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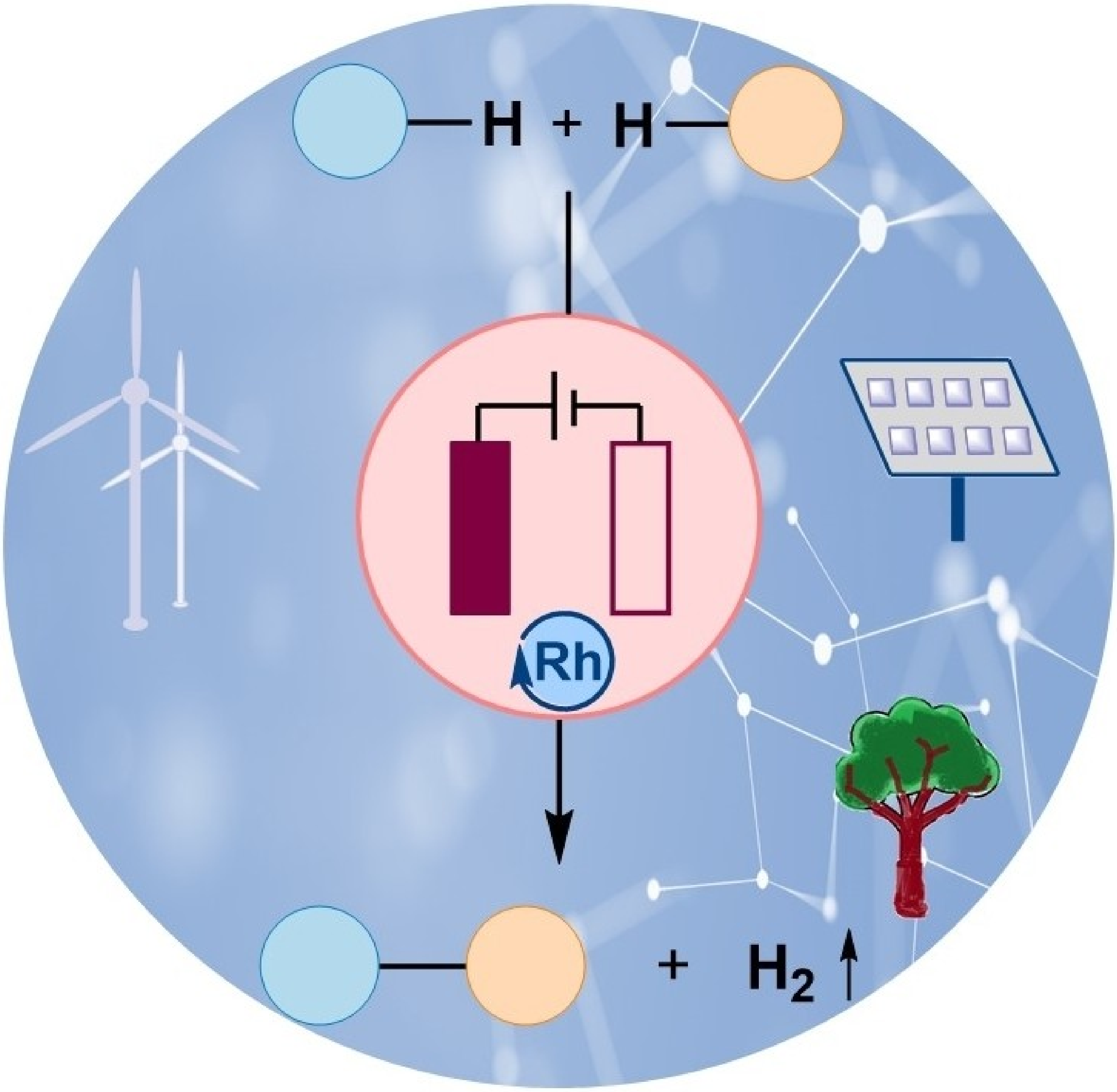
Recent Advances in Rhodium-Catalyzed Electrochemical C–H Activation

Vikash Kumar, Rajaram Maayuri, Lusina Mantry, and Parthasarathy Gandeepan*[a]



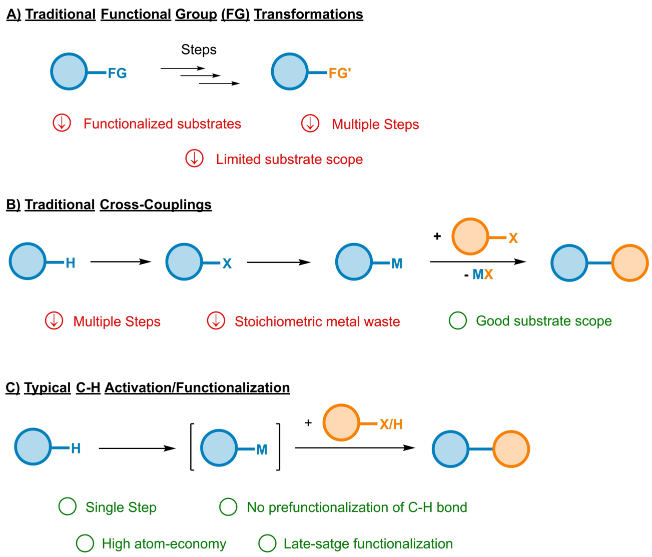
Abstract: Rhodium-catalyzed C–H activation has emerged as a powerful tool for forging C–C and C-heteroatom bonds. Nevertheless, the requirement of stoichiometric chemical oxidants for oxidative transformations significantly hampered the overall sustainability of the C–H activation transformations. The emergence of merging transition metal catalysis and electrochemistry, called metalla-electrocatalysis provides an excellent opportunity to construct organic molecules efficiently and sustainably. This review highlights the recent developments of rhodium-catalyzed electrochemical C–H activation transformations, challenges and opportunities for future developments.

1. Introduction

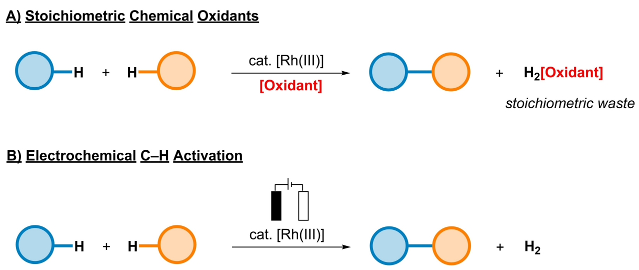
The construction of carbon-carbon (C–C) and carbon-heteroatom (C-het) bonds is the key step to producing all the synthetic organic molecules commonly used in medicines, agrochemicals, functional materials, polymers, paints, and many more.[1–3] Traditional functional group transformation approaches to get these chemicals and materials suffer greatly with poor efficiency, regio- and stereochemical issues, and lack of available starting compounds (Scheme 1). During the past few decades, transition metal-catalyzed cross-coupling strategy significantly advanced the organic synthesis field, resulting in shorter reaction time, high regio- and stereochemical outcomes, excellent functional group tolerance, and improved yields.[4–7] Despite these advances, the cross-coupling transformations demand functionalized organic electrophiles and organometallic nucleophiles (Scheme 1).[8–10] Preparation of starting materials for various coupling reactions required multiple synthetic steps, which significantly hampers the resource economy of the overall transformations.

