analyzed the data and wrote the manuscript, while M. R. supervised the project and the manuscript.

## Conflicts of interest

The authors declare no competing financial interests.

## Acknowledgements

This work was financially supported by the King Abdullah University of Science and Technology (KAUST), Saudi Arabia, Office of Sponsored Research (URF/1/4405).

## Notes and references

- 1 M. W. DeGregorio and V. J. Wiebe, *Tamoxifen and breast cancer*, Yale University Press, New Haven, CT, 2nd edn, 1999.
- 2 A. Levenson and V. Jordan, Selective oestrogen receptor modulation: molecular pharmacology for the millennium, *Eur. J. Cancer*, 1999, **35**, 1974–1985.

- 3 R. McCague, G. Leclercq, N. Legros, J. Goodman, G. M. Blackburn, M. Jarman and A. B. Foster, Derivatives of tamoxifen. Dependence of antiestrogenicity on the 4-substituent, *J. Med. Chem.*, 1989, **32**, 2527–2533.
- 4 C. E. Connor, J. D. Norris, G. Broadwater, T. M. Willson, M. M. Gottardis, M. W. Dewhirst and D. P. McDonnell, Circumventing tamoxifen resistance in breast cancers using antiestrogens that induce unique conformational changes in the estrogen receptor, *Cancer Res.*, 2001, **61**, 2917–2922.
- 5 A. Lai, M. Kahraman, S. Govek, J. Nagasawa, C. Bonnefous, J. Julien, K. Douglas, J. Sensintaffar, N. Lu and K.-j. Lee, Identification of GDC-0810 (ARN-810), an orally bioavailable selective estrogen receptor degrader (SERD) that demonstrates robust activity in tamoxifen-resistant breast cancer xenografts, *J. Med. Chem.*, 2015, **58**, 4888–4904.
- 6 B. L. Feringa, R. A. Van Delden, N. Koumura and E. M. Geertsema, Chiroptical molecular switches, *Chem. Rev.*, 2000, **100**, 1789–1816.
- 7 A. Schreivogel, J. Maurer, R. Winter, A. Baro and S. Laschat, Synthesis and Electrochemical Properties of Tetrasubstituted Tetraphenylethenes, *Eur. J. Org. Chem.*, 2006, **2006**, 3395–3404.
- 8 N. Mukherjee, S. Planer and K. Grela, Formation of tetrasubstituted C–C double bonds via olefin metathesis: challenges, catalysts, and applications in natural product synthesis, *Org. Chem. Front.*, 2018, **5**, 494–516.
- 9 D. D. La, S. V. Bhosale, L. A. Jones and S. V. Bhosale, Tetraphenylethylene-based AIE-active probes for sensing applications, *ACS Appl. Mater. Interfaces*, 2017, **10**, 12189–12216.
- 10 O. Reiser, Palladium-Catalyzed Coupling Reactions for the Stereoselective Synthesis of Tri- and Tetrasubstituted Alkenes, *Angew. Chem., Int. Ed.*, 2006, **45**, 2838–2840.
- 11 A. B. Flynn and W. W. Ogilvie, Stereocontrolled synthesis of tetrasubstituted olefins, *Chem. Rev.*, 2007, **107**, 4698–4745.
- 12 K. Murakami and H. Yorimitsu, Recent advances in transition-metal-catalyzed intermolecular carbomagnesiation and carbozincation, *Beilstein J. Org. Chem.*, 2013, **9**, 278–302.
- 13 V. P. Boyarskiy, D. S. Ryabukhin, N. A. Bokach and A. V. Vasilyev, Alkenylation of arenes and heteroarenes with alkynes, *Chem. Rev.*, 2016, **116**, 5894–5986.
- 14 P. Polák, H. Váňová, D. Dvořák and T. Tobrman, Recent progress in transition metal-catalyzed stereoselective synthesis of acyclic all-carbon tetrasubstituted alkenes, *Tetrahedron Lett.*, 2016, **57**, 3684–3693.
- 15 D. Müller and I. Marek, Copper mediated carbometalation reactions, *Chem. Soc. Rev.*, 2016, **45**, 4552–4566.
- 16 B. M. Trost and J. S. Tracy, Vanadium-catalyzed synthesis of geometrically defined acyclic tri- and tetrasubstituted olefins from propargyl alcohols, *ACS Catal.*, 2019, **9**, 1584–1594.
- 17 B. E. Maryanoff and A. B. Reitz, The Wittig olefination reaction and modifications involving phosphoryl-stabilized carbanions. Stereochemistry, mechanism, and selected synthetic aspects, *Chem. Rev.*, 1989, **89**, 863–927.



