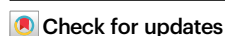


Alkyne dimerization-hydroarylation to form pentasubstituted 1,3-dienes via binuclear nickel catalysis

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Mono-metallic catalysts dominate in homogeneous catalysis, wherein all the element steps generally occur on one metal site. Inspired from bimetallic active sites in both enzymes and heterogeneous catalysts, the development of binuclear catalysis can offer the potential to induce novel intermediates, reactivity, and selectivity. Metal-catalyzed hydroarylation of alkynes generally leads to one alkyne incorporated products and alkyne dimerization-hydrocarbofunctionalization is rather challenging via conventional mono-metallic intermediates. Herein, a highly selective dimerization-hydrocarbofunctionalization of internal alkynes is achieved via dinickel catalysis, leading to the formation of synthetically challenging pentasubstituted 1,3-dienes. Mechanistic studies suggest that each Ni site can promote distinct elementary steps of two alkynes to generate a di-vinyl di-Ni intermediate. Such a mode of “binuclear convergent catalysis” is fundamentally different from the traditional mono-metallic catalysis and may provide new understanding on binuclear synergistic effects at atomic and molecular level.

Bimetallic active sites in both enzymes and heterogeneous catalysts are well known to be effective in mediating challenging and highly valuable reactions, which is largely attributed to synergistic effects between metals in close proximity^{1–4}. However, achieving a fundamental understanding on the bifunctional role at the atomic and molecular level is very challenging due to the structural complexity of the catalytic sites in metallic surfaces and metalloenzyme. Over the last several decades, many efforts have been devoted to modelling these multimetallic activation processes for discovery of novel catalysts, primarily using dinuclear metal complexes in homogenous catalysis^{5–14}. In this context, several types of bimetallic interaction models (e.g., co-activation of a single reactant by ligation with both

metal nuclei, and synergistic activation of both reactants on distinct metal centers etc) have been proposed to account for the significant binuclear synergistic effects. Compared to the classical mono-metallic catalysis wherein all the element steps generally occur on one metal site (Fig. 1a, left), binuclear metallic catalysis offers a unique approach wherein two metal sites may independently promote distinct elementary steps in a parallel way during the initial stage of the catalytic cycle, resulting the formation of new binuclear catalytic intermediates, which thus may lead to unusual reactivity unattainable with a typical mononuclear catalyst (Fig. 1a, right). This would be highly desirable for the development of new reactions and further exploration of novel binuclear catalytic mechanisms^{15–17}.

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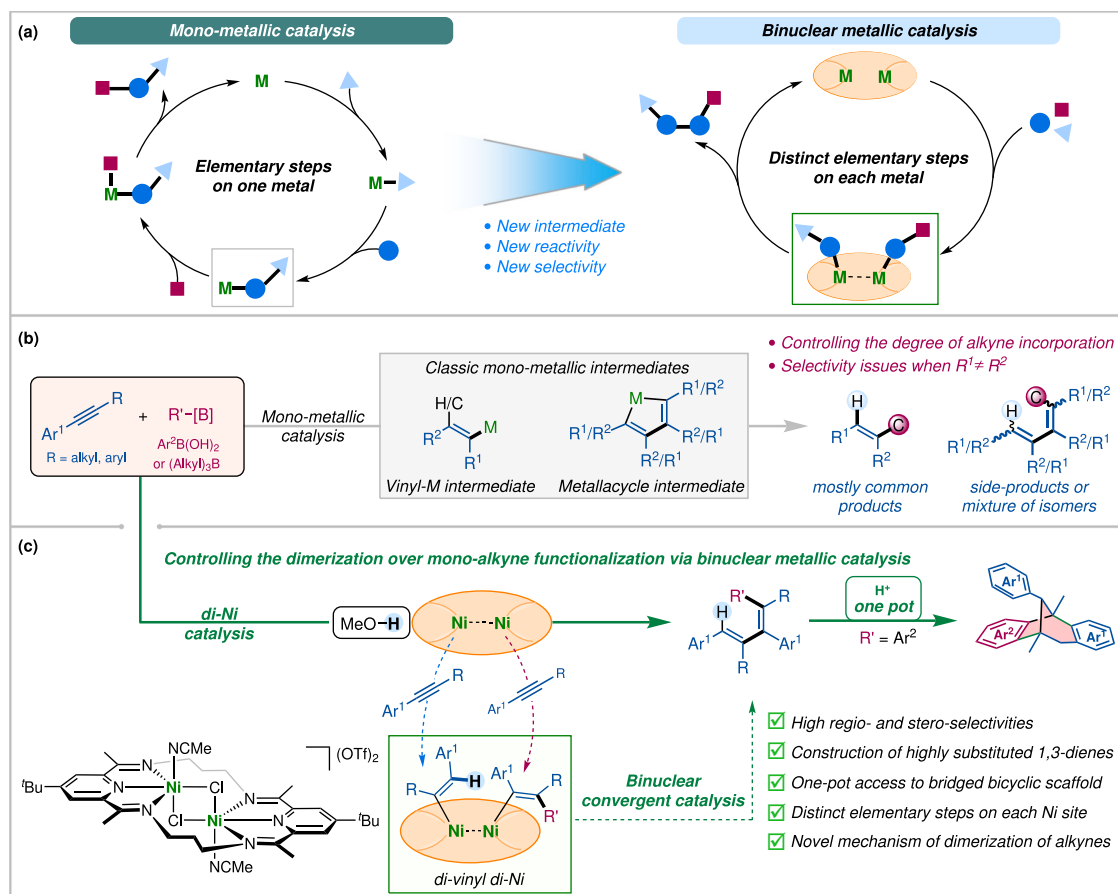


Fig. 1 | Challenges and strategies in transition-metal-catalyzed hydrocarbofunctionalization of alkynes. a Synergistic binuclear catalytic model. **b** Current status of transition-metal-catalyzed hydrocarbofunctionalization of alkynes. **c** This work: Binuclear Ni-catalyzed dimerization-hydrocarbofunctionalization of alkynes.

Alkynes are one of the most readily available feedstocks and versatile synthons^{18–23}. Transition metal-catalyzed hydrocarbofunctionalization of alkynes using organometallic reagents has emerged as one of the most reliable strategies to access a wide range of highly substituted olefins (Fig. 1b)^{24–28}. However, the reactions developed so far generally result in products with only a single equivalent of alkyne incorporated, and dimerization-hydrocarbofunctionalization of unsymmetrical internal alkynes with organometallic reagents remains elusive (mainly as side-reactions or giving a mixture of isomers)^{29–35}, even though this may constitute an attractive strategy for quick access to synthetically versatile yet hardly prepared poly-substituted 1,3-dienes^{36–43}. Controlling the degree of alkyne insertion as well as regio- and stereoselectivity constitutes nontrivial challenges, especially for an unsymmetrical internal alkyne via a general vinyl-metal intermediate or metallacyclopentadiene intermediate^{44–46}. Thus, novel catalytic modes involving distinct intermediates from the classic mono-metallic species may need to be invoked for alkyne dimerization-hydrocarbofunctionalization processes, which eventually allow for efficient access to highly substituted 1,3-dienes.