In the past two decades, transition metal-catalyzed positional selective activation of unactivated C–H bonds has been extensively studied and is now recognized as a promising strategy for the synthesis of complex organic compounds in atom-, step-, and resource-economical manners.[11–22] The C–H activation strategy holds several advantages; in particular, it allows the use of readily available, inexpensive, and less/unfunctionalized feedstocks, thereby ensuring high levels of the overall sustainability of the synthetic processes (Scheme 1). Thus, the C–H activation strategy is extensively utilized in natural products synthesis,[23–28] functional materials synthesis,[29–32] and drug discovery.[33–36] Among the various transition metal catalysts used for the C–H activation reactions, rhodium complexes are studied extensively for C–C and C-het bond formation reactions in an efficient fashion.[37–41] The rhodium(III)-catalyzed oxidative C–H activation strategy has proved to be instrumental in developing several key organic transformations under mild reaction conditions. Despite these advances, the use of expensive and toxic stoichiometric oxidants such as copper(II) or silver(I) salts in rhodium(III)-catalyzed oxidative reactions significantly reduces the overall sustainability of the C–H activation strategy (Scheme 2).

Recently, electrochemical organic synthesis has experienced a remarkable renaissance and has emerged as an attractive alternative to conventional oxidation and reduction reactions (Scheme 2).[42–50] Electrosynthesis does not require external chemical oxidants and reductants, as electron serves as the reagent. Until recently, the major C–H functionalization reactions were realized only based on substrates inherent reactivity under metal-free reaction conditions.[46–48] In sharp contrast, Jutand used electricity to promote palladium-catalyzed organometallic C–H activation in the presence of benzoquinone as the redox mediator.[51–53] Later, several exciting palladium-catalyzed



Scheme 1. Different strategies of organic synthesis. A) Traditional method of organic synthesis via functional group transformations. B) Organic synthesis via transition-metal catalyzed cross-couplings. C) Organic synthesis through transition metal-catalyzed direct functionalization of unactivated C–H bonds.



Scheme 2. Transition metal-catalyzed oxidative C–H activation. A) Traditional oxidative C–H activation with stoichiometric chemical oxidants. B) Electrochemical oxidative C–H activation with hydrogen evolution.

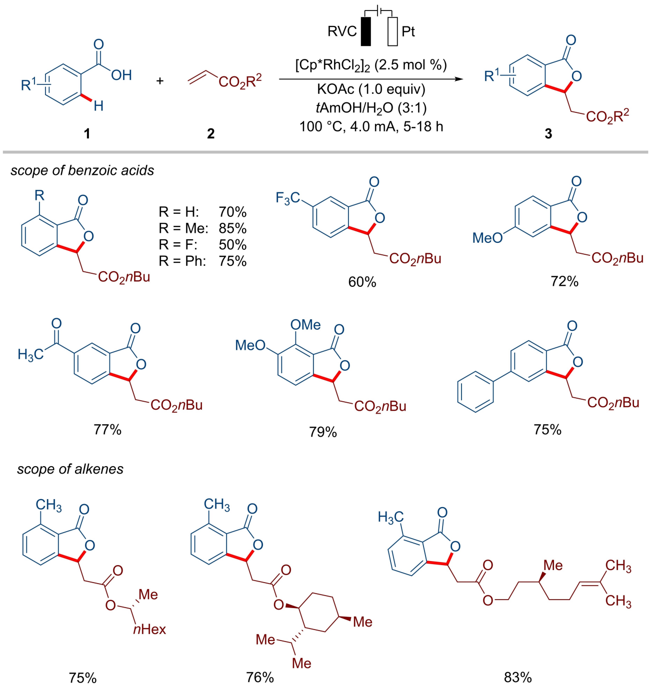
[a] V. Kumar, R. Maayuri, L. Mantry, Dr. P. Gandeepan
Department of Chemistry
Indian Institute of Technology Tirupati
Yerpedu-Venkatagiri Road, Yerpedu Post
Tirupati District, Andhra Pradesh 517619 (India)
E-mail: pgandeepan@iittp.ac.in

electrochemical transformations were realized.[54–57] Recently, the merger of transition metal-catalyzed C–H activation and electrochemistry received substantial attention, and many exciting works have been reported.[58–67] In this review, we summarize the development of electrochemical rhodium-catalyzed C–H activation for the formation of C–C and C-heteroatom bonds until February 2023.

2. C–C Bond Formation

2.1. C–H Activation with Alkenes

Oxidative alkenylation of unactivated C–H bond represents an important reaction type in organic synthesis.[68–74] A wide range of rhodium(III)-catalyzed C–H alkenylations have been realized in the presence of stoichiometric chemical oxidants, typically silver(I) or copper(II) salts.[38,75] In sharp contrast, the Ackermann group reported the first electrochemical rhodium-catalyzed oxidative C–H alkenylation without stoichiometric chemical oxidants (Scheme 3).[76] Thus, *ortho*-selective alkenylation of benzoic acids **1** with alkenes **2** was conveniently realized in a user-friendly undivided cell setup using reticulated vitreous carbon (RVC) anode and Pt cathode. Here, rhodium(III) complex, $[Cp^*RhCl_2]_2$ was identified as a catalyst to obtain expected



Scheme 3. Rhodium-catalyzed electrochemical C–H alkenylation of benzoic acids.

Vikash Kumar was born in Mahendergarh, Haryana, India. He completed his bachelor's degree in Chemistry from Maharshi Dayanand University, Rohtak in 2016 and his master's degree in Chemistry from National Institute of Technology Silchar, Assam, India, in 2018. Since August 2020, he has been pursuing his Doctoral studies under the supervision of Dr. Parthasarathy Gandeepan at the Indian Institute of Technology Tirupati, Andhra Pradesh, India. His research focuses on method development in organic synthesis using transition metal catalysts.

Rajaram Maayuri was born in Tiruchirappalli, Tamil Nadu, India. She obtained her bachelor's degree in Chemistry from Holy Cross College in 2018 and her master's degree in General Chemistry from Bharathidasan University, Tiruchirappalli, Tamil Nadu, India, in 2020. Since August 2021, she has been pursuing her PhD research work under Dr. Parthasarathy Gandeepan at the Indian Institute of Technology Tirupati, Andhra Pradesh, India. Her research focuses on method development for organic synthesis using 3d transition metal catalysts.

Lusina Mantry was born in Odisha, India. She obtained her bachelor's degree in Chemistry from Utkal University, Odisha in 2018 and her master's degree in General Chemistry from Berhampur University, India, in 2020. Since August 2020, she has been pursuing her Ph.D. under the supervision of Dr. Parthasarathy Gandeepan at the Indian Institute of Technology Tirupati, Andhra Pradesh, India. Her research work focuses on method development in organic synthesis using photoredox catalysis.