- 18 Y. Yang, S.-F. Zhu, C.-Y. Zhou and Q.-L. Zhou, Nickel-catalyzed enantioselective alkylative coupling of alkynes and aldehydes: synthesis of chiral allylic alcohols with tetrasubstituted olefins, *J. Am. Chem. Soc.*, 2008, **130**, 14052–14053.
- 19 D. Zell, C. Kingston, J. Jermaks, S. R. Smith, N. Seeger, J. Wassmer, L. E. Sirois, C. Han, H. Zhang and M. S. Sigman, Stereoconvergent and-divergent synthesis of tetrasubstituted alkenes by nickel-catalyzed cross-couplings, *J. Am. Chem. Soc.*, 2021, **143**, 19078–19090.
- 20 Y. Weng, Y. Zhang, A. Turluk, X. Wu, H. Li, F. Fei, Y. Yao, C. Wang, Z. Guo and J. Qu, Nickel-catalysed regio- and stereoselective acylzincation of unsaturated hydrocarbons with organozincs and CO, *Nat. Synth.*, 2023, **2**, 261–274.
- 21 W. You, Y. Li and M. K. Brown, Stereoselective synthesis of all-carbon tetrasubstituted alkenes from in situ generated ketenes and organometallic reagents, *Org. Lett.*, 2013, **15**, 1610–1613.
- 22 B. X. Li, D. N. Le, K. A. Mack, A. McClory, N.-K. Lim, T. Cravillon, S. Savage, C. Han, D. B. Collum and H. Zhang, Highly stereoselective synthesis of tetrasubstituted acyclic all-carbon olefins via enol tosylation and Suzuki–Miyaura coupling, *J. Am. Chem. Soc.*, 2017, **139**, 10777–10783.
- 23 Z. Lin, W. Hu, L. Zhang and C. Wang, Nickel-catalyzed asymmetric cross-electrophile *trans*-aryl-benzoylation of  $\alpha$ -naphthyl propargylic alcohols, *ACS Catal.*, 2023, **13**, 6795–6803.
- 24 M. Bera, S. D. Tambe, H. S. Hwang, S. Kim and E. J. Cho, Base-free NiH-catalyzed regio- and stereo-selective hydroacylation of allenes: A new route to synthesis of tetrasubstituted olefins, *Chem Catal.*, 2023, **3**, 100606.
- 25 U. Wille, Radical cascades initiated by intermolecular radical addition to alkynes and related triple bond systems, *Chem. Rev.*, 2013, **113**, 813–853.
- 26 T. Besset, T. Poisson and X. Pannecoucke, Direct vicinal difunctionalization of alkynes: an efficient approach towards the synthesis of highly functionalized fluorinated alkenes, *Eur. J. Org. Chem.*, 2015, **2015**, 2765–2789.
- 27 T. Koike and M. Akita, A versatile strategy for difunctionalization of carbon–carbon multiple bonds by photoredox catalysis, *Org. Chem. Front.*, 2016, **3**, 1345–1349.
- 28 M. C. Haibach, S. Shekhar, T. S. Ahmed and A. R. Ickes, Recent advances in nonprecious metal catalysis, *Org. Process Res. Dev.*, 2023, **27**, 423–447.
- 29 N. Iqbal, J. Jung, S. Park and E. J. Cho, Controlled trifluoromethylation reactions of alkynes through visible-light photoredox catalysis, *Angew. Chem., Int. Ed.*, 2014, **126**, 549–552.
- 30 T. Xu, C. W. Cheung and X. Hu, Iron-Catalyzed 1,2-Addition of Perfluoroalkyl Iodides to Alkynes and Alkenes, *Angew. Chem., Int. Ed.*, 2014, **126**, 4910–4914.
- 31 L. Huang, M. Rudolph, F. Rominger and A. S. K. Hashmi, Photosensitizer-free visible-light-mediated gold-catalyzed 1,2-difunctionalization of alkynes, *Angew. Chem., Int. Ed.*, 2016, **55**, 4808–4813.
