

REVIEW

View Article Online
View Journal | View IssueCite this: *Org. Chem. Front.*, 2020, 7, 3941Received 9th September 2020,
Accepted 13th October 2020

DOI: 10.1039/d0qo01097a

rsc.li/frontiers-organic

Ni-Catalyzed stereoselective difunctionalization of alkynes

Wenfeng Liu and Wangqing Kong *

Tri- and tetrasubstituted olefins are widely present in biologically active molecules and functional materials. However, the methods for the stereoselective construction of such moieties are still very limited and extremely challenging. The transition-metal-catalyzed difunctionalization of alkynes is one of the most straightforward and effective choices. In this review, we summarize the progress of the nickel-catalyzed alkyne difunctionalization reaction, with an emphasis on the strategy and control of stereochemistry.

1. Introduction

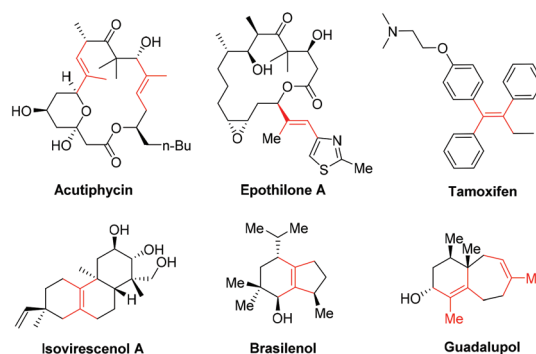
Tri- and tetra-substituted alkenes are widely present in many biologically and pharmacologically active molecules, including acutiphycin, epothilone A, tamoxifen, isovirescenol A, brasilenol and guadalupol (Scheme 1).¹ However, the methods for the stereoselective construction of these unique motifs are still very limited and extremely challenging.²

Alkynes are readily available and inexpensive raw materials. Transition-metal-catalyzed difunctionalization of alkynes which is the *syn*- or *anti*-selective introduction of two functional groups across the triple bond represents one of the most straightforward and powerful approaches for assembling stereodefined tri- and tetrasubstituted alkenes. Traditionally used rare noble metal catalysts based on Rh, Ir and Pd have been widely used in alkyne difunctionalization reactions.³ However, they are very expensive and their reserves are declining, thus limiting their applications in large-scale industrial processes. To develop more sustainable catalytic methods to produce chemicals, much attention has been directed to seek first row transition metals that are Earth-abundant and sustainable to replace these highly expensive and rare metals in alkyne difunctionalization reactions. In the past few decades, although tremendous progress has been made in the nickel-catalyzed difunctionalization of alkynes, there is still a lack of comprehensive discussion on stereoselectivity control.⁴ In this review, we summarize the progress of the nickel-catalyzed alkyne difunctionalization reaction for the construction of multisubstituted alkenes, with an emphasis on the strategy and control of

stereochemistry. Since the hydrofunctionalization of alkynes has been well reviewed, we will not discuss it in this paper.⁵

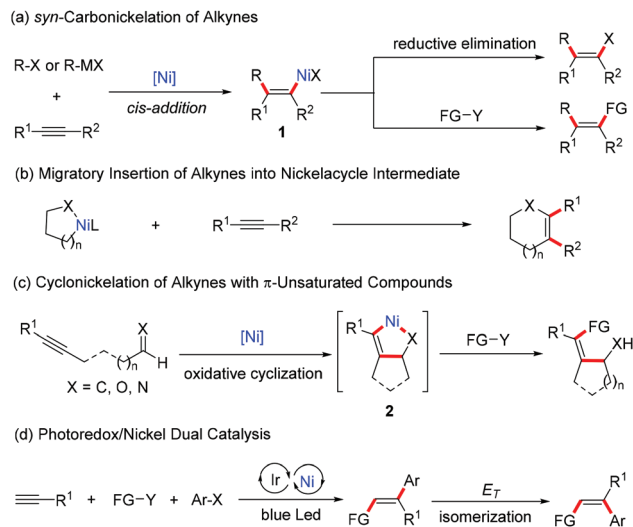
2. Ni-Catalyzed *syn*-difunctionalization of alkynes

The Ni-catalyzed *syn*-selective difunctionalization of alkynes has been well exploited, in which two functional groups are installed on the same side of the double bond in the products. As shown in Scheme 2, four effective strategies have been successfully developed. The most common strategy is to utilize the nature of *syn*-migratory insertion of an alkyne into organonickel species to form alkenyl-nickel intermediate **1**, which can undergo reductive elimination or further functionalization to provide a reliable route to multi-substituted alkenes (Scheme 2a). The migratory insertion of alkynes into a nickelacycle intermediate, followed by reductive elimination, is also a



Scheme 1 Representative biologically active compounds containing a tri- or tetrasubstituted alkene moiety.

The Center for Precision Synthesis (CPS), Institute for Advanced Studies (IAS),
Wuhan University, Wuhan, Hubei 430072, P. R. China. E-mail: wqkong@whu.edu.cn

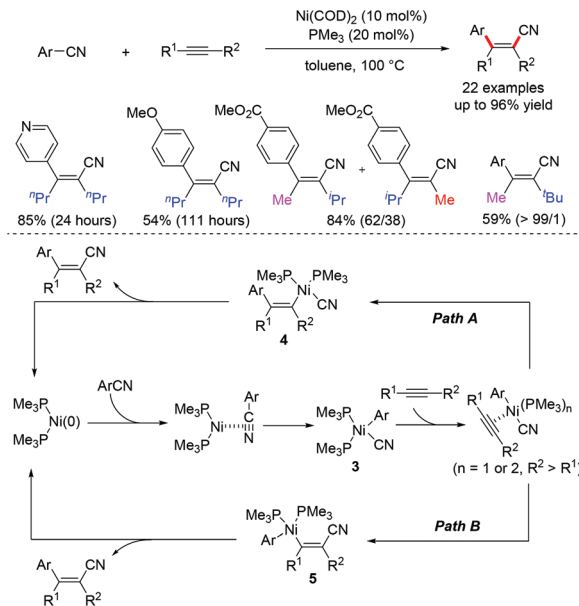
Scheme 2 Strategies for *syn*-selective difunctionalization of alkynes.

common method for the *syn*-selective difunctionalization of alkynes (Scheme 2b). Another powerful strategy is the coupling reaction of alkynes with π -unsaturated compounds, such as aldehydes, enones, and imines, which involves the formation of a five-membered nickelacycle intermediate **2** through oxidative cyclization (Scheme 2c). In addition, the merging of photoredox and nickel catalysis is emerging as an alternative strategy to access multi-substituted alkenes in a *syn*-selective manner (Scheme 2d).

2.1 *syn*-Carbonickelation of alkynes

The arylation reaction of alkynes involves the direct cleavage and addition of strong aryl-CN bonds across the carbon-carbon triple bond, and represents a high atom-economic and efficient route for the preparation of alkenyl nitriles. In 2004, Hiyama and co-workers demonstrated the first example of the Ni-catalyzed arylation of alkynes for the synthesis of β -aryl-substituted alkenyl nitriles (Scheme 3).⁶ The electron-deficient benzonitriles can react efficiently to give alkenyl nitriles in excellent yields. However, the arylation reaction of alkynes using electron-rich benzonitriles is generally sluggish.

Two possible mechanisms were considered for this transformation. The oxidative addition of Ar-CN to Ni(0) followed by the migratory insertion of alkynes into the resulting Ar-Ni(II)-CN species **3** at the Ar-Ni bond affords an alkenyl-nickel intermediate **4**, which undergoes reductive elimination to give the arylation products and regenerate the active Ni(0) catalyst (path A). Alternatively, the possibility of migratory insertion of alkyne into the Ar-Ni(II)-CN species **3** at the CN-Ni bond to form alkenylnickel intermediate **5** cannot be ruled out (path B). Interestingly, when asymmetric alkynes were examined, the reaction preferably produced the arylation product in which the aryl group is remote from the bulky isopropyl (62/38) or *tert*-butyl group (>99/1). These results indicate that the migratory insertion of alkynes into the Ni-Ar bond is



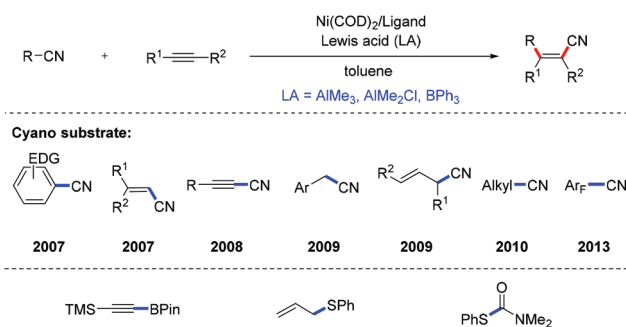
Scheme 3 Ni-Catalyzed arylation of alkynes.

feasible, and the nickel center prefers to be far away from the bulky groups due to steric hindrance.

Further theoretical studies by DFT calculation also validate that path A is more favourable because it is much more difficult to achieve migratory insertion of alkyne into the Ni-CN bond than the Ni-Ar bond.⁷

The same group further developed the carbocyanation of alkynes with the aid of nickel-Lewis acid dual catalysis, in which the Lewis acid co-catalyst was thought to activate the electrophilic CN center. With this strategy, a wide array of nitriles not only electron-rich benzonitriles, but also alkenyl, alkynyl, benzyl, allyl, alkyl, as well as pentafluorobenzyl nitriles were demonstrated to be compatible with this alkyne carbocyanation reaction (Scheme 4).⁸

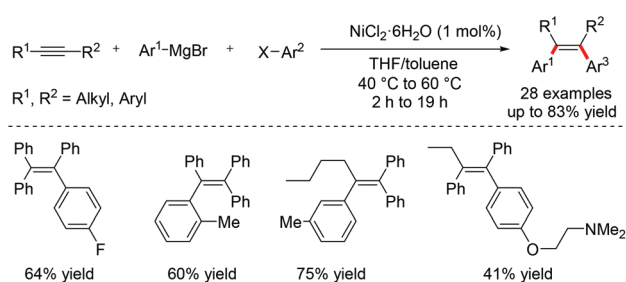
Ni-catalyzed intermolecular alkynylboration,⁹ thioallylation,¹⁰ and thiocarbamoylation¹¹ of alkynes were also developed for the efficient synthesis of alkenylborons and alkenylsulfides (Scheme 4), which are versatile synthetic intermediates in organic synthesis.