Parthasarathy Gandeepan has been Assistant Professor in the Department of Chemistry at the Indian Institute of Technology Tirupati since December 2019. He studied BSc (Chemistry) and MSc (Organic Chemistry) at the University of Madras and obtained his PhD (Chemistry) with Chien-Hong Cheng at the National Tsing Hua University, Taiwan. He did postdoctoral works with Chien-Hong Cheng (NTHU, Taiwan), Lutz Ackermann (University of Göttingen, Germany), and Beatrice Collins (University of Bristol, UK) before starting his independent research career. His research interests include transition metal-catalyzed organic transformations, photoredox catalysis, and sustainable methodology developments for organic synthesis.

product **3** in satisfactory yields. Similarly, the choice of acetate additive and reaction media proved crucial for better results. A wide range of benzoic acids **1** and alkenes **2** took part in the electro-catalytic reaction to offer desired products **3** in good yields and excellent regioselectivity. Further, this protocol was applied to vinylic C–H activation of acrylic acid derivatives **4** with alkenes **2** to give substituted 2-furanones **5** in good yields (Scheme 4).[76]

The rhodium(III)-catalyzed electrochemical C–H activation was not limited to aromatic and vinylic carboxylic acids. Aromatic amides **6** and indole substrates **8** also proved viable for oxidative alkenylated products (Scheme 5).[76] Thus, the reaction of N-methyl benzamide **6a** with *n*-butyl acrylate **2a** resulted in isoindolinone derivative **7a** in 51% yield. Similarly, the reaction of N-pyrimidyl (pym) indole **8a** with alkene **2a** offered regioselective C2-alkenylated product **9a** in 50% yield (Scheme 5).[76] Here, the pyrimidyl group served as directing group (DG) for regioselective C2–H cleavage of indole substrate.

The author proposed a plausible catalytic cycle based on detailed mechanistic studies, as shown in Figure 1.[76] The *in situ* generated rhodium(III) carboxylate species **1-I** undergo facile *ortho* C–H metalation to give five-membered rhodacycle **1-II**. After that, alkene coordination followed by migratory insertion to rhodium-carbon bond of **1-III** resulted seven-membered intermediate **1-IV**. Subsequently, the β-hydride elimination and reductive elimination events formed rhodium(I) intermediate **1-V**. Finally, the anodic oxidation of intermediate **1-V** releases the product **3** and regenerates the catalytically active rhodium (III) species **1-I**.

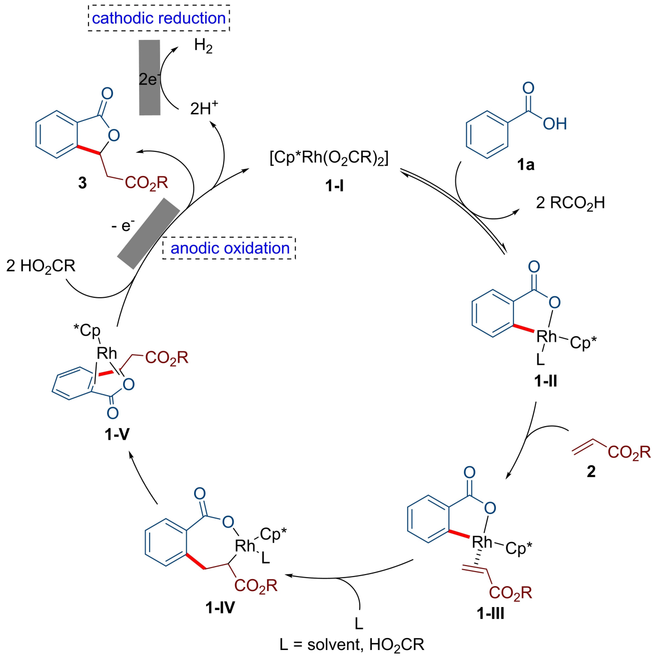
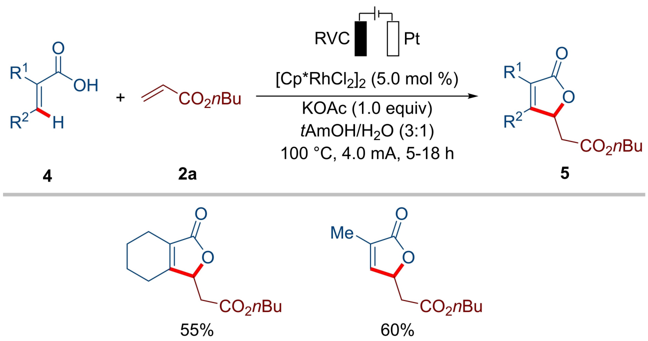
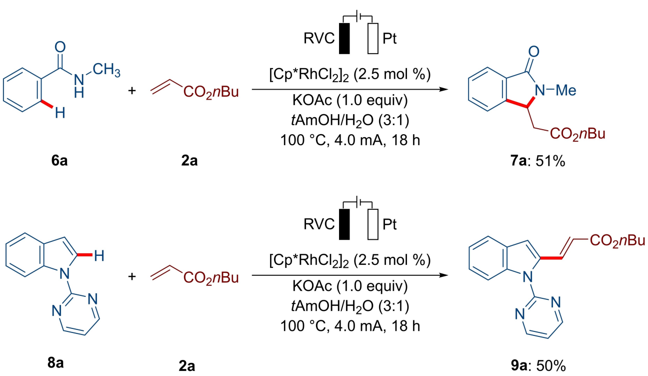


Figure 1. Proposed mechanism for rhodium-catalyzed electrochemical C–H alkenylation of benzoic acids.



Scheme 4. Rhodium-catalyzed electrochemical synthesis of 2-furanones.

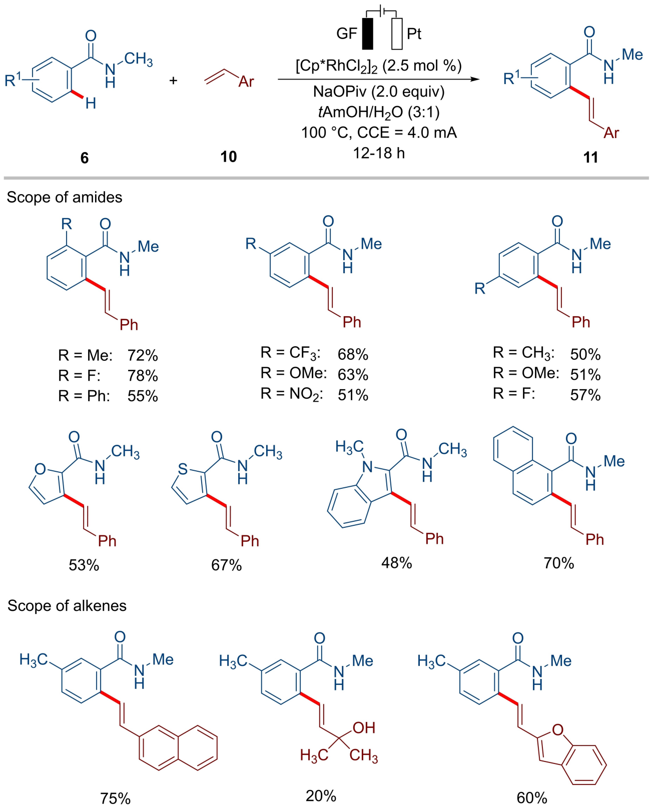


Scheme 5. Rhodium-catalyzed electrochemical C–H alkenylation of benzamide and indole.