- 32 M. H. Babu, G. R. Kumar, R. Kant and M. S. Reddy, Ni-Catalyzed regio- and stereoselective addition of arylboronic acids to terminal alkynes with a directing group tether, *Chem. Commun.*, 2017, **53**, 3894–3897.
- 33 Z. Li, E. Merino and C. Nevado, Stereoselective Carboperfluoroalkylation of Internal Alkynes: Mechanistic Insights, *Top. Catal.*, 2017, **60**, 545–553.
- 34 H. Yue, C. Zhu, R. Kancherla, F. Liu and M. Rueping, Regioselective Hydroalkylation and Arylalkylation of Alkynes by Photoredox/Nickel Dual Catalysis: Application and Mechanism, *Angew. Chem., Int. Ed.*, 2020, **59**, 5738–5746.
- 35 H. Yao, W. Hu and W. Zhang, Difunctionalization of alkenes and alkynes via intermolecular radical and nucleophilic additions, *Molecules*, 2020, **26**, 105.
- 36 Y. Jiang, J. Pan, T. Yang, Y. Zhao and M. J. Koh, Nickel-catalyzed site- and stereoselective reductive alkylalkynylation of alkynes, *Chem*, 2021, **7**, 993–1005.
- 37 N. Xiao, Y.-Z. Zhan, H. Meng and W. Shu, Access to *Z*-selective 1,3-enynes via Ni-catalyzed intermolecular cross-alkylalkynylation of terminal alkynes, *Org. Lett.*, 2021, **23**, 5186–5191.
- 38 Y.-Z. Zhan, N. Xiao and W. Shu, Ni-catalyzed regio- and stereo-defined intermolecular cross-electrophile dialkylation of alkynes without directing group, *Nat. Commun.*, 2021, **12**, 928.
- 39 S. Maiti and J. H. Rhlee, Reductive Ni-catalysis for stereoselective carboarylation of terminal aryl alkynes, *Chem. Commun.*, 2021, **57**, 11346–11349.
- 40 Y.-Z. Zhan, H. Meng and W. Shu, Rapid access to *t*-butylalkylated olefins enabled by Ni-catalyzed intermolecular regio- and *trans*-selective cross-electrophile *t*-butylalkylation of alkynes, *Chem. Sci.*, 2022, **13**, 4930–4935.
- 41 Y. Dai, F. Wang, S. Zhu and L. Chu, Selective Ni-catalyzed cross-electrophile coupling of alkynes, fluoroalkyl halides, and vinyl halides, *Chin. Chem. Lett.*, 2022, **33**, 4074–4078.
- 42 H. Li, F. Wang, S. Zhu and L. Chu, Selective Fluoromethyl Couplings of Alkynes via Nickel Catalysis, *Angew. Chem., Int. Ed.*, 2022, **134**, e202116725.
- 43 L. Zhou, M. Zhang, W. Li and J. Zhang, Furan-Based *o*-Quinodimethanes by Gold-Catalyzed Dehydrogenative Heterocyclization of 2-(1-Alkynyl)-2-alken-1-ones: A Modular Entry to 2,3-Furan-Fused Carbocycles, *Angew. Chem., Int. Ed.*, 2014, **53**, 6542–6545.
- 44 J. Sun, J.-K. Qiu, Y.-N. Wu, W.-J. Hao, C. Guo, G. Li, S.-J. Tu and B. Jiang, Silver-Mediated Radical C ( $sp^3$ )-H Biphosphinylation and Nitration of  $\beta$ -Alkynyl Ketones for Accessing Functional Isochromenes, *Org. Lett.*, 2017, **19**, 754–757.
- 45 J. Wang, X. Cao, S. Lv, C. Zhang, S. Xu, M. Shi and J. Zhang, Synthesis and structures of gold and copper carbene intermediates in catalytic amination of alkynes, *Nat. Commun.*, 2017, **8**, 14625.
- 46 S. Ge, W. Cao, T. Kang, B. Hu, H. Zhang, Z. Su, X. Liu and X. Feng, Bimetallic Catalytic Asymmetric Tandem Reaction of  $\beta$ -Alkynyl Ketones to Synthesize 6,6-Spiroketal, *Angew. Chem., Int. Ed.*, 2019, **58**, 4017–4021.
- 47 N. Iqbal, N. Iqbal, D. Maiti and E. J. Cho, Access to Multifunctionalized Benzofurans by Aryl Nickelation of