Herein, we report dimerization and hydroarylation/hydroalkylation of unsymmetrical internal alkynes with organoborons using a dinuclear nickel complex as the catalyst, providing a series of pentasubstituted 1,3-dienes with excellent regio- and stereoselectivities (Fig. 1c). The versatile synthetic utility, broad functional group compatibility, and excellent chemo- and regioselectivity are demonstrated by substrate scope evaluation and product derivatization. In addition, the protocol can be applied to a one-pot synthesis of valuable yet complicated bridged bicyclic scaffolds that are otherwise difficult to prepare. Notably, control experiments using several mononuclear Ni catalysts only afford low yields of the corresponding hydroarylation products with a single

equivalent of alkyne being incorporated, demonstrating the unique reactivity and distinct selectivity pattern of the current dinuclear Ni catalyst. Mechanistic studies suggest that two vinyl Ni moieties are generated intramolecularly on two Ni atoms, respectively, followed by a reductive elimination to form the final product. By analogy to “convergent strategies in total syntheses”^{47,48}, it is tempting to tentatively name this catalytic model as “binuclear convergent catalysis” in homogeneous catalysis, since binuclear core enables parallel substrates activation via distinct elementary steps on two metals and cooperative intermediate transfer across dual metal centers to deliver the final product, whereas monometallic catalysis is generally confined to sequential reaction pathways mediated solely through a single active site.

Results

Reaction development

Bis pyridyl diimine (PDI) ligands^{49–51} based binuclear metal complexes have been used as catalysts in olefin polymerizations⁵² and studied in activation of small molecules^{53,54}. Inspired by the striking potency of binuclear metallic catalysis^{5–14}, our group has developed a macrocyclic bi-PDI based dicobalt complex-catalyzed stereodivergent semi-reduction of alkynes⁵⁵ and a dinickel complex-catalyzed Z-selective 1,4-hydroarylation of 1,3-dienes⁵⁶. As our continuous interest in developing new reactions using binuclear metal complexes as catalysts, we aimed to investigate the coupling of organoboronic acids with alkynes using binuclear Ni complexes as the catalysts. The study was initiated using unsymmetrical internal alkyne, 1-phenyl-1-propyne **1a** and phenylboronic acid **2a** as the model substrates.

After a systematic screening of the reaction parameters (for details, see Supplementary Tables 1–10), we found that a mono-ene **3a**

and a pentasubstituted 1,3-diene product **4a** were obtained in 9% and 84% GC yields, respectively, in the presence of the dinickel complex **A**, NaBHET₃ and *t*-BuONa in a mixed solvent of MeOH and DMF at 80 °C (Table 1, entry 1). Lower efficiency was observed when the reaction was carried out at 60 °C (entry 2). Only trace amount of the target product **4a** was detected without MeOH, suggesting that the alcohol is crucial for the reaction (entry 3). Of note, the length of methylene linkers (where $n = 2-4$) of the catalyst proved to be a critical factor for the reaction efficiency. Compared to dinickel complex **A** ($n = 3$), the reaction using either dinickel complexes **B** ($n = 2$) or **C** ($n = 4$) led to the formation of 1,3-diene product **4a** in significantly lower yields (entries 4 and 5), suggesting that the Ni-Ni distances of the binuclear Ni complexes may influence the reaction outcomes, both in terms of activities and selectivities. Moreover, the catalytic performance of the dinuclear Ni complex was evaluated in comparison with a series of mono-nickel complexes bearing structurally related N-donor ligands, such as PDI (**D-G**), bipyridine (**L1**), bis-oxazoline (**L2**), and pyridine bis-oxazoline (**L3**). In these cases, though varying degrees of alkyne consumption was observed, no significant amount of 1,3-diene product **4a** was detected (entries 6–12). These results further attested the unique catalytic activity and distinct selectivity of the dinuclear catalysts.

Reaction scope

With the optimized reaction conditions in hand, we set out to explore the generality of this methodology, by applying various aryl, alkyl-disubstituted internal alkynes in the reaction with phenylboronic acid **2a** using dinickel complex **A** as the catalyst. The effect of substituents on the aromatic ring on the reaction outcomes was shown in Fig. 2a. Both electron-rich (methyl **1b-1c**, *tert*-butyl **1d**, methoxy **1e** and methylthio **1f**) and electron-deficient (fluoro **1g-1h**, chloro **1i**, bromo **1j** and ester **1k**) alkynes were well compatible with the protocol, to deliver the corresponding conjugated diene products (**4b-4k**) in 60–79% yields. It should be noted that the reaction of *ortho*-substituted aryl alkyne with large steric hindrance also proceeded smoothly to give the desired product **4h** in 49% yield. Moreover, multi-substituent alkynes (**1l-1n**) and 2-naphthyl alkyne **1o** underwent the hydroarylation reaction smoothly, resulting in the formation of 1,3-diene products **4l-4o** in 52–83% yields. Importantly, this method was found to be compatible with an array of heteroaromatic alkynes, including indole, benzofuran, thiophene, pyrazole and ferrocene, furnishing the corresponding products (**4p-4t**) in good yields. Subsequently, the reaction scope with respect to the alkyl moieties of the aryl-alkyl acetylenes was also evaluated. Alkyne substrates bearing different linear alkyl substituents, including Et- and ⁴Pr-, and cyclic substituent, cyclopropyl, were well compatible in the reaction, albeit with moderate yields of the corresponding products (**4u-4w**). Of particular interest is that some functional groups on the alkyl chain, such as ester, chloro, phthalimide and free hydroxyl were well tolerated in the reaction, furnishing pentasubstituted diene products **4x-4aa** in good yields. In addition, diphenylacetylene was also proved to be a suitable substrate for this transformation, giving the product **4ab** in 77% yield, with an olefin bond configuration different from that of the mono-Ni catalyzed transformation³³. Under the standard conditions, the reaction of dialkyl acetylenes only led to mono hydroarylation products (for failed examples, see Supplementary Information Page S35). The structure of **4a** was unambiguously confirmed by X-ray analysis.