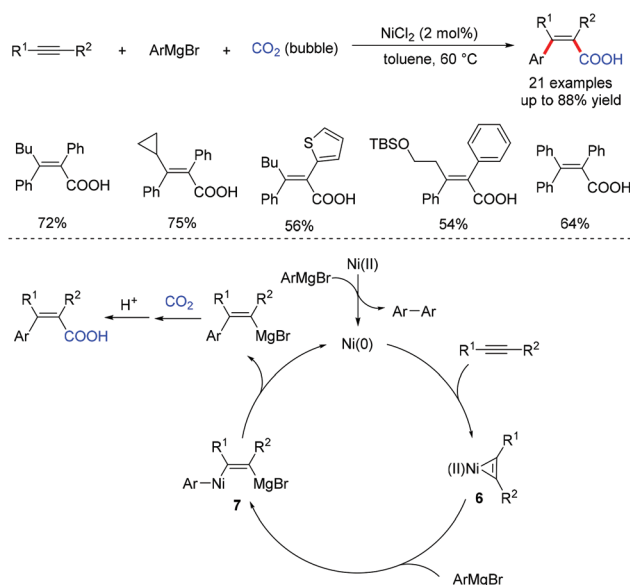
Scheme 4 Ni-Catalyzed carbocyanation, alkynylboration, thioallylation and thiocarbamoylation of alkynes.

The three-component redox neutral difunctionalization of alkynes is also a very effective method for constructing multi-substituted olefins by simultaneously introducing nucleophiles and electrophiles across the triple bonds. In 2015, Hayashi and co-workers reported a Ni-catalyzed cross coupling of alkynes with aryl Grignard reagents and aryl halides, providing an operationally simple method for synthesizing tetrasubstituted alkenes with high stereo- and regioselectivity (Scheme 5).¹²

Xi¹³ and Cheng¹⁴ independently reported the nickel-catalyzed regioselective arylcarboxylation of alkynes with arylmagnesium reagents and carbon dioxide (CO₂, 1 atm) for the synthesis of trisubstituted β -arylacrylic acids (Scheme 6). One possible mechanism is proposed in Scheme 6. The oxidative cycloaddition reaction of Ni(0) with alkyne affords the Ni(II) complex **6**, which undergoes transmetalation with the Grignard reagent to generate alkenyl-Ni(II) complex **7**. The reductive elimination of **7** followed by the addition of CO₂ and hydrolysis will deliver the desired β -arylacrylic acids.



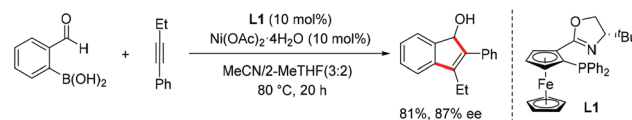
Scheme 5 Ni-Catalyzed three-component coupling of aryl Grignard reagents, alkynes and aryl halides.



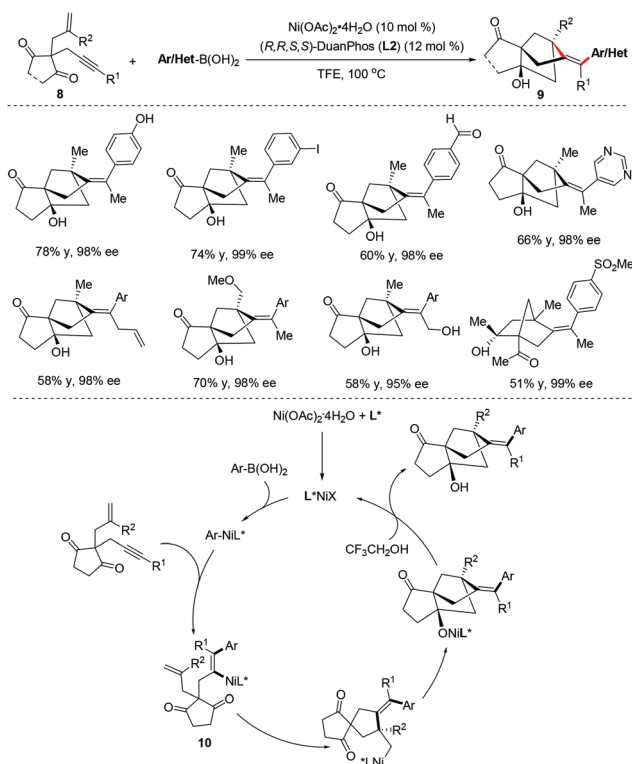
Scheme 6 Ni-Catalyzed arylcarboxylation of alkynes.

Following Hayashi¹⁵ and Murakami's pioneering studies¹⁶ on the Rh-catalyzed cyclization of *o*-formyl aryl boronic acids with alkynes, Lam reported the Ni-catalyzed cyclization reaction of 1-phenyl-1-butyne with 2-formylphenylboronic acid using (*S,S*)-^tBu-phosferrox (**L1**) as the chiral ligand, giving the indenol product in 81% yield with 87% ee (Scheme 7).¹⁷ The indene skeleton was constructed *via syn*-arylnickelation of the alkyne followed by nucleophilic addition of the resulting alkenylnickel species onto the aldehyde.

Our group reported a nickel-catalyzed cascade cyclization of enynones **8** for the modular synthesis of bridged tricyclo[5.2.1.0^{1,5}]decanes **9** with three quaternary stereocenters in good yields and excellent enantioselectivities (92–99% ee).¹⁸ A possible catalytic cycle is proposed in Scheme 8. The *syn*-selective addition of arylnickel species to the triple bond formed the alkenylnickel intermediate **10**. Intramolecular migratory insertion of alkenylnickel **10** to the double bond followed by nucleophilic cyclization onto one of the ketone groups affords the tricyclo[5.2.1.0^{1,5}]decane product **9** upon hydrolysis (Scheme 8).



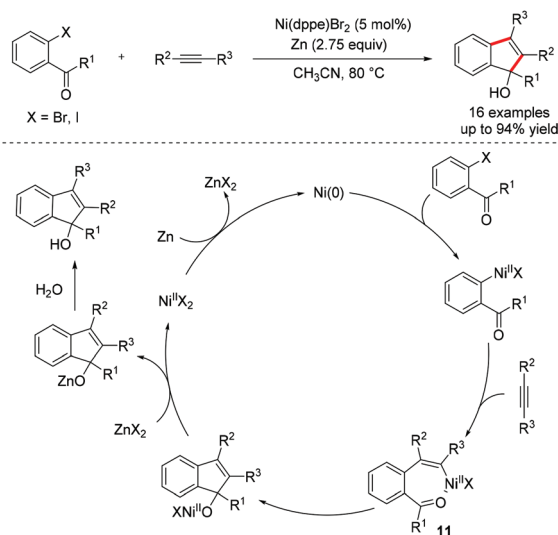
Scheme 7 Ni-Catalyzed cyclization of 2-formylphenylboronic acid with alkyne.



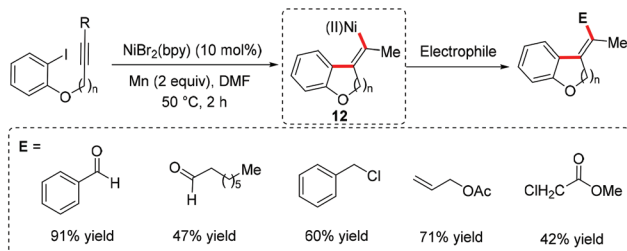
Scheme 8 Ni-Catalyzed enantioselective cyclization of enynones.

The reductive difunctionalization of alkynes has also been developed, which involves the simultaneous incorporation of two electrophiles to both sides of the triple bond without the use of preformed organometallic reagents. In 2002, Cheng *et al.* disclosed a Ni-catalyzed intermolecular reductive carbonylation of *o*-halophenyl ketones with alkynes using Zn powder as a reducing agent, providing an efficient route to functionalized indenol derivatives (Scheme 9).¹⁹ The oxidative addition of aryl halides to nickel(0) species, followed by the migratory insertion of alkynes into the Ni–Ar bond affords alkenylnickel intermediate **11**. Intramolecular nucleophilic addition of alkenylnickel **11** to the carbonyl, followed by transmetalation with zinc halide, delivers the indenol product upon hydrolysis. In addition, the same strategy has also been applied to the preparation of substituted quinolines²⁰ and (iso)quinolines.²¹

Maddaluno and co-workers described a Ni-catalyzed reductive arylfunctionalization of alkynes (Scheme 10).²² Remarkably, the nucleophilic alkenylnickel species **12** resulting from the intramolecular arylnickelation of the triple bond could be trapped by a variety of electrophiles, such as benzaldehyde,



Scheme 9 Ni-Catalyzed reductive carbocyclization of alkynes with *o*-halophenyl ketones.



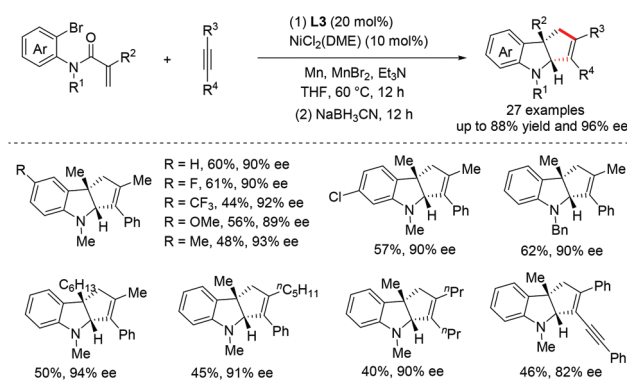
Scheme 10 Ni-Catalyzed reductive arylfunctionalization of alkynes.

nonanal, benzyl chloride, allyl acetate, and α -chloroesters, providing a convenient method for the synthesis of substituted benzofurans and chromanes.

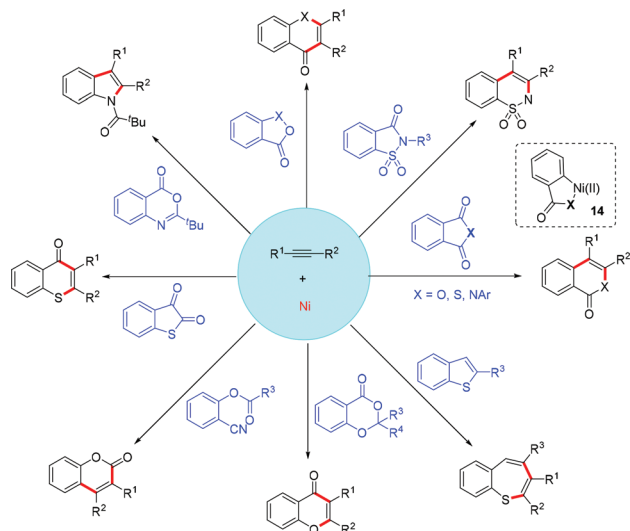
Recently, our group had also reported a Ni-catalyzed highly regio- and enantioselective reductive cyclization reaction of acrylamides with asymmetric internal alkynes.²³ This transformation takes place under mild conditions with high efficiency, providing rapid access to structurally diverse cyclopentannulated indolines in good yields with high regioselectivity (>20/1) and enantioselectivities (27 examples, 82–96% ee) (Scheme 11). A mechanistic study showed that the cyclopentannulated indolines are afforded through a highly regioselective migratory insertion of asymmetric internal alkynes into the σ -alkyl-Ni(II) species **13**, followed by nucleophilic addition of the resulting alkenyl nickel to unactivated amides.