- Alkynes: Efficient Synthesis of the Anti-Arrhythmic Drug Amiodarone, *Angew. Chem., Int. Ed.*, 2019, **58**, 15808–15812.
- 48 L. Guo and M. Rueping, Decarbonylative cross-couplings: nickel catalyzed functional group interconversion strategies for the construction of complex organic molecules, *Acc. Chem. Res.*, 2018, **51**, 1185–1195.
- 49 A. Chatupheeraphat, H.-H. Liao, W. Srimontree, L. Guo, Y. Minenkov, A. Poater, L. Cavallo and M. Rueping, Ligand-controlled chemoselective C (acyl)–O bond vs. C (aryl)–C bond activation of aromatic esters in nickel catalyzed C (sp<sup>2</sup>)–C (sp<sup>3</sup>) cross-couplings, *J. Am. Chem. Soc.*, 2018, **140**, 3724–3735.
- 50 S.-C. Lee, L. Guo and M. Rueping, Nickel-catalyzed exo-selective hydroacylation/Suzuki cross-coupling reaction, *Chem. Commun.*, 2019, **55**, 14984–14987.
- 51 C. Zhu, H. Yue and M. Rueping, Nickel catalyzed multicomponent stereodivergent synthesis of olefins enabled by electrochemistry, photocatalysis and photo-electrochemistry, *Nat. Commun.*, 2022, **13**, 3240.
- 52 T. Long, C. Zhu, L. Li, L. Shao, S. Zhu, M. Rueping and L. Chu, Ligand-controlled stereodivergent alkenylation of alkynes to access functionalized *trans*- and *cis*-1,3-dienes, *Nat. Commun.*, 2023, **14**, 55.
- 53 J. Corpas, P. Mauleon, R. G. Arrayás and J. C. Carretero, Transition-metal-catalyzed functionalization of alkynes with organoboron reagents: new trends, mechanistic insights, and applications, *ACS Catal.*, 2021, **11**, 7513–7551.
- 54 S. M. Gillbard and H. W. Lam, Nickel-Catalyzed Arylative Cyclizations of Alkyne-and Allene-Tethered Electrophiles using Arylboron Reagents, *Chem.–Eur. J.*, 2022, **28**, e202104230.
- 55 S. Z. Tasker, E. A. Standley and T. F. Jamison, Recent advances in homogeneous nickel catalysis, *Nature*, 2014, **509**, 299–309.
- 56 V. P. Ananikov, Nickel: The “Spirited Horse” of Transition Metal Catalysis, *ACS Catal.*, 2015, **5**, 1964–1971.
- 57 C. Clarke, C. A. Incerti-Pradillos and H. W. Lam, Enantioselective nickel-catalyzed anti-carbometallative cyclizations of alkynyl electrophiles enabled by reversible alkenylnickel *E/Z* isomerization, *J. Am. Chem. Soc.*, 2016, **138**, 8068–8071.
- 58 X. Zhang, X. Xie and Y. Liu, Nickel-catalyzed cyclization of alkyne-nitriles with organoboronic acids involving anti-carbometallation of alkynes, *Chem. Sci.*, 2016, **7**, 5815–5820.
- 59 Z. Li, A. García-Domínguez and C. Nevado, Nickel-catalyzed stereoselective dicarbofunctionalization of alkynes, *Angew. Chem., Int. Ed.*, 2016, **55**, 6938–6941.
- 60 C. Yap, G. M. J. Lenagh-Snow, S. N. Karad, W. Lewis, L. J. Diorazio and H. W. Lam, Enantioselective Nickel-Catalyzed Intramolecular Allylic Alkenylations Enabled by Reversible Alkenylnickel *E/Z* Isomerization, *Angew. Chem., Int. Ed.*, 2017, **56**, 8216–8220.
- 61 S. M. Gillbard, C.-H. Chung, S. N. Karad, H. Panchal, W. Lewis and H. W. Lam, Synthesis of multisubstituted pyrroles by nickel-catalyzed arylative cyclizations of *N*-tosyl alkynamides, *Chem. Commun.*, 2018, **54**, 11769–11772.