Encouraged by these results, we further examined the scope of arylboronic acids (Fig. 2b). The reactions of a series of *para*- and *meta*-substituted arylboronic acids, such as methyl, *tert*-butyl, trimethylsilyl, fluoro, chloro and ester, all afforded the desired 1,3-diene products **4ac-4ai** in satisfactory yields with excellent regio- and stereo-selectivity. In addition to monosubstituted arylboronic acids, polysubstituted arylboronic acids were also compatible with the procedure to give the corresponding products (**4aj**, 66% and **4ak**, 33%). It is worth mentioning that boronic acids derived from several heterocycles, such

as furan, benzofuran, dibenzo[*b,d*]thiophene, and carbazole, were also competent coupling partners, affording the corresponding pentasubstituted diene products **4al-4ao** in moderate yields (42–62%).

To further expand the use of this methodology, we proceeded to examine the reaction of trialkylborane with alkyne using dinickel complex **A** as the catalyst. Under modified conditions, the reaction of 1-phenyl-1-propyne **1a** and triethylborane **5a** led to the desired ethyl-substituted 1,3-diene product **6a** in 70% isolated yield (for details, see Supplementary Tables 11–14). Next, the substrate scope with regards to alkynes was examined (Fig. 3). Various aryl alkyl alkynes were amenable to this transformation, giving rise to the corresponding pentasubstituted diene products **6b-6m** in good yields with high regio- and stereoselectivities. Thereafter, the scope of this reaction with other organoboranes was further explored. Commercially available tri-*n*-butylborane reacted well to furnish **6n** in 54% yield. Additionally, the reactions using unpurified trialkylboranes (prepared from 1-hexene and 1-octene with BH₃·SMe₂) also gave **6o** and **6p** smoothly.

This strategy was subsequently applied into the functionalization of some alkynes bearing biologically relevant skeletons (Fig. 4a). The reactions of a range of internal alkynes derived from (–)-borneol, carbofuran phenol, canagliflozin, dapagliflozin, hymecromone, L-tyrosine or estrone with phenylboronic acid **2a** proceeded smoothly to give the corresponding pentasubstituted diene products **4ap-4av** in good yields with excellent regio- and stereoselectivity, respectively. All these results further underscored the good functional group compatibility of the reaction, attesting the robustness and practicality of the titled reaction.

Furthermore, a series of synthetic elaboration of the products **4a** and **6a** were conducted to showcase the synthetic versatility of the methodology (Fig. 4b). For examples, **4a** was quantitatively converted to substituted indene derivative **7** by methanesulfonic acid (MeSO₃H)-mediated intramolecular Friedel-Crafts cyclization, while Diels-Alder reaction of **4a** with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) and 4-phenyl-1,2,4-triazoline-3,5-dione delivered bicyclic products **8** and **9** in 80% and 92% yields, respectively. In addition, epoxidation of **6a** with varying amounts of 3-chloroperbenzoic acid (*m*-CPBA) gave mono-epoxide **10** or di-epoxide **11**, respectively, in moderate yields. It is noteworthy that sequential hydroarylation and double intramolecular Friedel-Crafts cyclization of two equivalents of alkyne **1** can be successfully achieved in one-pot via di-Ni catalysis followed by a treatment with trifluoromethanesulfonic acid (TfOH), leading to a series of biologically interesting dibenzobicyclo[3.2.1]octadienes **12** in remarkable efficiency (Fig. 4c).

Experimental and theoretical mechanistic studies

To gain some insight into the reaction mechanism, a series of experiments were conducted (Fig. 5). The use of 2,6-di-*tert*-butyl-4-methylphenol (BHT, 1.0 equiv), a radical scavenger, in the reaction of alkyne **1a** and phenylboronic acid **2a** under the standard conditions showed almost no adverse effect on the formation of the desired product **4a**, suggesting that the reaction was most likely not a radical-based process (Fig. 5a). Next, deuterium-labeling experiment was carried out to probe the origin of the hydrogen source for the hydroarylation. As shown in Fig. 5b, submission of **1a** and arylboroxine **13** to the reaction using CH₃OD resulted in **4a-D** with 90% deuterium incorporation at the olefinic carbon position, indicating that methanol proton acts as the hydrogen source in the reaction. Moreover, kinetic isotope effect (KIE) was measured on the reaction of **1a** and **2a** in MeOH and MeOD, respectively, to deliver a k_H/k_D value of 1.3 (Fig. 5c), suggesting that proton transfer is unlikely to be the rate-determining step. Additionally, a competitive reaction of two electronically reversed alkynes, **1e** and **1k**, with **2a** was run under the standard conditions (Fig. 5d). In this case, the homo-coupling products **4e** and **4k** were isolated in 17% and 45% yields, respectively, along with the formation of a 34% yield of cross-coupling product **4aw**. These results suggested that alkyne with electron-deficient substituent on the phenyl ring is more favorable in

Table 1 | Optimization of the reaction conditions^a

					Nickel catalysts and ligands	
Entry	[Ni]	Conv. (%) ^b	3a (%) ^b	4a (%) ^b		
1	A	98	9	84		
2 ^c	A	90	5	73		
3 ^d	A	60	trace	trace		
4	B	82	26	45		
5	C	85	21	40		
6	D	30	trace	trace		
7	E	45	10	trace		
8	F	46	13	10		
9	G	32	trace	trace		
10	Ni(OTf) ₂ / L1	51	15	trace		
11	Ni(OTf) ₂ / L2	65	8	trace		
12	Ni(OTf) ₂ / L3	42	trace	trace		

A, n = 3, R = Me, L = CH₃CN, X = OTf
B, n = 2, R = Me, L = THF, X = BArF₂₀
C, n = 4, R = H, L = CH₃CN, X = OTf

D, R = Dipp
E, R = Cy
F, R = Bn

L1 **L2** **L3**

^aReaction conditions: **1a** (0.40 mmol), **2a** (0.36 mmol), dinickel complex **A** (5.0 mol%), NaBHEt₃ (20 mol%) and *t*-BuONa (30 mol%) in MeOH (1.0 mL)/DMF (2.0 mL) at rt for 1.0 h and then 80 °C for 12 h; For mononickel catalyst, 10 mol% catalyst loading was used.

^bConversion and yields were determined by GC using mesitylene as the internal standard.

^c60 °C.

^dWithout MeOH, Dipp 2,6-diisopropylphenyl, Cy cyclohexyl, Bn benzyl, OTf⁻ trifluoromethanesulfonate, BArF₂₀⁻ trakis(pentafluorophenyl)borate, DMF *N,N*-dimethylformamide, CH₃CN acetonitrile, THF tetrahydrofuran. The bold formats (**A–G** and **L1–L3**) in Table 1 are respectively defined as the numbers of the catalysts and ligands.