2.2 Migratory insertion of alkynes into the nickelacycle intermediate

Another method for the *syn*-difunctionalization of alkynes is to replace a part of the cyclic compounds with low-valent nickel while eliminating small molecules such as CO or CO₂ to form the nickelacycle intermediate **14** followed by migratory insertion of alkynes. Matsubara and co-workers initiated the study of Ni-catalyzed decarbonylative cycloaddition of anhydrides to alkynes for the synthesis of isocoumarins (Scheme 12).²⁴ As shown in Scheme 12, a series of heterocycles could be effectively constructed by this strategy.²⁵



Scheme 11 Ni-Catalyzed enantioselective reductive cyclization of alkynes with arylbromide-tethered acrylamides.



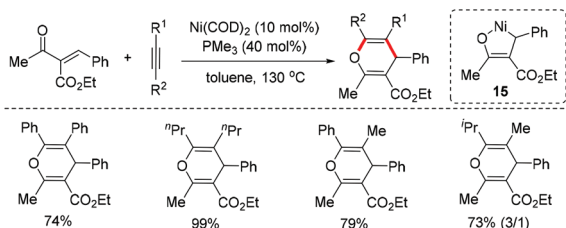
Scheme 12 Ni-Catalyzed cycloaddition reaction of unsaturated compounds with alkynes.

Matsubara and co-workers reported a Ni-catalyzed cycloaddition between α,β -unsaturated carbonyl compounds with alkynes.²⁶ Mechanistic studies have shown that the reaction proceeded through the oxidative cyclization of Ni(0) and enone to form an oxa-nickelacycle intermediate **15**, followed by migratory insertion of alkyne (Scheme 13).

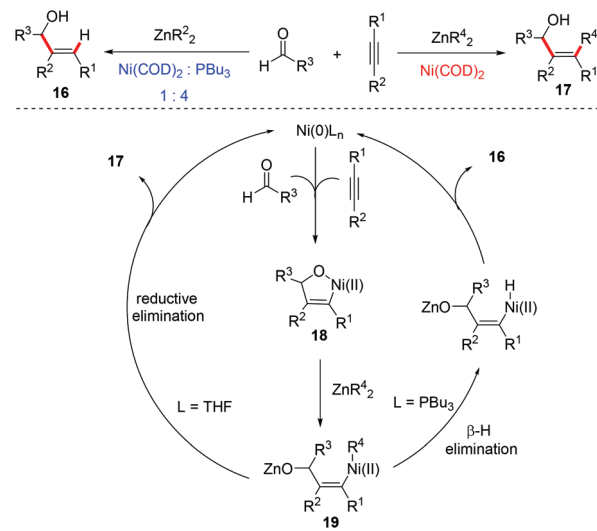
2.3 Cyclonickelation of alkynes with π -unsaturated compounds

Ni-Catalyzed reductive coupling of alkynes and aldehydes, pioneered by the group of Sato,²⁷ Montgomery,²⁸ and Jamison,²⁹ is an attractive and general approach for the synthesis of stereodefined allylic alcohols bearing tri- and tetrasubstituted alkenes.^{2d,30}

The Montgomery group demonstrated the first example of Ni-catalyzed cyclization/alkylation of alkynals with organozinc reagents to form cyclic allylic alcohols and the three-component coupling of aldehydes, organozincs and alkynes to synthesize acyclic allylic alcohols with complete control of alkene stereochemistry (Scheme 14).³¹ The oxidative cyclization of Ni(0) with aldehydes and alkynes affords a common oxa-nickelacycle intermediate **18**. Transmetalation of species **18** with an organozinc reagent gives the alkenylnickel species **19**, followed by reductive elimination to deliver the alkylated product **17**.



Scheme 13 Nickel-catalyzed cycloaddition of enone with alkynes.

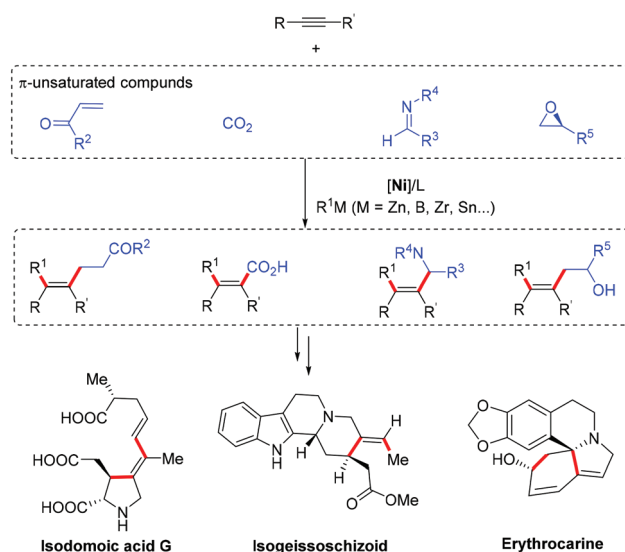


Scheme 14 Ni-Catalyzed reductive coupling of alkynes and aldehydes.

Alternatively, in the presence of a catalytic PPh_3 ligand, β -hydride elimination occurs prior to reductive elimination, therefore resulting in the reductive product **16**.

The reductive coupling reaction of alkynes with other unsaturated carbonyl compounds, such as enones,^{28a,32} carbon dioxide,³³ imines,^{29c} and epoxides,³⁴ have also been successfully developed for the synthesis of various functionalized tetrasubstituted alkenes (Scheme 15). This Ni-catalyzed multi-component coupling of alkynes has been applied to the total synthesis of many biologically active natural products, such as isodomoic acid **G**,³⁵ isogeissoschizoid,³⁶ and erythrocarine³⁷ (Scheme 15).

Asymmetric versions of the multi-component coupling of alkynes have been exploited. The Jamison group realized the



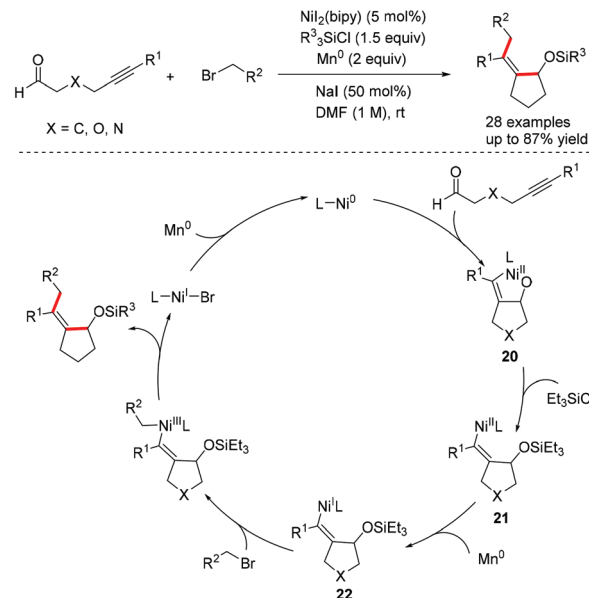
Scheme 15 Ni-Catalyzed reductive coupling of alkynes and various π -unsaturated compounds and synthetic applications.

asymmetric three-component reductive coupling of alkynes, Et_3B and imines using a P-chiral ferrocenyl phosphane ligand **L4**, providing an efficient way to enantiomerically enriched tetrasubstituted allylic amines (Scheme 16a).³⁸ Zhou and co-workers developed an Ni-catalyzed asymmetric alkylative coupling reaction of alkynes, aldehydes and ZnMe_2 using a spiro phosphoramidite ligand **L5** (Scheme 16b).³⁹ In addition, Tang's group used their own independently developed P-chiral phosphorus ligand **L6** to further explore this reaction (Scheme 16c).⁴⁰ The asymmetric transformation provides an efficient way to prepare chiral allylic alcohols bearing tetrasubstituted olefin functionality.

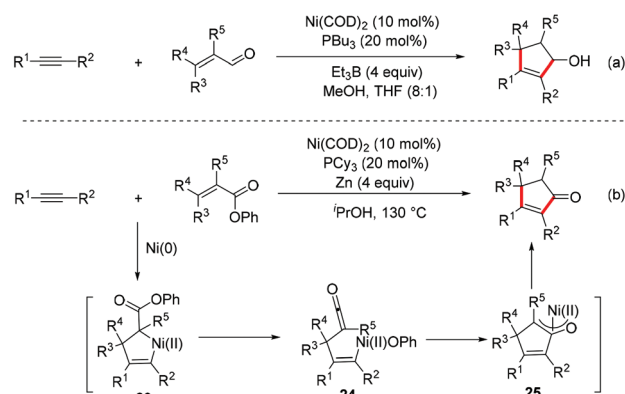
Recently, Montgomery *et al.* combined the Ni-catalyzed oxidative cyclization of alkynals and reductive cross-electrophile coupling together as a new approach for the synthesis of tetrasubstituted alkenes (Scheme 17).⁴¹ The reaction employed alkyl halide as an alkylating reagent and obviated the requirement for preformed organometallic reagents, greatly improving the functional group compatibility compared to the classic coupling method. The oxidative cyclization of nickel(0) with alkynals affords the nickelacycle intermediate **20**. The nickel-oxygen bond is cleaved by Et_3SiCl to form the silyl protected alkenyl nickel(II) intermediate **21**, which is reduced by $\text{Mn}(0)$ to generate the alkenyl Ni(I) species **22**. The oxidative addition of alkyl halide followed by reductive elimination delivers the desired products along with Ni(I) species, which undergoes further Mn-mediated reduction to regenerate the active Ni(0) catalyst (Scheme 17).

The same group further developed a Ni-catalyzed [3 + 2] reductive cycloaddition of alkynes with enals using $\text{Ni}(\text{COD})_2/\text{PBU}_3$ as the catalyst and Et_3B as the reductant. This method provides a novel strategy for the assembly of five-membered carbocyclic rings. Both inter- and intramolecular variants of the process could proceed smoothly to provide an array of cyclopentenol derivatives (Scheme 18a).⁴²

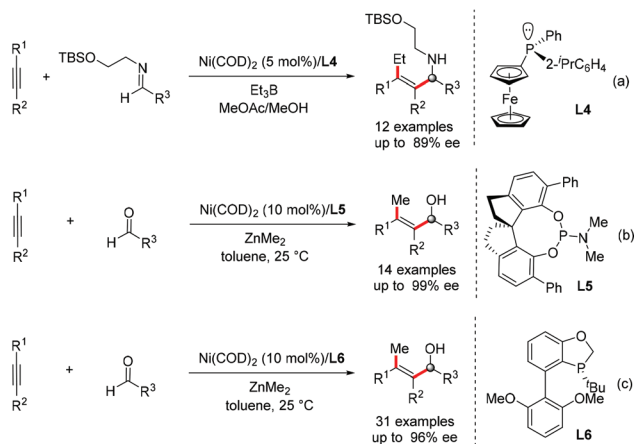
In addition, a Ni-catalyzed [3 + 2] cycloaddition reaction of α,β -unsaturated phenyl esters with alkyne in $i\text{PrOH}$ using Zn



Scheme 17 Ni-Catalyzed reductive coupling of alkynals with alkyl halides.