- 62 S. N. Karad, H. Panchal, C. Clarke, W. Lewis and H. W. Lam, Enantioselective Synthesis of Chiral Cyclopent-2-enones by Nickel-Catalyzed Desymmetrization of Malonate Esters, *Angew. Chem., Int. Ed.*, 2018, **57**, 9122–9125.
- 63 X. Zhang, X. Xie and Y. Liu, Nickel-catalyzed highly regioselective hydrocyanation of terminal alkynes with Zn (CN)<sub>2</sub> using water as the hydrogen source, *J. Am. Chem. Soc.*, 2018, **140**, 7385–7389.
- 64 C. Zhu, H. Yue, B. Maity, I. Atodiresei, L. Cavallo and M. Rueping, A multicomponent synthesis of stereodefined olefins *via* nickel catalysis and single electron/triplet energy transfer, *Nat. Catal.*, 2019, **2**, 678–687.
- 65 C. Zhu, H. Yue, L. Chu and M. Rueping, Recent advances in photoredox and nickel dual-catalyzed cascade reactions: pushing the boundaries of complexity, *Chem. Sci.*, 2020, **11**, 4051–4064.
- 66 C. Zhu, H. Yue, J. Jia and M. Rueping, Nickel-Catalyzed C-Heteroatom Cross-Coupling Reactions under Mild Conditions *via* Facilitated Reductive Elimination, *Angew. Chem., Int. Ed.*, 2021, **60**, 17810–17831.
- 67 T. Miura, M. Shimada and M. Murakami, Acyl 1,3-migration in rhodium-catalyzed reactions of acetylenic  $\beta$ -ketoesters with aryl boronic acids: application to two-carbon-atom ring expansions, *Angew. Chem., Int. Ed.*, 2005, **44**, 7598–7600.
- 68 E. P. Jackson, H. A. Malik, G. J. Sormunen, R. D. Baxter, P. Liu, H. Wang, A.-R. Shareef and J. Montgomery, Mechanistic basis for regioselection and regiodivergence in nickel-catalyzed reductive couplings, *Acc. Chem. Res.*, 2015, **48**, 1736–1745.
- 69 E. D. Entz, J. E. Russell, L. V. Hooker and S. R. Neufeldt, Small Phosphine Ligands Enable Selective Oxidative Addition of Ar–O over Ar–Cl Bonds at Nickel(0), *J. Am. Chem. Soc.*, 2020, **142**, 15454–15463.
- 70 M. H. Tse, P. Y. Choy and F. Y. Kwong, Facile assembly of modular-type phosphines for tackling modern arylation processes, *Acc. Chem. Res.*, 2022, **55**, 3688–3705.
- 71 T. Gensch, S. R. Smith, T. J. Colacot, Y. N. Timsina, G. Xu, B. W. Glasspoole and M. S. Sigman, Design and application of a screening set for monophosphine ligands in cross-coupling, *ACS Catal.*, 2022, **12**, 7773–7780.
- 72 C. Martinez, R. Alvarez and J. M. Aurrecoechea, Palladium-catalyzed sequential oxidative cyclization/coupling of 2-alkynylphenols and alkenes: a direct entry into 3-alkenylbenzofurans, *Org. Lett.*, 2009, **11**, 1083–1086.
- 73 R. Álvarez, C. Martínez, Y. Madich, J. G. Denis, J. M. Aurrecoechea and Á. R. de Lera, A General Synthesis of Alkenyl-Substituted Benzofurans, Indoles, and Isoquinolones by Cascade Palladium-Catalyzed Heterocyclization/Oxidative Heck Coupling, *Chem.–Eur. J.*, 2010, **16**, 12746–12753.
- 74 N. Iqbal, D. S. Lee, H. Jung and E. J. Cho, Synergistic effects of boron and oxygen interaction enabling nickel-catalyzed exogenous base-free stereoselective arylvinylolation of alkynes through vinyl transposition, *ACS Catal.*, 2021, **11**, 5017–5025.
- 75 J. Bae, W. Lee, H. S. Hwang, S. Kim, J. Kang, N. Iqbal and E. J. Cho, Nonclassical Arylative Meyer–Schuster Rearrangement through Ni-Catalyzed Inner-Sphere Acyloxy Migration, *ACS Catal.*, 2023, **13**, 10756–10764.