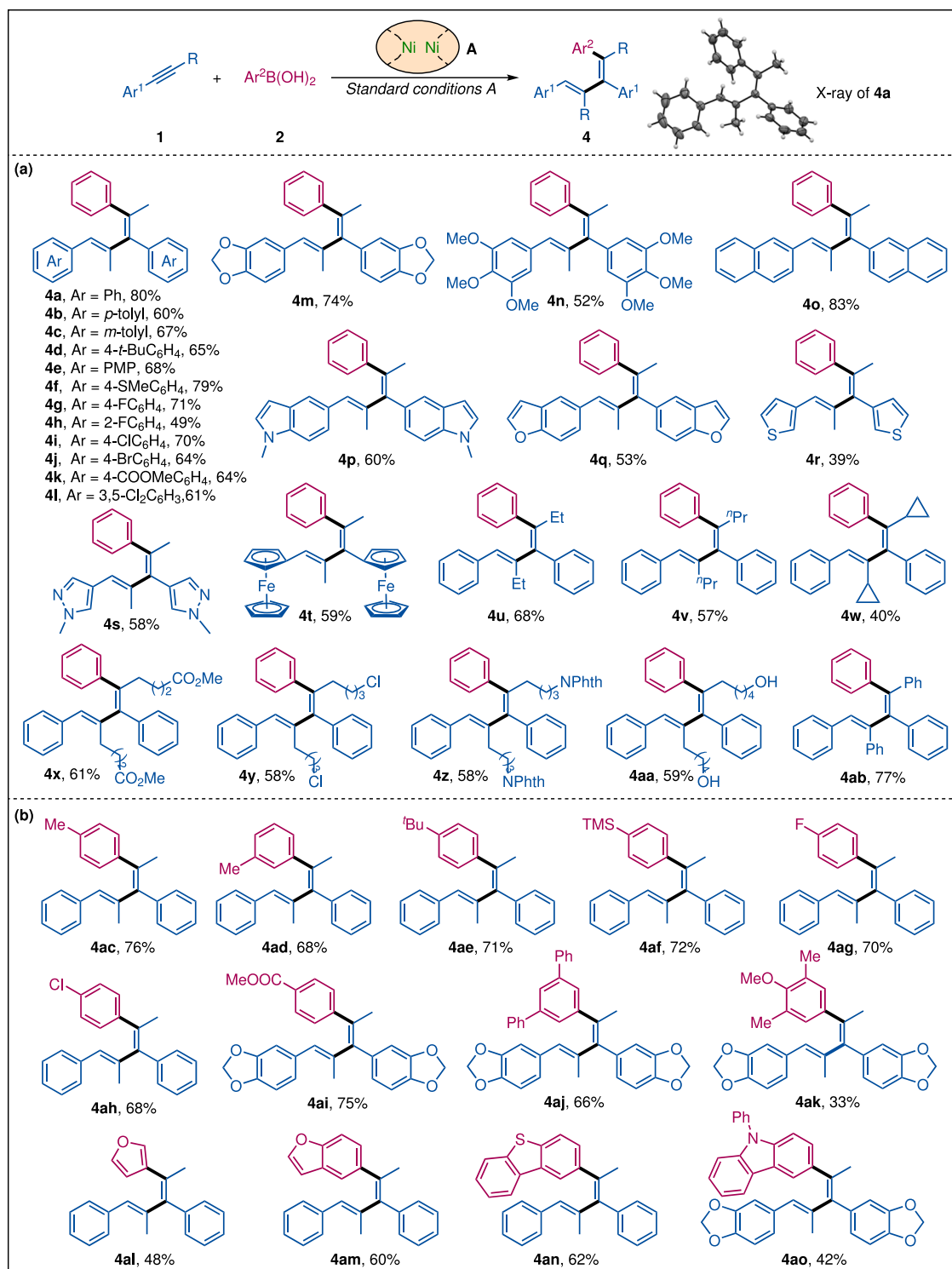


Fig. 2 | The scope of the dimerization-hydroarylation of internal alkynes. **a** Scope of alkynes. **b** Scope of arylboronic acids. Reaction conditions A: alkyne **1** (0.40 mmol), arylboronic acid **2** (0.36 mmol), dinickel complex **A** (5.0 mol%), NaBHET₃ (20 mol%) and *t*-BuONa (30 mol%) in MeOH (1.0 mL)/DMF (2.0 mL) at rt for

1.0 h and then 80 °C for 12 h. Yields shown are of isolated products. For **4h** and **4w**, the reactions were conducted at 100 °C. PMP *p*-methoxyphenyl, NPhth *N*-Phthalimido, TMS trimethylsilyl.

the competition reaction. Then, kinetic orders of the reaction were studied under the standard reaction conditions (Fig. 5e). The rate data show a linear dependence on the concentration of the dinuclear nickel catalyst **A** and alkyne **1a**, but a zero-order dependence is observed for arylboronic acid **2a**. These results suggested the involvement of one catalyst molecule and one alkyne molecule in the rate-determining step, and the binuclear Ni structure remains largely intact during the

catalytic process. Furthermore, Hammett studies were performed to investigate the electronic effect of substituents appended on the alkynes and arylboronic acids, respectively (Fig. 5f). A linear correlation between $\log(k_X/k_H)$ and the Hammett constant (σ_{para}) with a slightly positive slope of 0.157, indicating that the effect of electronic effects of alkyne on the reaction rate is not significant. Moreover, a ρ value of -1.455 was obtained for a series of *para*-substituted