Scheme 18 Ni-Catalyzed reductive [3 + 2] cycloaddition of alkynes with α,β -unsaturated carbonyl compounds.

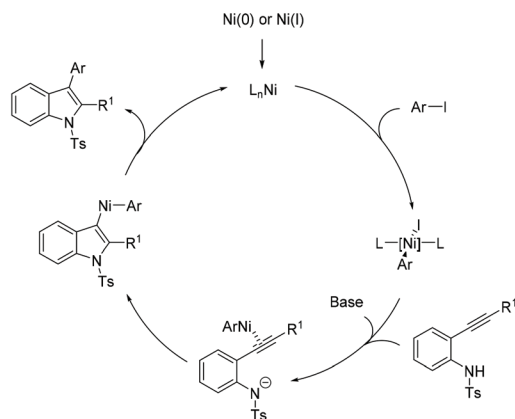
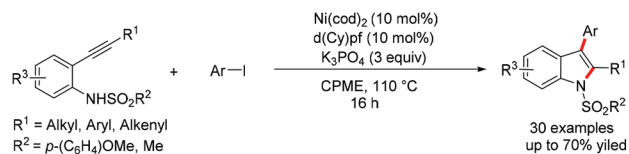


Scheme 16 Ni-Catalyzed asymmetric coupling of alkynes with imines or aldehydes.

powder as the reductant was also demonstrated by Ohashi and co-workers (Scheme 18b).⁴³ A possible mechanism involving C–O bond activation was proposed. The nickelacyclopentene intermediate **23** was formed through the oxidative cyclization of α,β -unsaturated phenyl ester with alkyne and nickel(0). β -Phenoxy elimination followed by insertion of the resulting ketene intermediate **24** into the C–Ni bond provides η^3 -oxaalylnickel species **25**, which undergoes alcoholysis to deliver the cyclopentenone product.

2.4 Ni/photoredox dual catalysis

Photoredox catalysis has been studied and can be used to promote the contra-thermodynamic *E/Z* isomerization of olefins through energy-transfer. Chu *et al.* reported an intermolecular *syn*-selective alkylarylation of terminal alkynes with



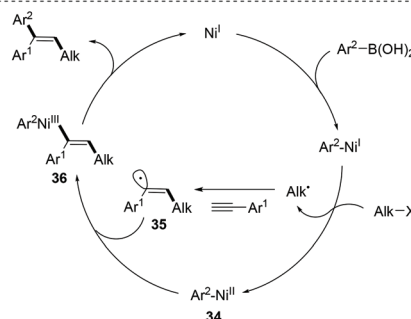
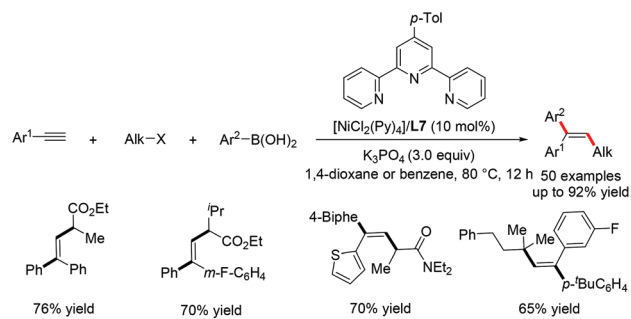
Scheme 22 Ni-Catalyzed *anti*-selective arylation of 2-alkynyl-*N*-sulfonylanilides.

reactivity pattern. Recently, Dake *et al.* reported a nickel-catalyzed *anti*-arylation of 2-alkynyl-*N*-sulfonylanilides to form 2,3-difunctionalized *N*-arylsulfonylindoles.⁴⁸ A possible mechanism involving oxidative addition, alkyne amination and reductive elimination was proposed (Scheme 22).

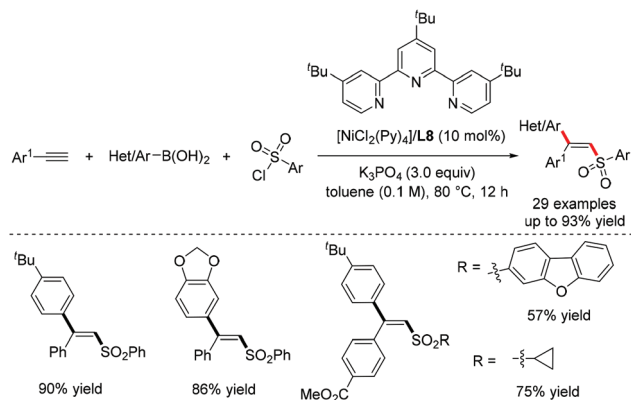
3.2 Radical addition/coupling with terminal alkynes

In 2016, Nevado and co-workers disclosed a Ni-catalyzed three-component coupling reaction of terminal alkynes, alkyl halides and boronic acids for the stereoselective synthesis of trisubstituted alkenes (Scheme 23).⁴⁹ The protocol, involving the simultaneous incorporation of both aryl and alkyl groups across the triple bond in a highly regio- and stereocontrolled manner. Significantly, both activated and unactivated alkyl halides were well tolerated under the optimized reaction conditions. The proposed mechanism starts with the generation of active Ni(I) species *in situ* and reacts with organoboron reagents through transmetalation. The resulting Ar-Ni(I) species is responsible for the activation of alkyl halides to produce an alkyl radical along with the Ar-Ni(II) intermediate **34**. The alkyl radical then undergoes highly selective addition to the terminal alkyne to deliver vinyl radical intermediate **35**. The subsequent recombination of the vinyl radical intermediate **35** with Ar-Ni(II) **34** will afford the key Ni(III) intermediate **36**, which undergoes reductive elimination to furnish the desired products while regenerating the active Ni(I) catalyst (Scheme 23).

The same group further reported a similar stereoselective carbosulfonylation of terminal alkynes by utilizing sulfonyl chlorides as radical precursors, enabling the rapid synthesis of β,β -disubstituted vinyl sulfones with broad functional group compatibility (Scheme 24).⁵⁰



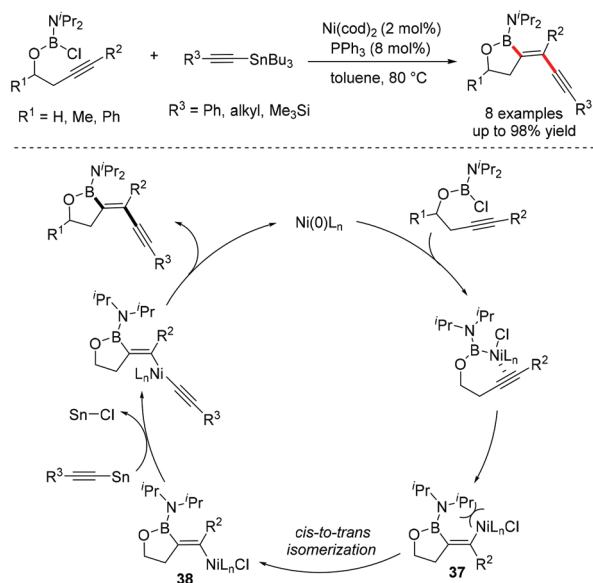
Scheme 23 Ni-Catalyzed *anti*-selective arylalkylation of terminal alkynes.



Scheme 24 Ni-Catalyzed *anti*-selective carbosulfonylation of terminal alkynes.

3.3 E/Z isomerization of alkenylnickel species

3.3.1 E/Z isomerization driven by steric hindrance of substrates. In 2005, Sugimoto's group reported a nickel-catalyzed *trans*-carbonylation of chloroboryl homopropargylic ethers with organotin reagents, which provided a new way for the stereoselective synthesis of highly functionalized organoboron compounds (Scheme 25).⁵¹ A possible mechanism was put forward to elucidate the observed *trans*-addition mode. The oxidative addition of the B-Cl bond to nickel, followed by intramolecular *cis*-migratory insertion of alkyne into the B-Ni bond resulted in *cis*-alkenylnickel intermediate **37**. It was speculated that the considerable steric repulsion caused by the diisopropylamino group and the chlorobis-(triphenylphosphine)nickel moiety forced the

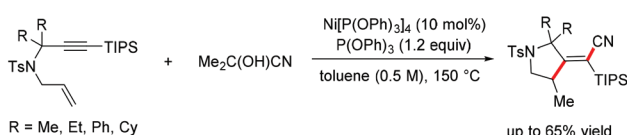
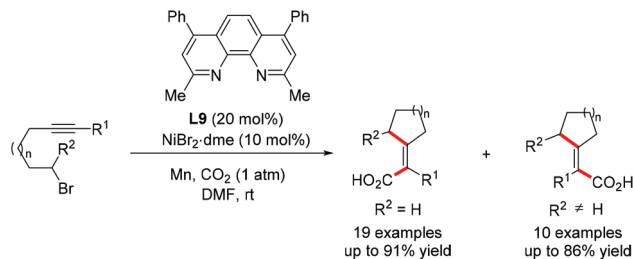
Scheme 25 Ni-Catalyzed *anti*-carboration of alkynes.

isomerization of *cis*-alkenylnickel to *trans*-alkenylnickel **38**. Delivery of the alkynyl group from the organotin reagent *via* the transmetalation step and the subsequent reductive elimination would afford *trans*-alkynylboronation products (Scheme 25).

Inspired by the dramatic impact of steric factors on promoting the isomerization of alkenyl nickel species, an unprecedented *anti*-carbocyanation of 1,6-enynes under nickel catalysis was realized by the Arai group (Scheme 26).⁵² The catalytic protocol was triggered by hydronickelation of alkenes followed by carbonickelation of alkynes. Mechanism studies have shown that bulky substituents such as TIPS or TMS are essential for causing steric repulsion after enyne cyclization, and this effect would control the geometry of the C–C double bond through a key nickel–carbene intermediate.

Martin and co-workers reported a Ni-catalyzed reductive cyclization/carboxylation of unactivated alkyl halides with carbon dioxide (Scheme 27).⁵³ This robust protocol fused the CO₂ fixation with a cascade reductive process, resulting in carbonylated carbocyclic products with a divergent *syn/anti* selectivity pattern modulated by substrates. Specifically, the *cis*-selective cyclization/carboxylation products were exclusively produced as preliminary alkyl halides were used, however, the *trans*-selectivity was favoured with bulk substituents at the α -position of alkyl bromides.