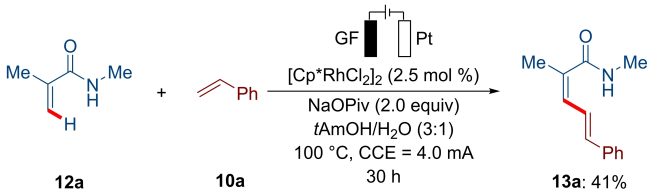
The Ackermann group discovered a suitable electrochemical reaction system for the formation of uncyclized *ortho*-alkenylated benzamide products **11** (Scheme 6).[77] The reaction was smoothly accomplished in an undivided cell using graphite felt (GF) anode and Pt cathode under constant current electrolysis (CCE). Under the catalytic reaction conditions, various aromatic and heteroaromatic amides **6** were coupled with styrenes **10** to offer the desired products **11**. Notably, acrylamide **12a** was also identified as the viable substrate under identical reaction conditions used for aromatic amide C–H activation (Scheme 7).[77]

The catalyst's working mode was proposed to commence by amide chelation-assisted cyclorhodation at the *ortho* position to form five-membered rhodacycle **2-II** (Figure 2).[77] After that, alkene migratory insertion and anodic oxidation events resulted seven-membered rhodium(IV) intermediate **2-IV**. The cyclic intermediate **2-IV** then releases the product **11** and a rhodium(II) species **2-V** by β-hydrogen elimination. Finally, electrochemical oxidation of rhodium(II) species regenerates catalytically active rhodium(III) species **2-I**. The generation of molecular hydrogen at the cathode completes the catalytic cycle.

The versatile rhodium(III)-catalyzed electrochemical C–H alkenylation strategy was further explored to include alkylidenecyclopropanes as an alkene coupling partner by the Ackermann group (Scheme 8).[78] Thus, the reaction of N-pyrimidyl indoles **8** with (cyclopropylidenemethyl)benzenes **14** in the presence of $[Cp^*RhCl_2]_2$ as the catalyst, NaO_2CAd and cyclopentanecarboxylic acid ($CypCO_2H$) as the additives in 1,4-



Scheme 6. Rhodium-catalyzed electrochemical oxidative C–H alkenylation of benzamides.



Scheme 7. Rhodium-catalyzed electrochemical oxidative C–H alkenylation of acrylamide.

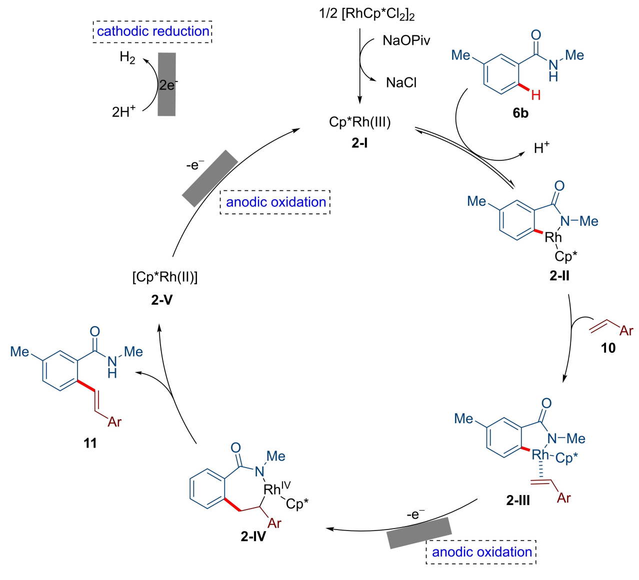
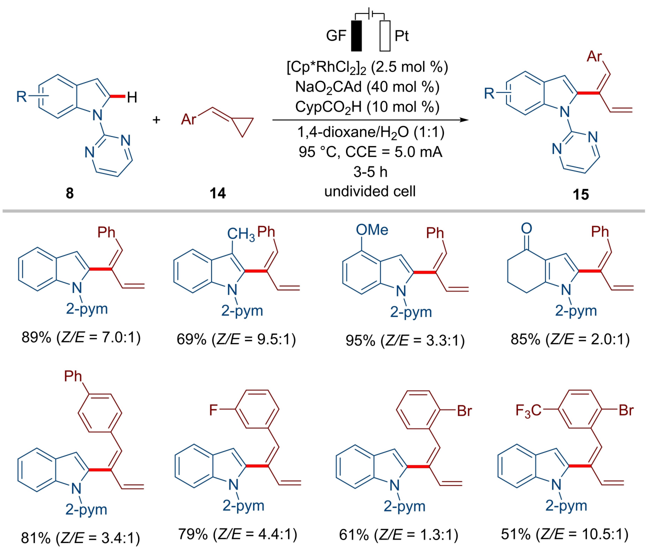


Figure 2. Proposed catalytic cycle for rhodium-catalyzed electrochemical oxidative C–H alkenylation of benzamides.

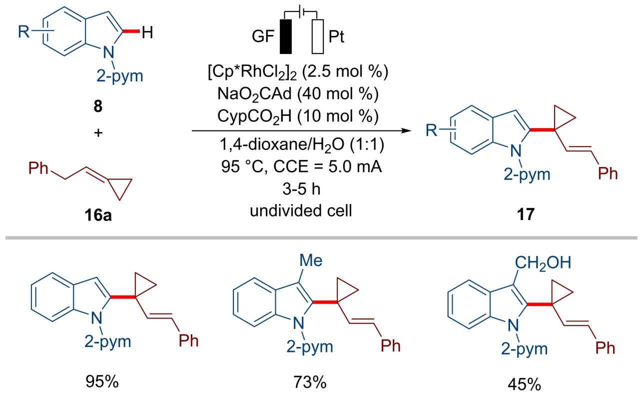


Scheme 8. Rhodium-catalyzed electrochemical C–H dienylation of indoles with alkylidenecyclopropanes.

dioxane/H_2O reaction media gave the dienylated product **15** in good yields with moderate *E/Z* diastereoselectivity. Interestingly, when alkylidenecyclopropane switches from **14** to **16**, the reaction afforded diversely substituted cyclopropanes **17** (Scheme 9).[78]

The authors proposed a plausible catalytic cycle for the rhodaelectro-C–H-cyclopropylation (Figure 3).[78] Here, *in situ* generated active catalyst **3-I** readily undergoes chelation-assisted C2 selective C–H cyclometallation. Then, alkene migratory insertion followed by β-hydride elimination release the desired product **17a** and rhodium(I) species **3-IV**. Finally, the anodic oxidation processes regenerate the active rhodium(III) catalytic species while generating molecular hydrogen at the cathode to complete the catalytic cycle.