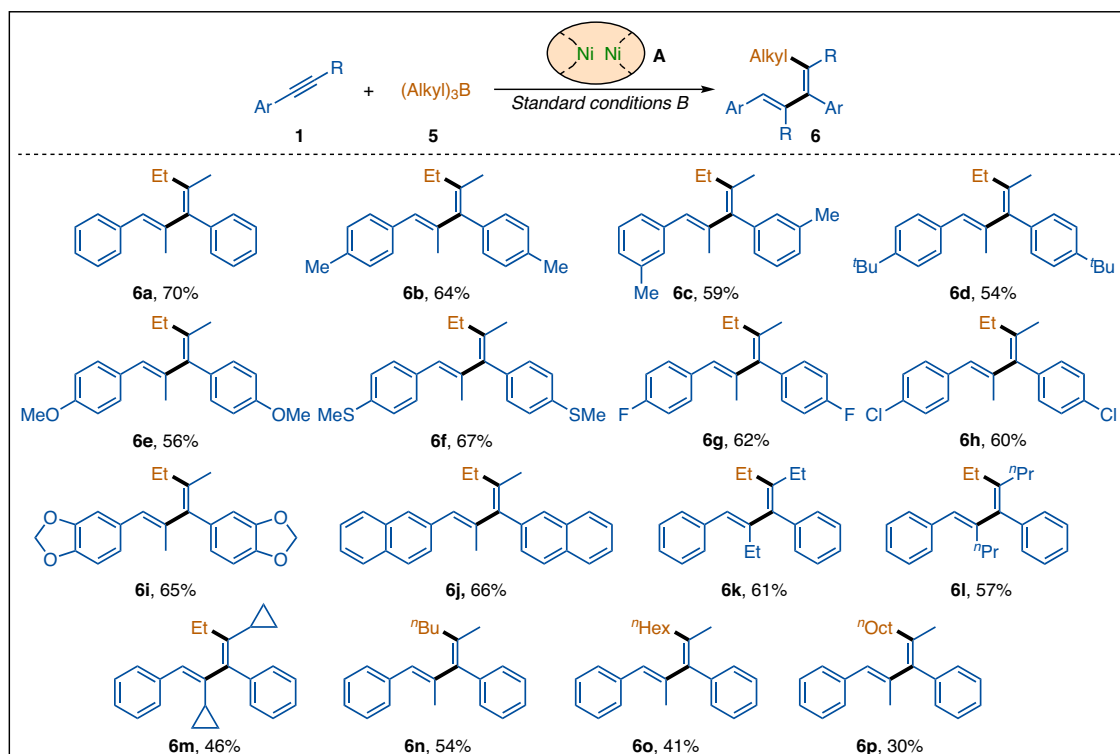


Fig. 3 | The scope of the dimerization-hydroalkylation of unsymmetrical internal alkynes. Reaction conditions B: alkyne **1** (0.40 mmol), trialkylborane **5** (0.40 mmol), dinickel complex **A** (5.0 mol%), NaBH₄Et₃ (30 mol%) and *t*-BuOLi

(50 mol%) in MeOH (10 equiv)/DMF (0.30 mL) at rt for 1.0 h and then 80 °C for 12 h. Yields shown are of isolated products. For **6n–6p**, B₂Pin₂ (10 mol%) was used instead of NaBH₄Et₃.

arylboronic acids, suggesting that the presence of an electron-rich group on arylboronic acid is favorable for the reaction.

To further unveil the mechanistic details of this multicomponent reaction, density functional theory (DFT) calculations were further performed at SMD-M06L-D3/def2-TZVP//M06L/def2-TZVP/def2-SVP level of theory (see detailed introduction in Supplementary Information). A formally reduced [(PDI)Ni⁰]₂ (**INT1**) is firstly generated via in situ reduction of the catalyst precursor **A** (Fig. 6)⁵⁶. Based on our previous work, herein the formal [(PDI)Ni⁰]₂ can be described more appropriately as [(PDI)Ni^I]₂, a dinuclear Ni(I) complex in ground state of triplet⁵⁶, which facilitates the activation of alkyne **1a** (**INT1A**, −22.7 kcal/mol) rather than methanol (**INT1C**, −13.3 kcal/mol, see detailed mechanism of Path C in Supplementary Fig. 15). Oxidative cyclization of the alkyne π bond across the two Ni centers forms a four-membered bimetallic intermediate **INT1A** with the C1–C2 bond length being elongated to 1.34 Å, which is close to a C=C double bond of alkenes (1.33 Å)⁴⁵. This similar reactivity and coordination model was disclosed on the addition of diphenylacetylene to a neutral bis-pyridyldiimine dicobalt complex by Tomson group⁵⁷. In addition, we failed to locate the side-on mode (μ-η²:η²) of alkyne with the C≡C triple bond perpendicular to the Ni–Ni direction^{58,59}, which would spontaneously transfer to the end-on mode (μ-η¹:η¹) **INT1A**, possibly due to the steric linkage (–C₃H₆–) of PDI ligands. Therefore, the reaction may be initiated by the oxidative addition of the first alkyne triple bond across the dinuclear Ni core (**INT1A**). The viability of synergistic oxidative cyclometallation of two alkynes on ³[Ni₂] to form ³INT2B was also assessed as Path B^{58,59}, however, it was found unfavorable due to the much higher energy barrier (ΔG[‡] = 32.2 kcal/mol, Supplementary Fig. 16). More pathways can be envisioned starting from **INT1A** to generate the intermediate ³INT4A or ³INT4B, depending on the order of protonation, transmetalation and alkyne insertion (Paths A1–A4 in Fig. 6). The protonation of **INT1A** with MeOH to give **INT2A** would be a pathway more favorable than the alkyne insertion of **INT1A** with the

second alkyne (**1a**) on di-Ni core to ³INT2B in Path A1 (see detailed mechanism in Supplementary Fig. 14). After the formation of intermediate **INT2A**, the direct transmetalation to form **INT3A** needs to overcome an energy barrier of +21.9 kcal/mol, which is more accessible than the second alkyne (**1a**) insertion to form ³INT3B (Path A2, 41.8 kcal/mol via ³TS2B in Supplementary Fig. 14). However, the following alkyne insertion into the Ni_a–C2 bond of **INT3A** as depicted in Path A3 is associated with a rather high energy barrier (32.5 kcal/mol), suggesting that the butadienyl intermediate **INT4B** might not be accessible. Alternatively, the second alkyne (**1a**) can be selectively inserted into the Ni_b–C_{ph} bond at the C4 site with a favorable energy barrier (ΔG[‡] = 28.7 vs 33.1 kcal/mol at C3 site, path A4), resulting in two different vinyl-Ni moieties within intermediate **INT4A** and finally generates the diene products through a bimetallic reductive elimination. Detailed free energy profiles were depicted in Fig. 7.

The calculated pathway with the most favorable energy profile was found to consist of species mostly occurring in the triplet state, and spin populations of Ni_a and Ni_b in the relevant intermediates and transition states may vary throughout the reaction course, and some of intermediates were found to adopt singlet as their ground states (See unfavored pathway of singlet states in Supplementary Fig. 17). Oxidative addition of alkyne (**1a**) with two Ni centers would result in the formation of a bimetallic intermediate **INT1A** via a MECP with a barrierless process (see Supplementary Fig. 18 for further discussion), which could react with MeOH via a binuclear concerted protonation process to give **INT2A**. NPA charges of **1a** and **INT1A** indicated that binuclear Ni₂ core acts as an electron-donor to achieve two-electron transfer to the triple bond of **1a**, and hence the accumulated electron density on C1 rather than C2 in **INT1A** would favor the capture the proton of MeOH by C1 (20.4 kcal/mol in ³TS1A vs 21.9 kcal/mol in ³TS1A'), which is consistent with the regioselective protonation of C1 site as revealed by the deuterium labelling experiment (Fig. 5b). Upon generation of **INT2A**, the methoxy group in **INT2A** readily associates