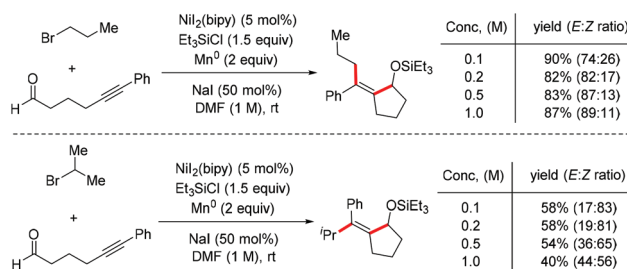
Similar effects have been demonstrated in Montgomery's work on three-component reaction of aldehydes, alkynes, and

Scheme 26 Ni-Catalyzed *anti*-carbocyanation of 1,6-enynes.Scheme 27 Ni-Catalyzed divergent cyclization/carboxylation of unactivated alkyl bromides with CO₂.

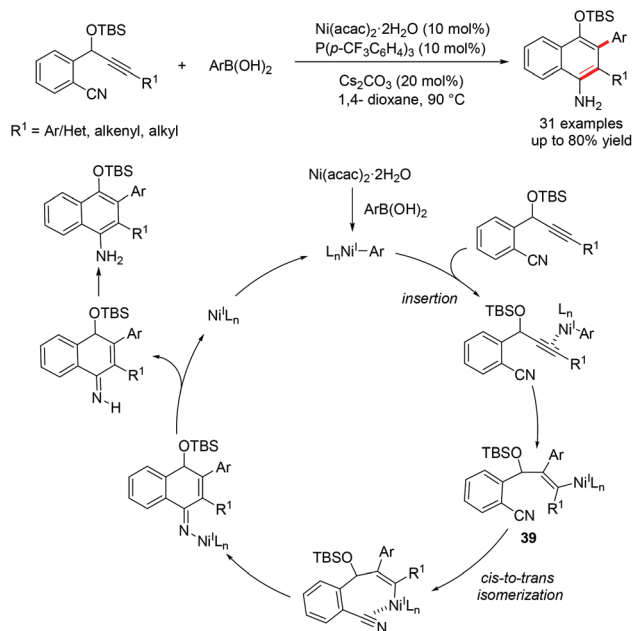
alkyl halides, in which the *Z* isomer of alkylative cyclization products predominated when secondary alkyl bromides were employed (Scheme 28).⁴¹ The result of this *Z/E* isomerization may be driven by the crowded steric environment of the vinyl-nickel intermediate. Significantly, the reaction concentration also has an extraordinary effect on the *E/Z* selectivity, where the proportion of the *Z* isomer of the product increases as the reaction concentration decreases.

3.3.2 *E/Z* isomerization driven by the formation of chelated alkenyl-nickel species. In 2016, Liu *et al.* disclosed a nickel-catalyzed addition/cyclization of alkyne-nitriles with organoboronic acids, enabling the construction of highly functionalized 1-naphthylamines (Scheme 29).⁵⁴ Remarkably, aryl boronic acids bearing a wide range of diverse substituents underwent the cyclization smoothly to afford the desired 1-naphthylamines in moderate to high yields. On the basis of mechanistic studies, the author proposed a catalytic cycle triggered by Ni(I) species, which was generated by the disproportionation reaction of Ni(0) and Ni(II). Transmetalation of Ni(I) species with arylboronic acid leading to an arylnickel(I) complex, followed by migratory insertion of the carbon–carbon triple bond into Ar–Ni(I) species affords an alkenylnickel(I) intermediate **39**. The tethered cyano group may play a role in facilitating the *cis*–*trans* isomerization by stabilizing the alkenylnickel(I) species. An intramolecular nucleophilic addition of the alkenylnickel(I) **39** to the cyano group, followed by protonation and tautomerization, will furnish 1-naphthylamines and regenerate the active Ni(I) catalyst (Scheme 29).

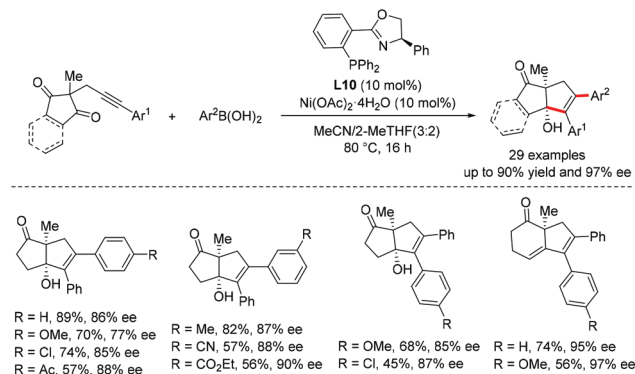
Lam and co-workers independently reported a Ni-catalyzed enantioselective *anti*-arylation cyclization of alkynones and



Scheme 28 Ni-Catalyzed oxidative cyclization and reductive cross electrophile coupling of aldehydes, alkynes, and alkyl halides.



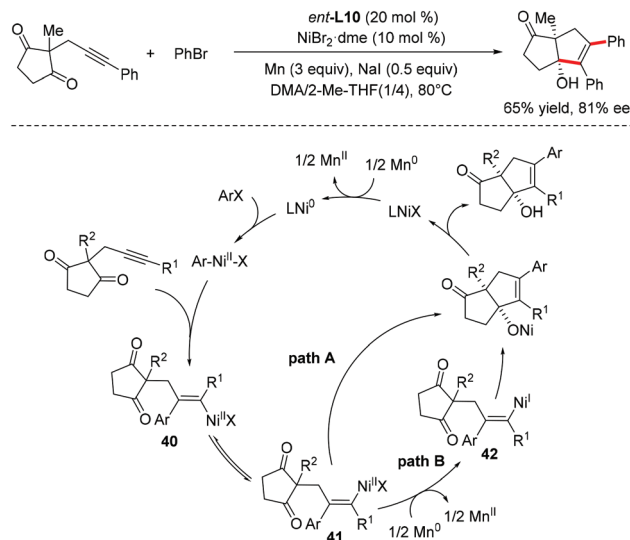
Scheme 29 Ni-Catalyzed *anti*-addition/cyclization of alkyne-nitriles with organoboronic acids.



Scheme 30 Ni-Catalyzed enantioselective *anti*-arylate cyclization of alkynyl electrophiles with organoboronic acids.

organoboronic acids (Scheme 30).¹⁷ By using the (*R*)-Ph-Phox as a ligand, a wide variety of alkynones or cyclohexa-1,3-dienones are compatible with this transformation and exhibit excellent enantioselectivities.

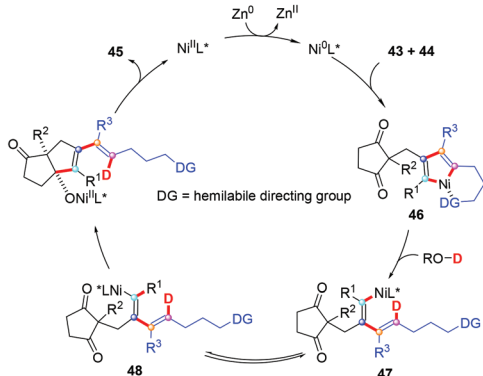
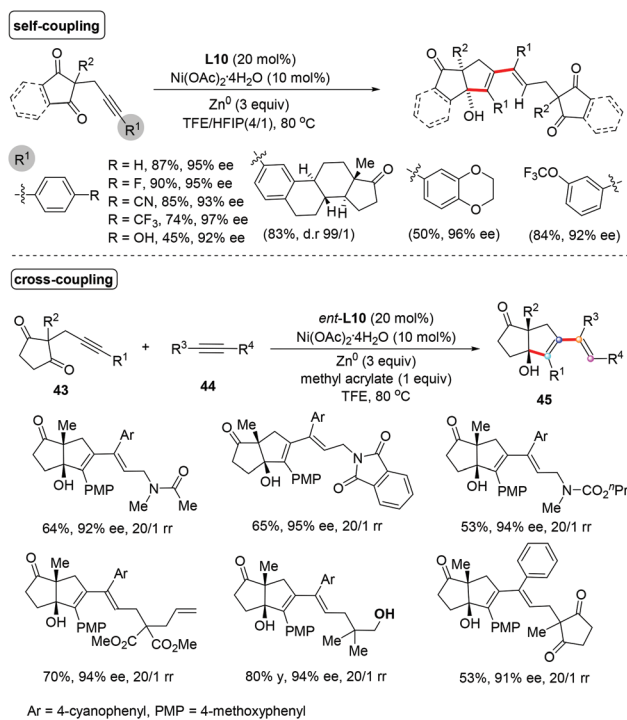
Our group recently developed a new catalyst system for the *anti*-arylate cyclization of alkynones and aryl halides through a reductive cross-coupling strategy.⁵⁵ The transformation proceeds smoothly in the absence of organometallic reagents and features high functional group tolerance, providing an effective platform to access a wide variety of synthetically useful *endo*-cyclic tetrasubstituted allylic alcohols in a stereoselective manner (Scheme 31). A possible reaction mechanism for the reductive arylation cyclization of alkynone was proposed. The oxidative addition of ArX followed by migratory insertion of alkyne into the resulting arylnickel(II)



Scheme 31 Ni-Catalyzed enantioselective *anti*-arylate cyclization of alkynones with aryl halides.

species affords an alkenyl-Ni(II) intermediate **40**. A reversible *E/Z* isomerization process takes place to produce a new alkenyl-Ni(II) intermediate **41**, which could be reduced by Mn⁰ to give more nucleophilic alkenyl-Ni(I) species **42**. Nucleophilic addition of alkenyl-Ni(I) **42** to the ketone followed by protonolysis produced the *endo*-cyclic tetrasubstituted allylic alcohols. The catalytically active Ni(0) species was then regenerated upon Mn⁰ reduction (path B, Scheme 31). The direct cyclization of the alkenyl-Ni(II) intermediate **41** to the ketone carbonyl cannot be excluded (path A, Scheme 31).