Very recently, versatile rhodaelectrocatalysis has been successfully applied for the *peri* C–H alkenylation of 1-naphthols.[79] The finding is important and challenging as substrate 1-naphthols have been known to readily undergo undesired dimerization or polymerization.[80–82] Thus, the Ackermann group discovered the catalytic conditions consist of $[Cp^*RhCl_2]_2$ as the catalyst, KOPiv as the additive in *t*-AmOH/H_2O for the *peri*-selective oxidative alkenylation of 1-naphthols **18** with alkenes **10** (Scheme 10).[79] The reactions were conveniently realized in the user-friendly galvanostatic conditions (CCE = 4.0 mA) in an undivided cell employing graphite felt (GF) anode and a platinum cathode. The reaction also proceeds under potentiostatic conditions at 0.8 V, however with increased reaction time for satisfactory results. Notably, the reaction gave 0–10% yields of desired alkenylation product formation using chemical oxidants (air, $Cu(OAc)_2{\cdot}H_2O$, AgOAc, $PhI(OAc)_2$, $K_2S_2O_8$, NFSI) in place of electricity, highlighting the crucial role of



Scheme 9. Rhodium-catalyzed electrochemical C–H cyclopropylation of indoles.

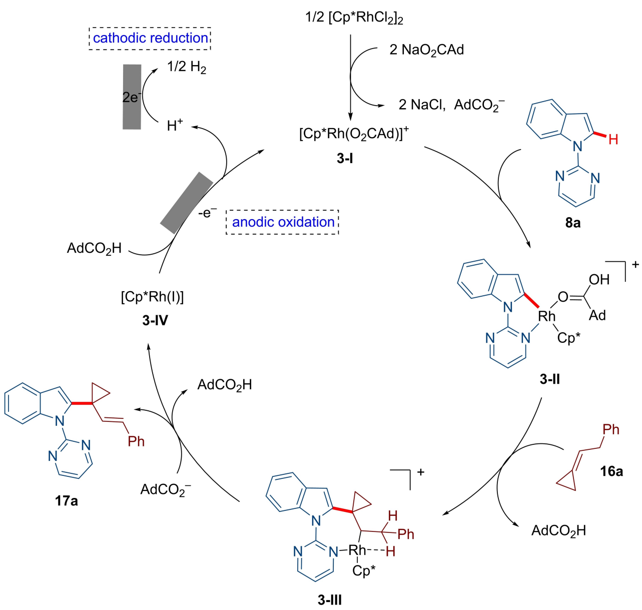
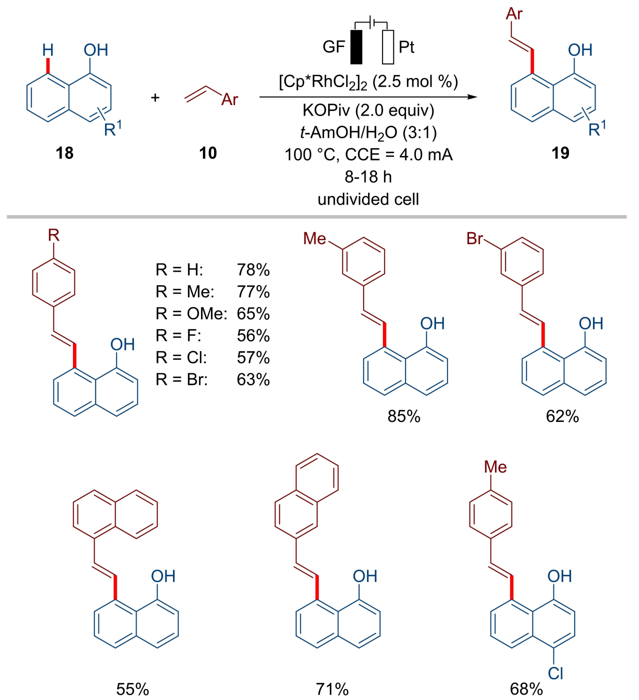
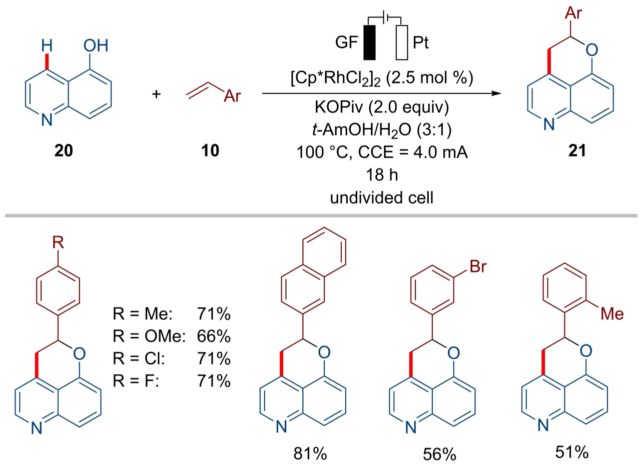


Figure 3. Proposed mechanism for rhodium-catalyzed electrochemical C–H cyclopropylation of indoles with alkylidenecyclopropanes.



Scheme 10. Rhodium-catalyzed electrocatalytic C–H alkenylation of 1-naphthols with alkenes.



Scheme 11. Rhodium-catalyzed electrocatalytic C–H alkenylation of 5-hydroxyquinoline with alkenes.

electro oxidation. As to the scope, a wide variety of styrenes **10** were proved viable substrates to give the desired products **19** in good yields. Interestingly, the use of 5-hydroxyquinoline **20** as the substrate resulted the unprecedented 2-phenyl-2,3-dihydropyranoquinoline derivatives **21** under similar reactions (Scheme 11).[79]

Based on the detailed experimental and computational studies, a plausible catalytic cycle was proposed as depicted in Figure 4.[79] The catalytic cycle begins with the *in situ* formation of [Cp*Rh(OPiv)$_2$] **4-I** from the reaction of pre-catalyst [Cp*RhCl$_2$]$_2$ and KOPiv. After that, *O*-chelation assisted *peri*-C–H activation event generates cyclic rhodium intermediate **4-II**. Next, coordination of alkene **10** to **4-III** followed by migratory insertion and subsequent anodic oxidation forms the seven-membered rhodium(IV) intermediate **4-IV**. The high valent rhodium complex **4-IV** undergoes β-hydrogen elimination and concomitant reductive elimination to afford the desired product **19** and rhodium(II) species **4-V**. Finally, the anodic oxidation of **4-V** regenerates catalytically active rhodium(III) species **4-I**, while generating molecular hydrogen as the by-product at the cathode.

2.2. C–H Activation with Alkynes

Rhodium(III)-catalyzed oxidative annulation reactions with alkynes are well studied.[32,38–39] However, these methods often suffer by the need of toxic and expensive stoichiometric oxidants such as copper(II) or silver(I) salts. To overcome these