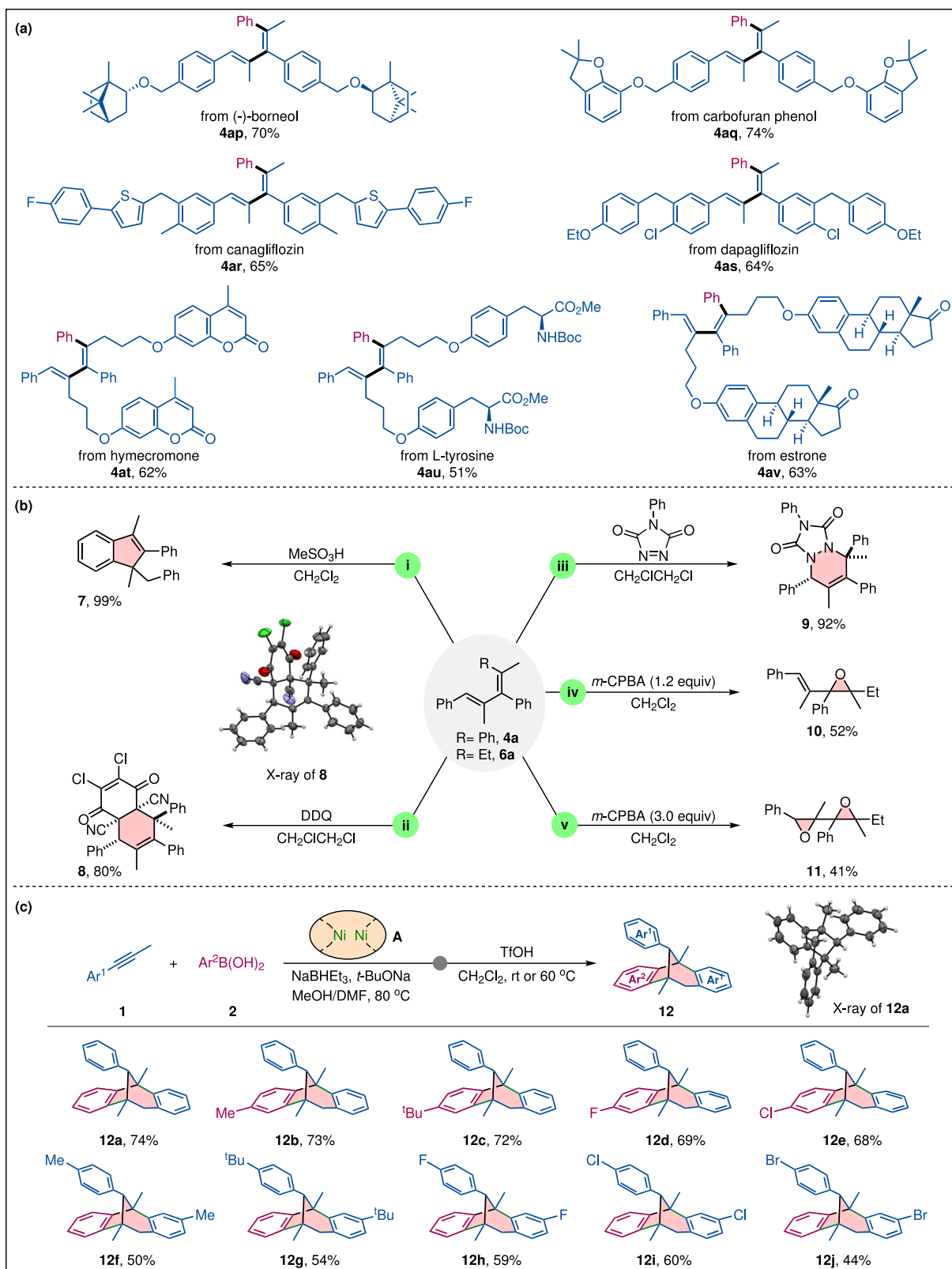


Fig. 4 | Late-stage functionalization and synthetic applications. a Transformations of complex alkyne substrates. **b** Transformations of products. **c** One-pot synthesis of bridged bicyclic compounds. Boc, *t*-butoxycarbonyl.

with phenylboronic acid **2a**, which undergoes transmetalation on Ni_b (21.9 kcal/mol in $^3\text{TS2A}$) under the triplet state, which is more stable than the corresponding singlet state species (40.3 kcal/mol in $^1\text{TS2A}$, see Supplementary Fig. 17). After release of MeOB(OH)_2 in $^1\text{INT3A}$, the following reductive elimination of the aryl and alkenyl on Ni_a and Ni_b ,

respectively, has to overcome a relatively high energy barrier of 30.2 kcal/mol, which would prevent the formation of the hydroarylation product **3a** with incorporation of only one alkyne (for details, see Supplementary Fig. 19). Alternatively, through the ligand exchange of the second alkyne **1a** with MeOB(OH)_2 ligand of $^1\text{INT3A}$, the second