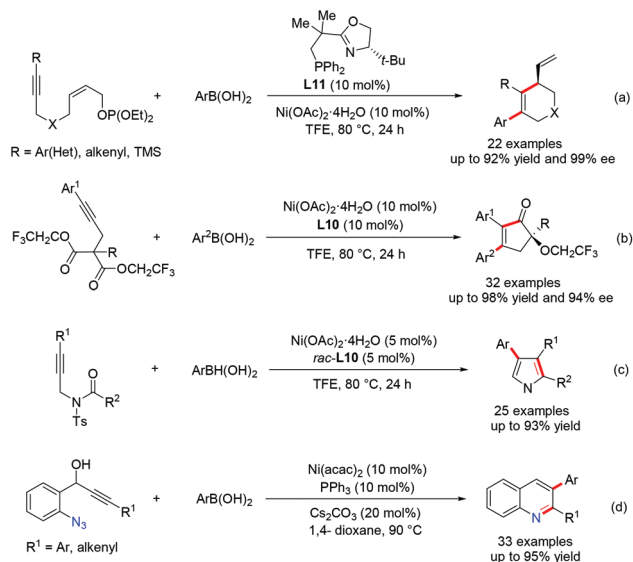
Our group further demonstrated the Ni-catalyzed reductive coupling of unsymmetrical internal alkynes, which is still a significant challenge in organic synthesis (Scheme 32).⁵⁶ Both self-coupling and cross-coupling versions of reductive coupling of two unsymmetrical internal alkynes were achieved using a hemilabile directing group strategy, enabling rapidly access to a series of synthetically challenging pentasubstituted 1,3-dienes with diverse functional groups in good yields with high regio- and enantioselectivity (mostly >20/1 rr, >90% ee). Compared to traditional cross-coupling reactions, the reaction features high atom- and step-economy, without requiring the use of prepared stereodefined coupling partners such as vinyl halides or vinyl organometallics. A rationalized mechanism for this transformation was proposed based on the mechanistic studies. Initially, a catalytically active Ni(0) species was formed upon the reduction of the Ni(II) precatalyst by Zn dust. Oxidative cyclization of alkynone **43** with another unsymmetrical internal alkyne **44** gave a nickelacycle **46**, in which the tethered carbonyl or hydroxyl group serves as a hemilabile directing group to control the regioselectivity. Then, selective protonation of **46** by alcohol would afford the conjugated dienylnickel species **47**, which could undergo a reversible *cis-trans* isomerization to produce a new dienylnickel intermediate **48**. Finally, the target pentasubstituted 1,3-diene **45** was



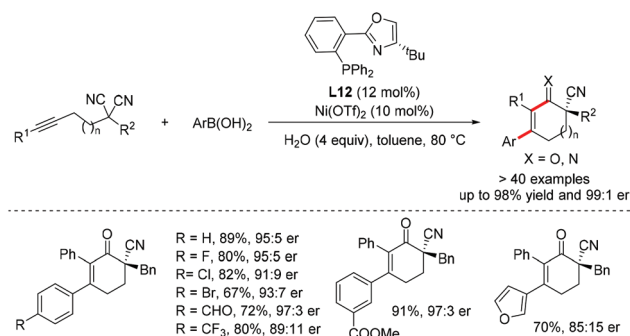
Scheme 32 Ni-Catalyzed reductive coupling of unsymmetrical internal alkynes.

formed through intramolecular nucleophilic attack of the dienickel **48** to carbonyls and the subsequent protonation.

Several other types of electrophiles were demonstrated to be suitable for this nickel-catalyzed *anti*-carbonickelation cyclization reaction. In 2017, the Lam group developed highly enantioselective allylic alkenylations of *Z*-allylic phosphate tethered alkynes which provide a range of chiral 1,4-diene-containing carbo- and heterocycles (Scheme 33a).⁵⁷ In 2018, the same group further developed a nickel-catalyzed desymmetrization of malonate esters for the enantioselective synthesis of highly functionalized cyclopent-2-enones, and the cyclization is enabled by the reversible *E/Z* isomerization of alkenylnickel species (Scheme 33b).⁵⁸ Later, the less electrophilic *N*-Ts-amides were proved to effectively capture the alkenylnickel species to obtain multisubstituted pyrroles (Scheme 33c).⁵⁹ Trapping the alkenylnickel intermediate by an azide group, a non-carbon center electrophile has also



Scheme 33 Ni-Catalyzed cyclization of alkyne electrophiles with organoboronic acids involving *anti*-carbonickelation of alkynes.



Scheme 34 Ni-Catalyzed enantioselective *anti*-arylation of alkyne-tethered malononitriles.

been developed for the efficient synthesis of 2,3-diarylquinolines (Scheme 33d).⁶⁰

Ni-Catalyzed desymmetrization of alkyne-tethered malononitriles with aryl boronic acids was developed by Liu group (Scheme 34).⁶¹ This protocol involves the *cis*-addition of aryl boronic acids to alkynes, followed by *E/Z* isomerization of alkenylnickel species and selective nitrile insertion, providing unprecedented access to 5–7-membered skeletons bearing a nitrile-containing quaternary stereocenter in good yields with excellent enantioselectivities.

4. Conclusions

In this review, we summarize the recent advances in the nickel-catalyzed stereoselective alkyne difunctionalization reaction. Different strategies for controlling stereoselectivity towards the synthesis of stereodefined tri- and tetrasubstituted alkenes have been highlighted. Although considerable pro-

gress has been made in this rapidly evolving field in the past few decades, many intriguing challenges still lie ahead to extend the use of these methodologies.

Firstly, most of these methods require the use of stoichiometric organometallic reagents, which impose limitations in their synthetic applicability. The stereoselective difunctionalization of alkynes *via* the reductive cross-coupling strategy would be more advantageous, but there are very minimal successful examples in this area.

Secondly, the stereoselective difunctionalization of alkynes is still tailored for a specific substrate class. In particular, the *anti*-difunctionalization of alkynes by the radical-mediated process is restricted to terminal alkynes.

Thirdly, the detailed reaction mechanism for controlling stereoselectivity is still indistinct in many transformations. Thus more effort needs to be focused on the detailed mechanistic studies, as it will be conducive for designing and developing innovative catalytic systems.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We acknowledged financial support from the “1000-Youth Talents Plan”, Wuhan University and National Natural Science Foundation of China (No. 21702149).

Notes and references

- (a) F. C. Engelhardt, Y. J. Shi, C. J. Cowden, D. A. Conlon, B. Pipik, G. Zhou, J. M. McNamara and U. H. Dolling, Synthesis of a NO-releasing prodrug of rofecoxib, *J. Org. Chem.*, 2006, **71**, 480–491; (b) N. F. McKinley and D. F. O’Shea, Carbolithiation of diphenylacetylene as a stereoselective route to (*Z*)-tamoxifen and related tetrasubstituted olefins, *J. Org. Chem.*, 2006, **71**, 9552–9555; (c) J. Wang, Z. Dong, C. Yang and G. Dong, Modular and regioselective synthesis of all-carbon tetrasubstituted olefins enabled by an alkenyl Catellani reaction, *Nat. Chem.*, 2019, **11**, 1106–1112; (d) M. Li, T. Y. Yao, S. Z. Sun, T. X. Yan, L. R. Wen and L. B. Zhang, The ruthenium(II)-catalyzed C–H olefination of indoles with alkynes: the facile construction of tetrasubstituted alkenes under aqueous conditions, *Org. Biomol. Chem.*, 2020, **18**, 3158–3163.
- (a) A. B. Flynn and W. W. Ogilvie, Stereocontrolled synthesis of tetrasubstituted olefins, *Chem. Rev.*, 2007, **107**, 4698–4745; (b) R. Chinchilla and C. Najera, Chemicals from alkynes with palladium catalysts, *Chem. Rev.*, 2014, **114**, 1783–1826; (c) H. Yoshida, Borylation of alkynes under base/coinage metal catalysis: some recent developments, *ACS Catal.*, 2016, **6**, 1799–1811; (d) R. M. Moslin, K. Miller-Moslin and T. F. Jamison, Regioselectivity and enantioselectivity in nickel-catalyzed reductive coupling reactions of alkynes, *Chem. Commun.*, 2007, **2007**, 4441–4449.
- For selected reviews, see: (a) G. Zeni and R. C. Larock, Synthesis of heterocycles via palladium π -olefin and π -alkyne chemistry, *Chem. Rev.*, 2004, **104**, 2285–2309; (b) E. Negishi, Z. Huang, G. Wang, S. Mohan, C. Wang and H. Hattori, Recent advances in efficient and selective synthesis of di-, tri-, and tetrasubstituted alkenes via Pd-catalyzed alkenylation–carbonyl olefination synergy, *Acc. Chem. Res.*, 2008, **41**, 1474–1485; (c) R. Dorel and A. M. Echavarren, Gold(I)-catalyzed activation of alkynes for the construction of molecular complexity, *Chem. Rev.*, 2015, **115**, 9028–9072.
- When we were preparing the manuscript, a review article about Ni-catalyzed *anti*-selective alkyne functionalization reactions was published: S. E. Bottcher, L. E. Hutchinson and D. J. Wilger, Nickel-catalyzed *anti*-selective alkyne functionalization reactions, *Synthesis*, 2020, **52**, 2807–2820.
- (a) F. Alonso, I. P. Beletskaya and M. Yus, Transition-metal-catalyzed addition of heteroatom-hydrogen bonds to alkynes, *Chem. Rev.*, 2004, **104**, 3079–3159; (b) R. Severin and S. Doye, The catalytic hydroamination of alkynes, *Chem. Soc. Rev.*, 2007, **36**, 1407–1420; (c) V. P. Ananikov, A. V. Makarov and I. P. Beletskaya, Catalytic hydrofunctionalization of alkynes through P–H bond addition: the unique role of orientation and properties of the phosphorus group in the insertion step, *Chem. – Eur. J.*, 2011, **17**, 12623–12630; (d) X. Zeng, Recent advances in catalytic sequential reactions involving hydroelement addition to carbon-carbon multiple bonds, *Chem. Rev.*, 2013, **113**, 6864–6900; (e) G. Lalic and A. Suess, Copper-catalyzed hydrofunctionalization of alkynes, *Synlett*, 2016, **27**, 1165–1174; (f) Y. Zheng and W. Zi, Transition-metal catalyzed enantioselective hydrofunctionalization of alkynes, *Tetrahedron Lett.*, 2018, **59**, 2205–2213; (g) H. Wen, G. Liu and Z. Huang, Recent advances in tridentate iron and cobalt complexes for alkene and alkyne hydrofunctionalizations, *Coord. Chem. Rev.*, 2019, **386**, 138–153.
- Y. Nakao, S. Oda and T. Hiyama, Nickel-catalyzed arylcyanation of alkynes, *J. Am. Chem. Soc.*, 2004, **126**, 13904–13905.
- Y. Ohnishi, Y. Nakao, H. Sato, Y. Nakao, T. Hiyama and S. Sakaki, A theoretical study of nickel(0)-catalyzed phenylcyanation of alkynes. Reaction mechanism and regioselectivity, *Organometallics*, 2009, **28**, 2583–2594.
- (a) Y. Nakao, T. Yukawa, Y. Hirata, S. Oda, J. Satoh and T. Hiyama, Allylcyanation of alkynes: regio- and stereoselective access to functionalized di- or trisubstituted acrylonitriles, *J. Am. Chem. Soc.*, 2006, **128**, 7116–7117; (b) Y. Nakao, A. Yada, S. Ebata and T. Hiyama, A dramatic effect of Lewis-acid catalysts on nickel-catalyzed carbocyanation of alkynes, *J. Am. Chem. Soc.*, 2007, **129**, 2428–2429; (c) Y. Nakao, Y. Hirata, M. Tanaka and T. Hiyama, Nickel/BPh₃-catalyzed alkynylcyanation of alkynes and 1,2-dienes: an efficient route to highly functionalized conjugated enynes, *Angew. Chem., Int. Ed.*, 2008, **47**, 385–387; (d) Y. Nakao and T. Hiyama, Nickel-catalyzed carbocyanation