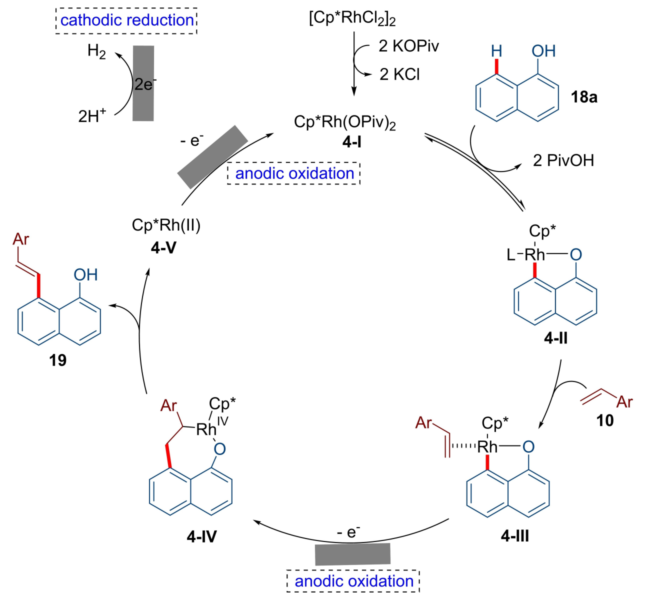
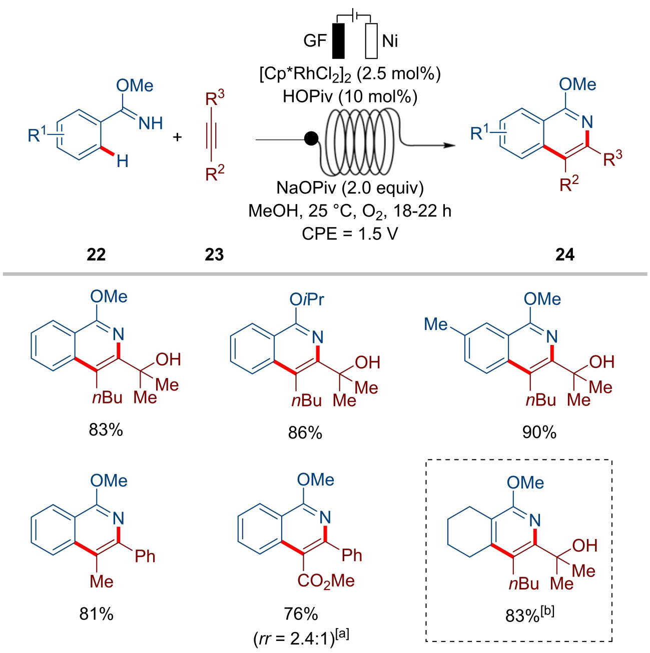


Figure 4. Proposed catalytic cycle for the electro oxidative alkenylation of 1-naphthol with alkene.

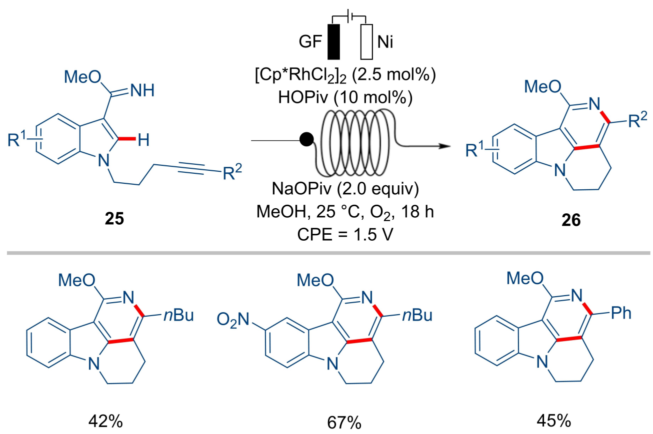
limitations and improve the sustainability of the C–H activation strategy, Ackermann and coworkers elegantly combined the rhodium-catalyzed C–H activation, electrochemistry and flow chemistry.[83] Thus, the flow-rhodaelectro-catalyzed oxidative annulation reaction of aryl imidates **22** and alkynes **23** through C–H activation to form isoquinolines **24** was realized (Scheme 12).[83] Here, a modular electro-flow cell with graphite felt (GF) anode and Ni plate cathode setup was used at a constant potential of 1.5 V and flow rate of 400 μL/min at oxygen atmosphere. The oxygen atmosphere is beneficial because it prevents the cathodic reduction of highly reactive rhodium intermediates. As to the scope, a wide range of aryl imidates **22** and alkynes **23** were compatible and afforded the products **24** in good yields. Interestingly, the unsymmetrical alkynes were displayed an excellent regioselectivity. An example of alkenyl imidate also shown to form the desired annulation product under the reaction conditions (Scheme 12). Furthermore, the rhodium-catalyzed electro-flow approach was successfully applied for intramolecular C–H/N–H functionalization of alkyne tethered N-alkyl indoles **25** to afford azo-tetracycles **26** in moderate to good yields (Scheme 13).

Based on the competition experiments and kinetic isotopic effect (KIE), the authors suggested that C–H activation may occur via base-assisted internal electrophilic substitution (BIES)[84–86] mechanism and C–H metalation step is facile and not to be rate determining. A plausible catalytic cycle was proposed based on detailed experimental and computational studies as illustrated in Figure 5.[83] The *in situ* generated $Cp^*Rh(OPiv)_2$ undergoes cyclometallation with substrate **22a**, providing rhodacycle **5-II**. Coordination of alkyne **23** to **5-II** followed by migratory insertion gives a seven-membered rhodacycle intermediate **5-IV**. Subsequently, anodic oxidation of **5-IV** forms rhodium(IV) intermediate **5-V**, which readily undergoes reductive elimination to provide rhodium(II) species **5-VI**. Anodic oxidation of **5-VI** regenerates the active catalyst **5-I** and release the product **24**.

The versatile transition metal-catalyzed C–H activation strategy has been well exploited for the synthesis of π-extended polycyclic aromatic hydrocarbons (PAHs) by Itami,[87–90] and others.[91–96] The reported methods are generally required stoichiometric chemical oxidants. In sharp contrast, in 2019, Ackermann showcased the potential of rhodaelectrocatalysis for the synthesis of PHAs **28** from aryl boronic acids **27** and alkynes **23** in the absence of any external chemical oxidants (Scheme 14).[97] The optimization studies of the reaction displayed less efficiencies for ruthenium-, iridium- or palladium based catalysts to deliver the desired PAHs. A wide range of aryl boronic acids **27** were effectively underwent annulative C–H



Scheme 12. Flow-rhodaelectro-catalyzed oxidative annulation reaction of aryl imidates with alkynes. [a] rr = regioisomeric ratio; major isomer is shown. [b] 5.0 mol% of $[Cp^*RhCl_2]_2$ used for 10 h.



Scheme 13. Synthesis of azo-tetracycles via flow rhodaelectro-catalyzed intramolecular C–H/N–H functionalization.