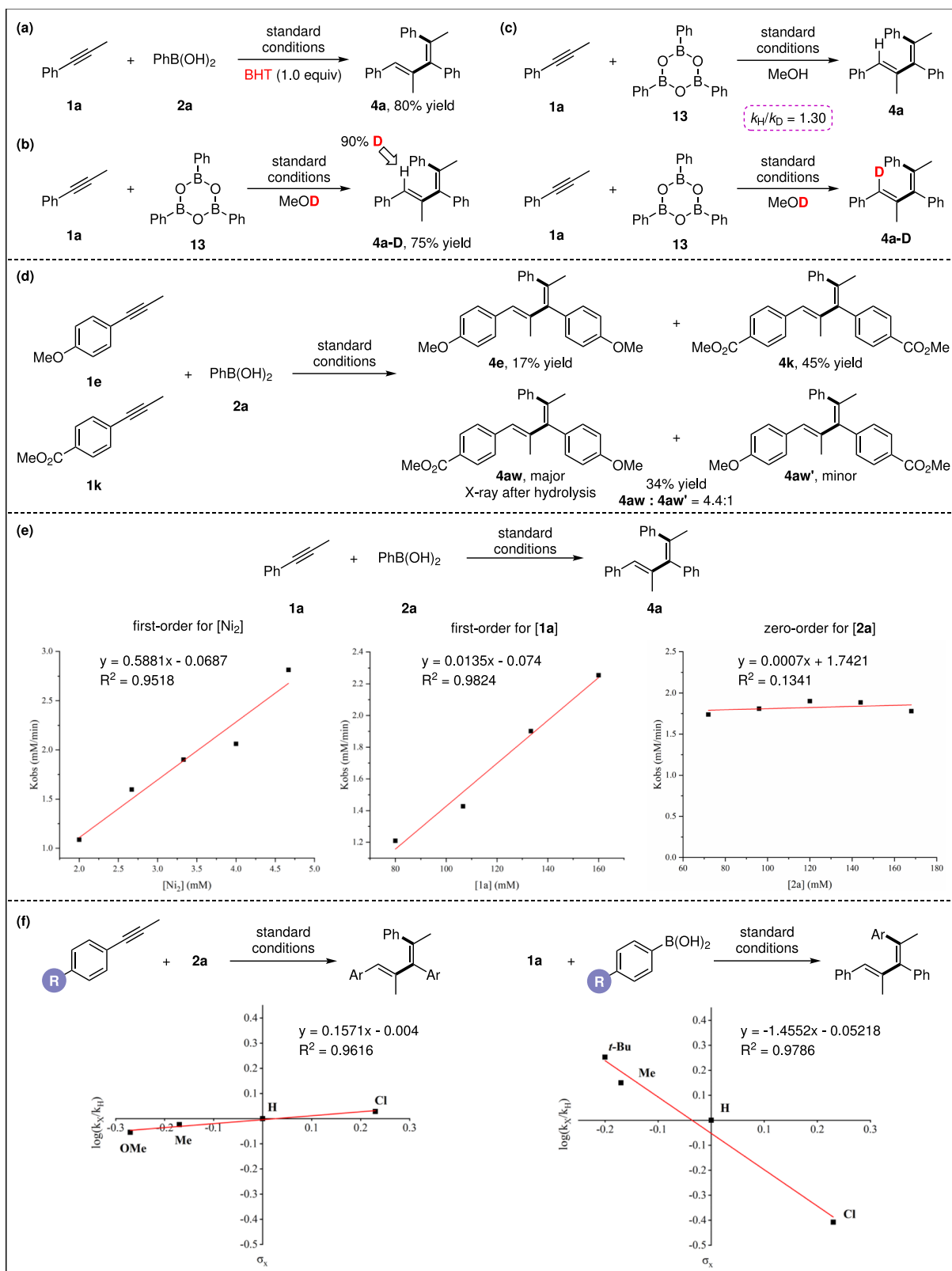
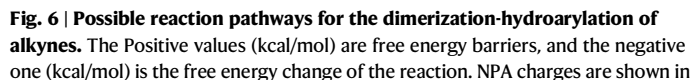


Fig. 5 | Experimental mechanistic studies. a Radical inhibition experiment. **b** Deuterium-labeling experiment. **c** KIE experiment. **d** Competition experiment. **e** Kinetic order studies. **f** Hammett studies.

alkyne insertion of $\text{Ni}_b\text{-C}_{\text{Ph}}$ bond proceeds via transition state $^3\text{TS3A}$ to form intermediate $^3\text{INT4A}$ featured by $\pi\text{-}\pi$ interactions between styrenyl- Ni_a and the phenyl group from the second alkyne as well as the $\pi\text{-}\pi$ interactions between PDI and the phenyl group from phenylboronic acid (IGMH analysis in Fig. 6). The activation barrier for the

migratory insertion of the phenyl group to C4 site was 4.4 kcal/mol lower than that for C3 site (28.7 kcal/mol in $^3\text{TS3A}$ vs 33.1 kcal/mol in $^3\text{TS3A}'$), which is consistent with the regioselectivity observed in the reaction. Closer inspections of $^3\text{TS3A}$ revealed that the electronic interaction between aryl group and alkyne substrate is the key to



In summary, we have developed an efficient dimerization and hydrocarbofunctionalization of alkynes with organoborons using a bis-PDI dinickel complex as the catalyst, affording a wide spectrum of penta-substituted 1,3-dienes with excellent regio- and stereoselectivities. This protocol exhibits high functional group tolerance and broad substrate scope, and the resulting products are amenable to a variety of transformations, especially for the efficient synthesis of bridged bicyclic compounds. Experimental and theoretical mechanistic studies suggested that each Ni site can facilitate distinct elementary steps of two alkynes to generate a key di-vinyl di-Ni intermediate, followed by a