- tion of alkynes, *Pure Appl. Chem.*, 2008, **80**, 1097–1107; (e) Y. Hirata, T. Yukawa, N. Kashihara, Y. Nakao and T. Hiyama, Nickel-catalyzed carbocyanation of alkynes with allyl cyanides, *J. Am. Chem. Soc.*, 2009, **131**, 10964–10973; (f) A. Yada, T. Yukawa, Y. Nakao and T. Hiyama, Nickel/ AlMe_2Cl -catalysed carbocyanation of alkynes using arylacetonitriles, *Chem. Commun.*, 2009, 3931–3933; (g) Y. Nakao, A. Yada and T. Hiyama, Heteroatom-directed alkylcyanation of alkynes, *J. Am. Chem. Soc.*, 2010, **132**, 10024–10026; (h) Y. Minami, H. Yoshiyasu, Y. Nakao and T. Hiyama, Highly chemoselective carbon-carbon σ -bond activation: nickel/Lewis acid catalysed polyfluoroarylcyanation of alkynes, *Angew. Chem., Int. Ed.*, 2013, **52**, 883–887.
- 9 M. Suginome, M. Shirakura and A. Yamamoto, Nickel-catalyzed addition of alkynylboranes to alkynes, *J. Am. Chem. Soc.*, 2006, **128**, 14438–14439.
 - 10 R. Hua, H. Takeda, S. Y. Onozawa, Y. Abe and M. Tanaka, Nickel-catalyzed thioallylation of alkynes with allyl phenyl sulphides, *Org. Lett.*, 2007, **9**, 263–266.
 - 11 T. Inami, T. Kurahashi and S. Matsubara, Nickel-catalysed synthesis of tetrasubstituted vinyl sulfides from thiocarbamates and internal alkynes, *Chem. Commun.*, 2015, **51**, 1285–1288.
 - 12 F. Xue, J. Zhao, T. S. Hor and T. Hayashi, Nickel-catalyzed three-component domino reactions of aryl Grignard reagents, alkynes, and aryl halides producing tetrasubstituted alkenes, *J. Am. Chem. Soc.*, 2015, **137**, 3189–3192.
 - 13 S. Wang and C. Xi, Nickel-catalyzed arylative carboxylation of alkynes with arylmagnesium reagents and carbon dioxide leading to trisubstituted acrylic acids, *Org. Lett.*, 2018, **20**, 4131–4134.
 - 14 C.-H. Hung, R. Santhoshkumar, Y.-C. Chang and C.-H. Cheng, Synthesis of trisubstituted acrylic acids through nickel-catalyzed carbomagnesianation of alkynes and carbon dioxide fixation, *Eur. J. Org. Chem.*, 2018, 6924–6928.
 - 15 R. Shintani, K. Okamoto and T. Hayashi, Rhodium-catalyzed synthesis of indenols by regioselective coupling of alkynes with *ortho*-carbonylated arylboronic acids, *Chem. Lett.*, 2005, **34**, 1294–1295.
 - 16 T. Matsuda, M. Makino and M. Murakami, Synthesis of 1*H*-inden-1-ol derivatives via rhodium-catalyzed annulation of *o*-acylphenylboronic acids with alkynes, *Chem. Lett.*, 2005, **34**, 1416–1417.
 - 17 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.
 - 18 J. Chen, Y. Wang, Z. Ding and W. Kong, Synthesis of bridged tricyclo[5.2.1.0^{1,5}]decanes via nickel-catalyzed asymmetric domino cyclization of enynones, *Nat. Commun.*, 2020, **11**, 1882.
 - 19 (a) D. K. Rayabarapu and C. H. Cheng, Nickel-catalyzed regioselective carbocyclization of *ortho*-halophenyl ketones with propiolates: an efficient route to disubstituted indenols, *Chem. Commun.*, 2002, 942–943; (b) D. K. Rayabarapu, C. H. Yang and C. H. Cheng, Regioselective synthesis of indenols via nickel-catalyzed carbocyclization reaction, *J. Org. Chem.*, 2003, **68**, 6726–6731.
 - 20 R. P. Korivi and C. H. Cheng, Nickel-catalyzed cyclization of 2-iodoanilines with arylalkynes: an efficient route for quinoline derivatives, *J. Org. Chem.*, 2006, **71**, 7079–7082.
 - 21 R. P. Korivi and C. H. Cheng, Highly efficient synthesis of isoquinolines via nickel-catalyzed annulation of 2-iodobenzaldimines with alkynes: evidence for dual pathways of alkyne insertion, *Org. Lett.*, 2005, **7**, 5179–5182.
 - 22 (a) M. Durandetti, L. Hardou, M. Clement and J. Maddaluno, Heterocyclization by catalytic carbonickelation of alkynes: a domino sequence involving vinylnickels, *Chem. Commun.*, 2009, 4753–4755; (b) M. Durandetti, L. Hardou, R. Lhermet, M. Rouen and J. Maddaluno, Synthetic applications of the nickel-catalyzed cyclization of alkynes combined with addition reactions in a domino process, *Chem. – Eur. J.*, 2011, **17**, 12773–12783.
 - 23 Y. Ping, K. Wang, Q. Pan, Z. Ding, Z. Zhou, Y. Guo and W. Kong, Ni-catalyzed regio- and enantioselective domino reductive cyclization: one-pot synthesis of 2,3-fused cyclopentannulated indolines, *ACS Catal.*, 2019, **9**, 7335–7342.
 - 24 Y. Kajita, T. Kurahashi and S. Matsubara, Nickel-catalyzed decarbonylative addition of anhydrides to alkynes, *J. Am. Chem. Soc.*, 2008, **130**, 17226–17227.
 - 25 For selected reviews, see: (a) T. Kurahashi and S. Matsubara, Nickel-catalyzed reactions directed toward the formation of heterocycles, *Acc. Chem. Res.*, 2015, **48**, 1703–1716. For selected examples, see: (b) Y. Kajita, S. Matsubara and T. Kurahashi, Nickel-catalyzed decarbonylative addition of phthalimides to alkynes, *J. Am. Chem. Soc.*, 2008, **130**, 6058–6059; (c) A. Ooguri, K. Nakai, T. Kurahashi and S. Matsubara, Nickel-catalyzed cycloaddition of salicylic acid ketals to alkynes via elimination of ketones, *J. Am. Chem. Soc.*, 2009, **131**, 13194–13195; (d) N. Maizuru, T. Inami, T. Kurahashi and S. Matsubara, Nickel-catalyzed cycloaddition of anthranilic acid derivatives to alkynes, *Org. Lett.*, 2011, **13**, 1206–1209; (e) K. Nakai, T. Kurahashi and S. Matsubara, Nickel-catalyzed cycloaddition of *o*-arylcarboxybenzotrioles and alkynes via cleavage of two carbon-carbon σ bonds, *J. Am. Chem. Soc.*, 2011, **133**, 11066–11068; (f) T. Shiba, T. Kurahashi and S. Matsubara, Nickel-catalyzed decarbonylative alkylidenation of phthalimides with trimethylsilyl-substituted alkynes, *J. Am. Chem. Soc.*, 2013, **135**, 13636–13639; (g) W. Guan, S. Sakaki, T. Kurahashi and S. Matsubara, Reasons two nonstrained C–C σ -bonds can be easily cleaved in decyanative [4+2] cycloaddition catalyzed by nickel(0)/Lewis acid systems. theoretical insight, *ACS Catal.*, 2014, **5**, 1–10; (h) T. Inami, T. Kurahashi and S. Matsubara, Nickel-catalyzed reaction of thioisatins and alkynes: a facile synthesis of thiochromones, *Org. Lett.*, 2014, **16**, 5660–5662; (i) P. Mi, P. Liao, T. Tu and X. Bi, decarbonylative C–C bond-forming reactions of saccharins by nickel catalysis: homocoupling and cycloaddition, *Chem.* –