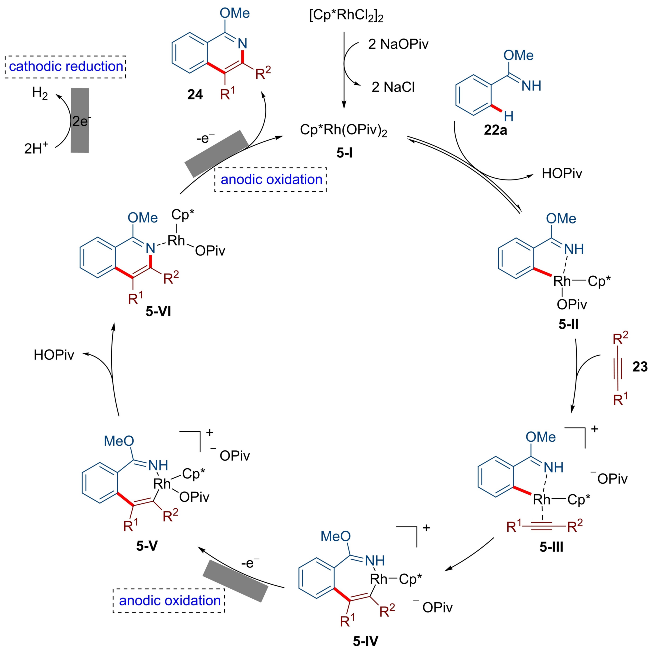
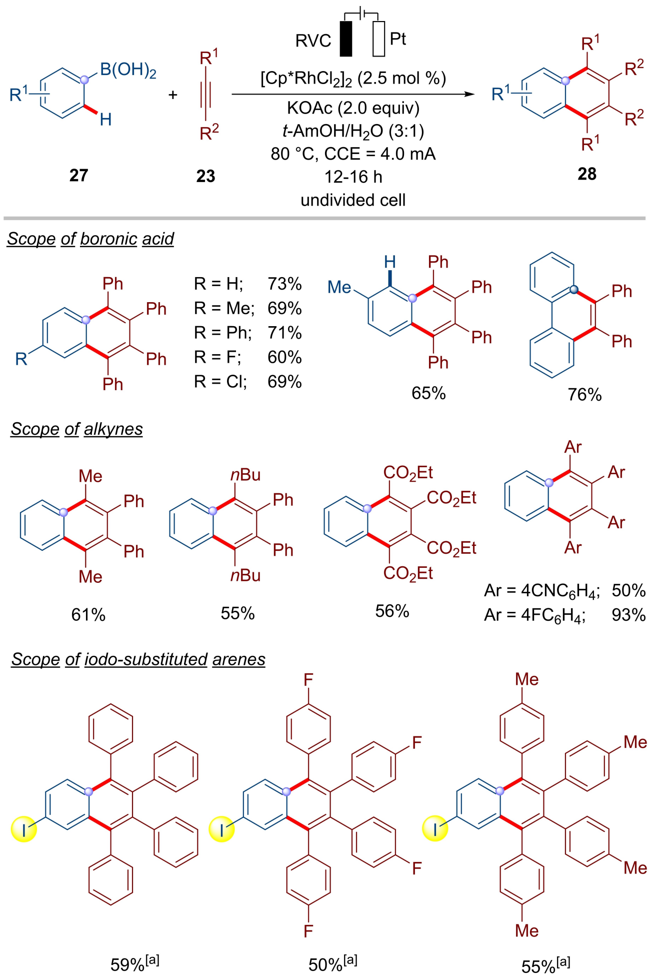


Figure 5. Proposed catalytic cycle for flow-rhodaelectro-catalyzed oxidative annulation reaction of aryl imidates with alkynes.



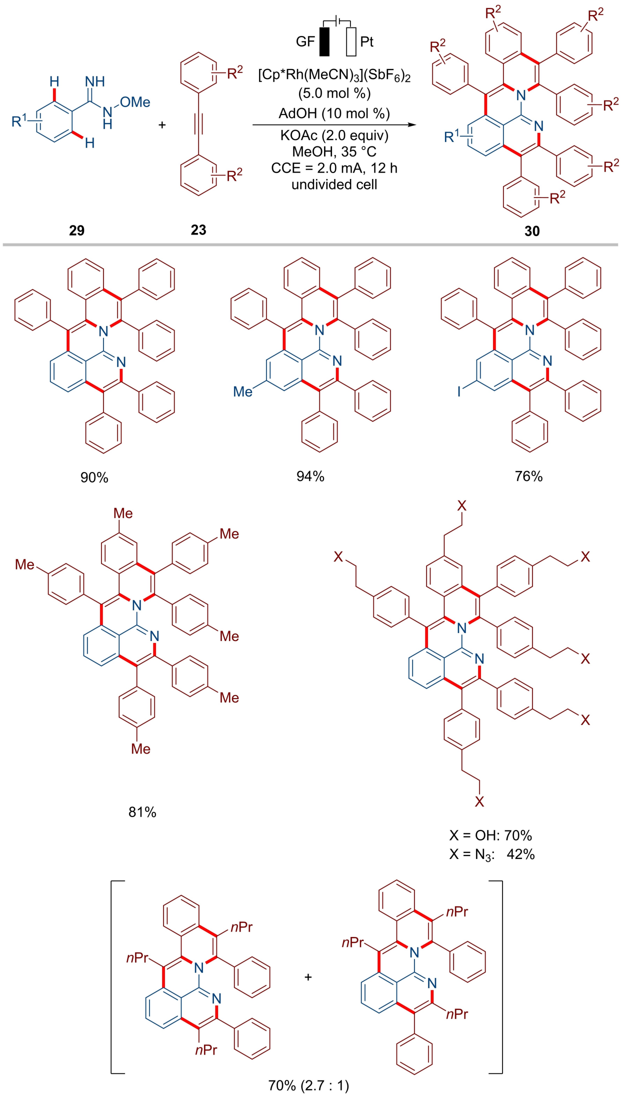
Scheme 14. Rhodaelectro-catalyzed annulative C–H activation of aryl boronic acid with alkynes. [a] CCE = 3.0 mA.

activation with alkynes **23** to deliver the desired products **28**. The *meta*-substituted arenes regioselectively functionalized at less-hindered site due to the steric factors. Interestingly, the unsymmetrical alkynes delivered the desired annulative products in a highly regioselective manner. The DFT analysis was performed to understand the excellent regioselectivity; suggested that non-covalent interactions are the key for regioselective insertion of alkynes. Furthermore, the rhodaelectrocatalysis is shown to be compatible with iodo-substituted arenes, deliver the annulation products **28** in good yields, without affecting the sensitive C–I bond (Scheme 14).[97]

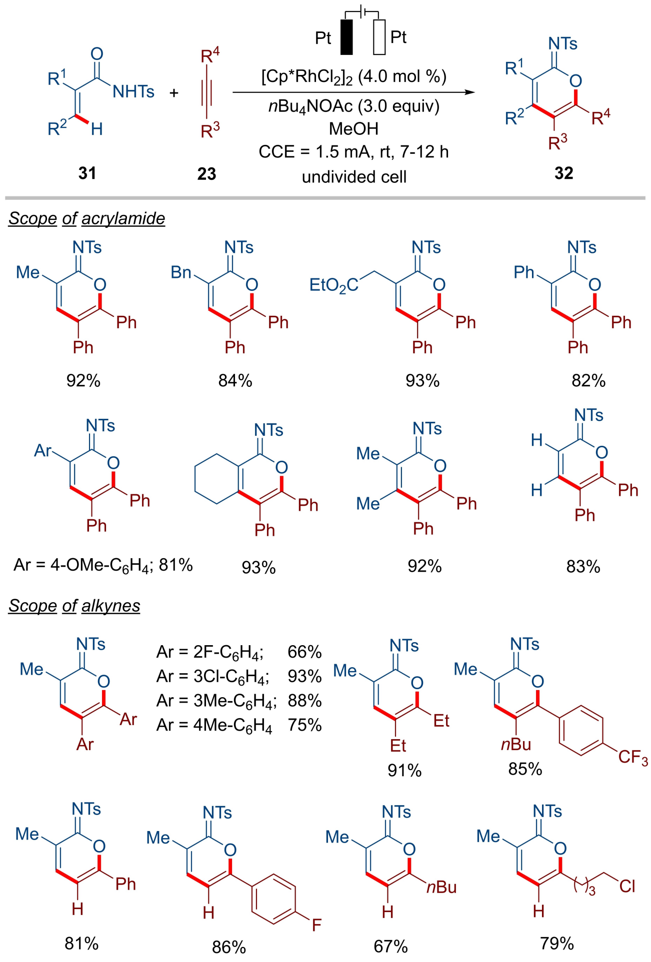
Further, the Ackermann group exploited the rhodaelectrocatalysis for nitrogen-containing polycyclic aromatic hydrocarbons (aza-PAHs) via a cascade C–H activation and annulation of amidoximes **29** with and alkynes **23**.[98] These multiple C–H activation reactions were performed in methanol as the solvent in the presence of cationic rhodium complex $[Cp^*Rh(MeCN)_3](SbF_6)_2$ as the catalyst. The reactions were conveniently performed in an undivided cell, using GF anode and Pt cathode. Amidoximes **29** having different substituents nicely reacted with a range of alkynes **23** afforded the desired products **30** in good yields (Scheme 15).[98] Notably, unsymmetrical alkynes delivered the annulation products with two regioisomers.