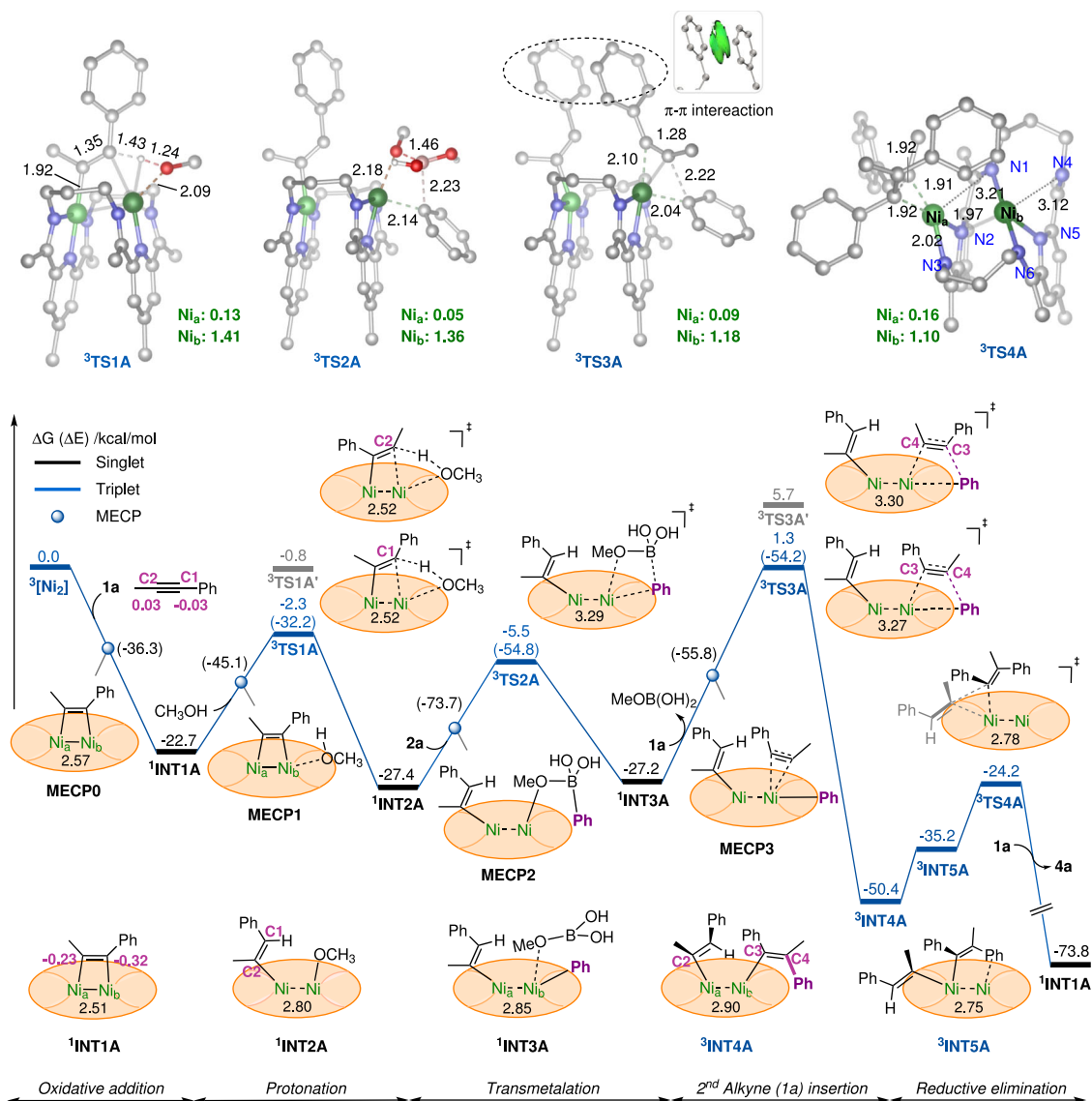


Fig. 7 | Calculated mechanism of dimerization-hydroarylation of alkynes. See unfavored pathways of singlet states in Supplementary Fig. 17; NPA charges are shown in purple; Spin population in green and bond length (Å) in black. IGMH analysis of $^3\text{TS3A}$ with $\delta g^{\text{inter}} = 0.004$. MECP the minimum energy crossing points.

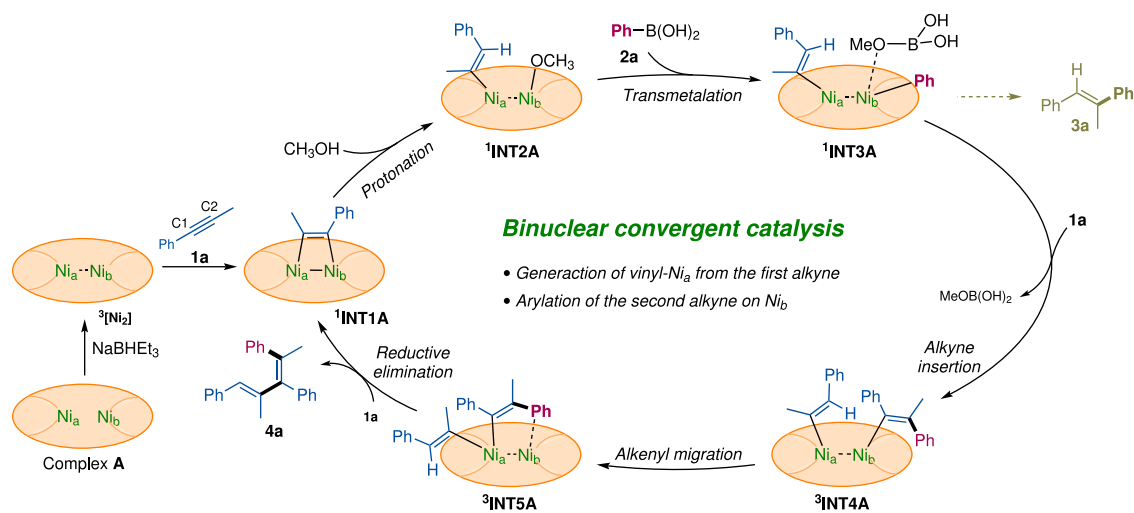


Fig. 8 | Proposed mechanism. Proposed catalytic cycle for binuclear Ni-catalyzed dimerization-hydrocarbofunctionalization of alkynes.

reductive elimination to release the final product, which is substantially different from classic mono-metallic catalysis. This work may stimulate the development of novel reactions via binuclear catalysis and provides an improved understanding of the binuclear catalytic mechanisms in industrial / biocatalytic systems.

Methods

Procedure for dimerization-hydroarylation of alkynes

Under argon atmosphere, arylboronic acid (0.36 mmol, 1.8 equiv), dinuclear nickel complex **A** (10.8 mg, 5.0 mol%) and ^tBuONa (5.7 mg, 30 mol%) were added to an oven-dried 10 mL Schlenk tube equipped with a magnetic stir bar. Then the Schlenk tube was moved to a nitrogen-filled glovebox, alkyne (0.40 mmol, 2.0 equiv), MeOH (1.0 mL), DMF (2.0 mL) and NaBHET₃ (40 μ L, 20 mol%, 1.0 M in THF) were added sequentially. After that, the tube was sealed and moved out of the glovebox. The reaction mixture was stirred at room temperature for 1.0 h, then heated to 80 °C and stirred for 12 h. After cooling to room temperature, saturated brine was added, and the reaction mixture was extracted with ethyl acetate. The organic layer was concentrated in vacuum and the residue was purified by chromatography on silica gel to give the product.

Procedure for dimerization-hydroalkylation of alkynes

Under argon atmosphere, dinuclear nickel complex **A** (10.8 mg, 5.0 mol%) and ^tBuOLi (8.0 mg, 50 mol%) were added to an oven-dried 10 mL Schlenk tube equipped with a magnetic stir bar. Then the Schlenk tube was moved to a nitrogen-filled glovebox, alkyne (0.40 mmol, 2.0 equiv), trialkylborane (400 μ L, 2.0 equiv, 1.0 M in THF), MeOH (81 μ L, 10 equiv), DMF (0.30 mL) and NaBHET₃ (60 μ L, 30 mol%, 1.0 M in THF) were added sequentially. After that, the tube was sealed and moved out of the glovebox. The reaction mixture was stirred at room temperature for 1.0 hour, then heated to 80 °C and stirred for 12 h. After cooling to room temperature, saturated brine was added, and the reaction mixture was extracted with ethyl acetate. The organic layer was concentrated in vacuum and the residue was purified by chromatography on silica gel to give the product.

Data availability

The authors declare that all data supporting the findings of this study are available within the article and Supplementary Information files, and are also available from the corresponding author upon request. Crystallographic data coordinates for structures reported in this article have been deposited at the Cambridge Crystallographic Data Center (CCDC), under deposition numbers CCDC 2364647 (product **4a**), CCDC 2364651 (product **8**), CCDC 2364652 (product **12a**) and CCDC 2364654 (product **4ax**). These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via http://www.ccdc.cam.ac.uk/data_request/cif. Cartesian coordinates of the calculated structures are available from Supplementary Data.

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Author contributions

K.C., X.W., and K.D. directed the project and designed the experiments; K.C. and S.J. performed all the experiments and analyzed all the data with X.W.; Q.P. directed the project by the theoretical study and wrote the related manuscript with H.Z. who completed the DFT calculations. K.C. and X.W. wrote the manuscript with contributions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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