- Eur. J.*, 2015, **21**, 5332–5336; (j) T. Inami, T. Takahashi, T. Kurahashi and S. Matsubara, Nickel-catalyzed [5+2] cycloaddition of 10 π -electron aromatic benzothiophenes with alkynes to form thermally metastable 12 π -electron nonaromatic benzothiepienes, *J. Am. Chem. Soc.*, 2019, **141**, 12541–12544; (k) P. Mi, L. He, T. Shen, J. Z. Sun and H. Zhao, A novel fluorescent skeleton from disubstituted thiochromenones via nickel-catalyzed cycloaddition of sulfobenzoic anhydrides with alkynes, *Org. Lett.*, 2019, **21**, 6280–6284.
- 26 I. Koyama, T. Kurahashi and S. Matsubara, Nickel-catalyzed [4+2] cycloaddition of enones with alkynes, *J. Am. Chem. Soc.*, 2009, **131**, 1350–1351.
- 27 (a) N. Saito, T. Katayama and Y. Sato, Nickel-catalyzed highly regioselective multicomponent coupling of ynamides, aldehydes, and silane: a new access to functionalized enamides, *Org. Lett.*, 2008, **10**, 3829–3832; (b) N. Saito, Y. Sugimura and Y. Sato, A facile construction of bi- or tricyclic skeletons by nickel-catalyzed stereoselective cyclization of alkynylcycloalkane, *Org. Lett.*, 2010, **12**, 3494–3497.
- 28 (a) J. Montgomery and A. V. Savchenko, Nickel-catalyzed cyclizations of alkynyl enones with concomitant stereoselective tri- or tetrasubstituted alkene introduction, *J. Am. Chem. Soc.*, 1996, **118**, 2099–2100; (b) X.-Q. Tang and J. Montgomery, Nickel catalysis in the stereoselective preparation of quinolizidine, pyrrolizidine, and indolizidine alkaloids: total synthesis of (+)-Allopumiliotoxin 267A, *J. Am. Chem. Soc.*, 1999, **121**, 6098–6099; (c) X. Qi and J. Montgomery, New three-component synthesis of 1,3-dienes employing nickel catalysis, *J. Org. Chem.*, 1999, **64**, 9310–9313; (d) M. Lozanov and J. Montgomery, A new two-step four-component synthesis of highly functionalized cyclohexenols by sequential nickel-catalyzed couplings, *J. Am. Chem. Soc.*, 2002, **124**, 2106–2107; (e) Y. Ni, K. K. Amarasinghe and J. Montgomery, Nickel-catalyzed cyclizations and couplings with vinylzirconium reagents, *Org. Lett.*, 2002, **4**, 1743–1745.
- 29 (a) W.-S. Huang, J. Chan and T. F. Jamison, Highly selective catalytic intermolecular reductive coupling of alkynes and aldehydes, *Org. Lett.*, 2000, **2**, 4221–4223; (b) J. Chan and T. F. Jamison, Synthesis of (-)-terpestacin via catalytic, stereoselective fragment coupling: siccanol is terpestacin, not 11-epi-terpestacin, *J. Am. Chem. Soc.*, 2003, **125**, 11514–11515; (c) S. J. Patel and T. F. Jamison, Catalytic three-component coupling of alkynes, imines, and organoboron reagents, *Angew. Chem., Int. Ed.*, 2003, **42**, 1364–1367; (d) K. M. Miller, W. Huang and T. F. Jamison, Catalytic asymmetric reductive coupling of alkynes and aldehydes: enantioselective synthesis of allylic alcohols and α -hydroxy ketones, *J. Am. Chem. Soc.*, 2003, **125**, 3442–3443; (e) E. A. Colby, K. C. O'Brien and T. F. Jamison, Total syntheses of amphidinolides T1 and T4 via catalytic, stereoselective, reductive macrocyclizations, *J. Am. Chem. Soc.*, 2005, **127**, 4297–4307.
- 30 For selected reviews, see: (a) S. Saito and Y. Yamamoto, Recent advances in the transition-metal-catalyzed regioselective approaches to polysubstituted benzene derivatives, *Chem. Rev.*, 2000, **100**, 2901–2916; (b) J. Montgomery, Nickel-catalyzed cyclizations, couplings, and cycloadditions involving three reactive components, *Acc. Chem. Res.*, 2000, **33**, 467–473; (c) J. Montgomery, Nickel-catalyzed reductive cyclizations and couplings, *Angew. Chem., Int. Ed.*, 2004, **43**, 3890–3908; (d) M. Jeganmohan and C.-H. Cheng, Cobalt- and nickel-catalyzed Regio- and stereoselective reductive coupling of alkynes, allenes, and alkenes with alkenes, *Chem. – Eur. J.*, 2008, **14**, 10876–10886; (e) H. A. Malik, R. D. Baxter and J. Montgomery, Nickel-Catalyzed Reductive Couplings and Cyclizations, in *Catalysis without Precious Metals*, ed. R. M. Bullock, Wiley-VCH, Weinheim, 1st edn, 2010, pp. 181–210; (f) 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; (g) E. A. Standley, S. Z. Tasker, K. L. Jensen and T. F. Jamison, Nickel catalysis: synergy between method development and total synthesis, *Acc. Chem. Res.*, 2015, **48**, 1503–1514; (h) M. Holmes and L. A. Schwartz, Intermolecular metal-catalyzed reductive coupling of dienes, allenes, and enynes with carbonyl compounds and imines, *Chem. Rev.*, 2018, **118**, 6026–6052.
- 31 E. Oblinger and J. Montgomery, A New Stereoselective method for the preparation of allylic alcohols, *J. Am. Chem. Soc.*, 1997, **119**, 9065–9066.
- 32 (a) S.-i. Ikeda and Y. Sato, Synthesis of stereodefined enynes by the nickel-catalyzed coupling reaction of alkynyltins, alkynes, and enones, *J. Am. Chem. Soc.*, 1994, **116**, 5975–5976; (b) S.-i. Ikeda, K. Kondo and Y. Sato, Nickel-catalyzed tandem coupling of α,β -enones, alkynes, and alkynyltins for the regio- and stereoselective synthesis of conjugated enynes, *J. Org. Chem.*, 1996, **61**, 8248–8255; (c) J. Montgomery, M. V. Chevliakov and H. L. Brielmann, Nickel-catalyzed heterocycle construction with stereoselective exocyclic alkene introduction, *Tetrahedron Lett.*, 1997, **53**, 16449–16462; (d) S.-i. Ikeda, K. Kondo and Y. Sato, Nickel-catalyzed tandem coupling of enones, alkynes, alkynylzinc, and chlorotrimethylsilane, *Chem. Lett.*, 1999, **28**, 1227–1228; (e) S. Mannathan, M. Jeganmohan and C. H. Cheng, Nickel-catalyzed borylative coupling of alkynes, enones, and bis (pinacolato)diboron as a route to substituted alkenyl boronates, *Angew. Chem., Int. Ed.*, 2009, **48**, 2192–2195; (f) C. M. Yang, M. Jeganmohan, K. Parthasarathy and C. H. Cheng, Highly selective nickel-catalyzed three-component coupling of alkynes with enones and alkenyl boronic acids: a novel route to substituted 1,3-dienes, *Org. Lett.*, 2010, **12**, 3610–3613.
- 33 M. Takimoto, K. Shimizu and M. Mori, Nickel-promoted alkylation or arylation carboxylation of alkynes, *Org. Lett.*, 2001, **3**, 3345–3347.
- 34 K. M. Miller, C. Molinaro and T. F. Jamison, Catalytic reductive carbon-carbon bond-forming reactions of alkynes, *Tetrahedron: Asymmetry*, 2003, **14**, 3619–3625.

- 35 Y. Ni, K. K. D. Amarasinghe, B. Ksebati and J. Montgomery, First total synthesis and stereochemical definition of isodomoic acid G, *Org. Lett.*, 2003, **5**, 3771–3773.
- 36 R. S. Fornicola, K. Subburaj and J. Montgomery, A new entry to the isogeissoschizoid skeleton, *Org. Lett.*, 2002, **4**, 615–617.
- 37 K. Shimizu, M. Takimoto and M. Mori, Novel synthesis of heterocycles having a functionalized carbon center via nickel-mediated carboxylation: total synthesis of erythrocarine, *Org. Lett.*, 2003, **5**, 2323–2325.
- 38 S. J. Patel and T. F. Jamison, Asymmetric catalytic coupling of organoboranes, alkynes, and imines with a removable (trialkylsilyloxy)ethyl group-girect access to enantiomerically pure primary allylic amines, *Angew. Chem., Int. Ed.*, 2004, **43**, 3941–3944.
- 39 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.
- 40 M. Nie, W. Fu, Z. Cao and W. Tang, Enantioselective nickel-catalyzed alkylative alkyne–aldehyde cross-couplings, *Org. Chem. Front.*, 2015, **2**, 1322–1325.
- 41 K. W. Shimkin and J. Montgomery, Synthesis of tetrasubstituted alkenes by tandem metallacycle formation/cross-electrophile coupling, *J. Am. Chem. Soc.*, 2018, **140**, 7074–7078.
- 42 A. Herath and J. Montgomery, Catalytic intermolecular enal–alkyne [3+2] reductive cycloadditions, *J. Am. Chem. Soc.*, 2006, **128**, 14030–14031.
- 43 M. Ohashi, T. Taniguchi and S. Ogoshi, Nickel-catalyzed formation of cyclopentenone derivatives via the unique cycloaddition of α,β -unsaturated phenyl esters with alkynes, *J. Am. Chem. Soc.*, 2011, **133**, 14900–14903.
- 44 L. Guo, F. Song, S. Zhu, H. Li and L. Chu, *syn*-Selective alkylation of terminal alkynes via the combination of photoredox and nickel catalysis, *Nat. Commun.*, 2018, **9**, 4543.
- 45 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.
- 46 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.
- 47 For selected reviews, see: (a) G. Zeni and R. C. Larock, Synthesis of heterocycles via palladium-catalyzed oxidative addition, *Chem. Rev.*, 2006, **106**, 4644–4680; (b) K. Krüger, A. Tillack and M. Beller, Catalytic synthesis of indoles from alkynes, *Adv. Synth. Catal.*, 2008, **350**, 2153–2167; (c) L. N. Guo, X. H. Duan and Y. M. Liang, Palladium-catalyzed cyclization of propargylic compounds, *Acc. Chem. Res.*, 2011, **44**, 111–122; (d) K. Majumdar, S. Samanta and B. Sinha, Recent developments in palladium-catalyzed formation of five- and six-membered fused heterocycles, *Synthesis*, 2012, **44**, 817–847; (e) M. Platon, R. Amardeil, L. Djakovitch and J. C. Hierso, Progress in palladium-based catalytic systems for the sustainable synthesis of annulated heterocycles: a focus on indole backbones, *Chem. Soc. Rev.*, 2012, **41**, 3929–3968; (f) R. Vicente, Recent advances in indole syntheses: New routes for a classic target, *Org. Biomol. Chem.*, 2011, **9**, 6469–6480.
- 48 C. N. Voth and G. R. Dake, Nickel-catalyzed arylyative additions on 2-alkynyl-N-arylsulfonylanilides to construct functionalized indoles, *Eur. J. Org. Chem.*, 2020, **2020**, 744–748.
- 49 Z. Li, A. Garcia-Dominguez and C. Nevado, Nickel-catalyzed stereoselective dicarbofunctionalization of alkynes, *Angew. Chem., Int. Ed.*, 2016, **55**, 6938–6941.
- 50 A. Garcia-Dominguez, S. Muller and C. Nevado, Nickel-catalyzed intermolecular carbosulfonylation of alkynes via sulfonyl radicals, *Angew. Chem., Int. Ed.*, 2017, **56**, 9949–9952.
- 51 A. Yamamoto and M. Suginome, Nickel-catalyzed *trans*-alkynylboration of alkynes via activation of a boron–chlorine bond, *J. Am. Chem. Soc.*, 2005, **127**, 15706–15707.
- 52 T. Igarashi, S. Arai and A. Nishida, *Anti* carbocyanative cyclization of enynes under nickel catalysis, *J. Org. Chem.*, 2013, **78**, 4366–4372.
- 53 X. Wang, Y. Liu and R. Martin, Ni-catalyzed divergent cyclization/carboxylation of unactivated primary and secondary alkyl halides with CO₂, *J. Am. Chem. Soc.*, 2015, **137**, 6476–6479.
- 54 X. Zhang, X. Xie and Y. Liu, Nickel-catalyzed cyclization of alkyne–nitriles with organoboronic acids involving *anti*-carbometalation of alkynes, *Chem. Sci.*, 2016, **7**, 5815–5820.
- 55 Z. Zhou, W. Liu and W. Kong, Ni-catalyzed reductive antiarylyative cyclization of alkynones, *Org. Lett.*, 2020, **22**, 6982–6987.
- 56 Z. Zhou, J. Chen, H. Chen and W. Kong, Stereoselective synthesis of pentasubstituted 1,3-dienes via Ni-catalyzed reductive coupling of unsymmetrical internal alkynes, *Chem. Sci.*, 2020, **11**, 10204–10211.
- 57 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.
- 58 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.
- 59 S. M. Gillbard, C. H. Chung, S. N. Karad, H. Panchal, W. Lewis and H. W. Lam, Synthesis of multisubstituted pyrroles by nickel-catalyzed arylyative cyclizations of N-tosyl alkynamides, *Chem. Commun.*, 2018, **54**, 11769–11772.
- 60 G. R. Kumar, R. Kumar, M. Rajesh and M. S. Reddy, A nickel-catalyzed *anti*-carbometalative cyclization of alkyne–azides with organoboronic acids: synthesis of 2,3-diarylquinolines, *Chem. Commun.*, 2018, **54**, 759–762.
- 61 Z. Lu, X. D. Hu, H. Zhang, X. W. Zhang, J. Cai, M. Usman, H. Cong and W. B. Liu, Enantioselective assembly of cycloenones with a nitrile-containing all-carbon quaternary center from malononitriles enabled by Ni catalysis, *J. Am. Chem. Soc.*, 2020, **142**, 7328–7333.