Alkenyl C–H bond activation and annulation of alkene substrates with alkynes is attractive approach for construction of a wide range of heterocycles. Inspired by Miura's seminal work of acrylic acid C–H activation and annulation reaction, several groups have reported the related C–H annulation with alkynes by means of various metal catalysts.[99–106] Recently, iridium-[107] and ruthenium-based electrochemical reactions have also developed.[108] However, ruthenium-catalyzed reaction required elevated reaction temperature (140 °C); whereas iridium-catalyzed transformation not compatible with terminal alkynes. To overcome these limitations, Ackermann employed rhodium-catalysis under electrochemical reaction conditions for acrylamide C–H activation.[109] Thus, synthesis of cyclic imidates **32** and α-pyridones **34** were realized from alkynes **23** annulation of *N*-tosyl acrylamides **31** and *N*-phenyl acrylamides **33**, respectively (Scheme 16 and Scheme 17). As to the scope, various vinylic substrates having diverse α- and β-substituents underwent the reaction to give the desired products in very good yields. Unsymmetrical internal alkynes afforded the products with excellent regioselectivities. Terminal alkynes were proved viable substrates to give the desired products in good yields and excellent regioselectivities.

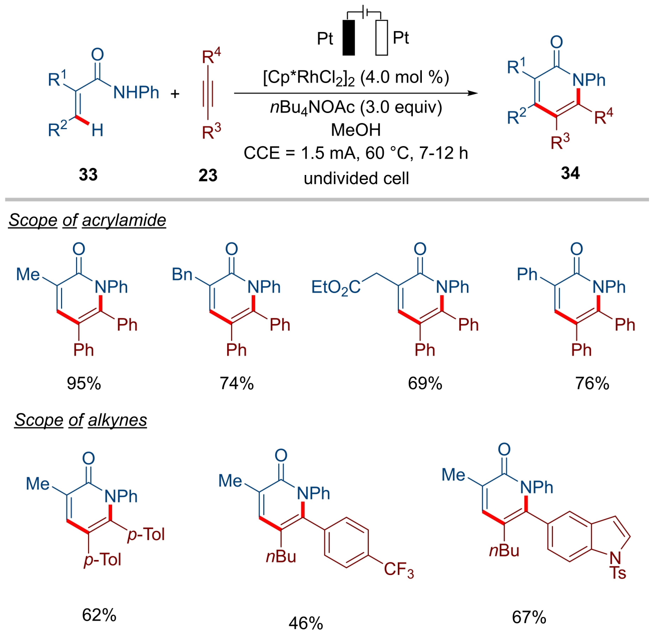
Based on the detailed computational and experimental mechanistic studies, authors proposed a plausible reaction mechanism as shown in Figure 6.[109] Initially, cyclometalated intermediate **6-II** formed through chelation-assisted C–H activation of acrylamide **31** or **33**. Then, alkyne coordination to the rhodium center by ligand exchange followed by migratory alkyne insertion resulted in the seven-membered rhodacycle **6-IV**. This intermediate **6-IV** undergoes reductive elimination (neutral concerted reductive elimination or ionic step-wise reductive elimination) to provide the rhodium(I) intermediate **6-V** or **6-VI**. Upon anodic oxidation, the desired product **32** or **34**



Scheme 15. Rhoda-electro catalyzed synthesis of aza-polycyclic aromatic hydrocarbons.



Scheme 16. Synthesis of cyclic imidates from N-tosyl acrylamide and alkynes.



Scheme 17. Synthesis of α-pyridones from N-aryl acrylamides and alkynes.

released from **6-V** or **6-VI**, respectively, and catalytically active rhodium(III) species **6-I** are regenerated.

Recently, the same group reported an elegant method for rhodium-catalyzed electrochemical C–H/O–H activation to access seven-membered benzoxepines **36** in external chemical oxidant-free conditions (Scheme 18).[110] Among the tested metal catalysts such as $Pd(OAc)_2$, Cp*-ligated iridium and cobalt complexes, $[Cp^*RhCl_2]_2$ only proved to be effective for the desired [5+2] annulation of 2-vinylphenols **35** and alkynes **23**. The reaction was performed in an undivided cell using *t*AmOH/H_2O (3:1) as the media at 100 °C. A wide range of alkynes was compatible, giving the desired products **36** in good yields. The annulation reaction with unsymmetrical alkynes **23** gave the corresponding products **36** in high regioselectivity. The computational studies revealed that the regioisomeric having an aryl group proximal to the heteroatom is favored because of the non-covalent secondary interaction stabilization of the preferred transition state.

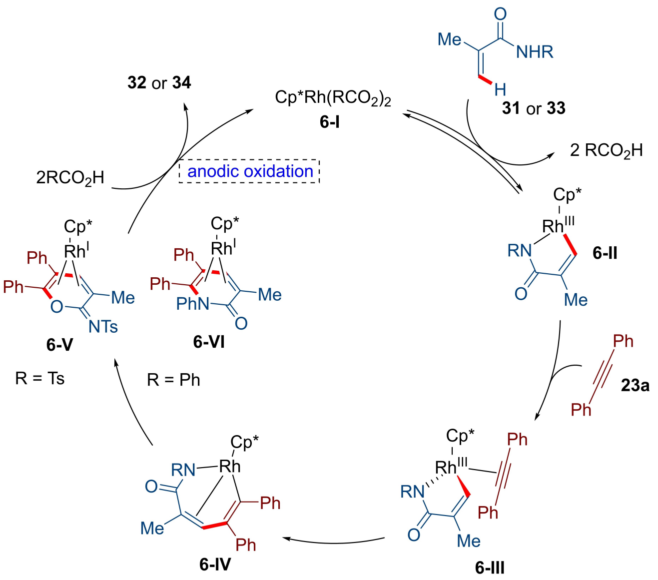


Figure 6. Proposed mechanism for rhodium(III)-catalyzed electrochemical alkenyl C–H activation and annulation with alkynes.

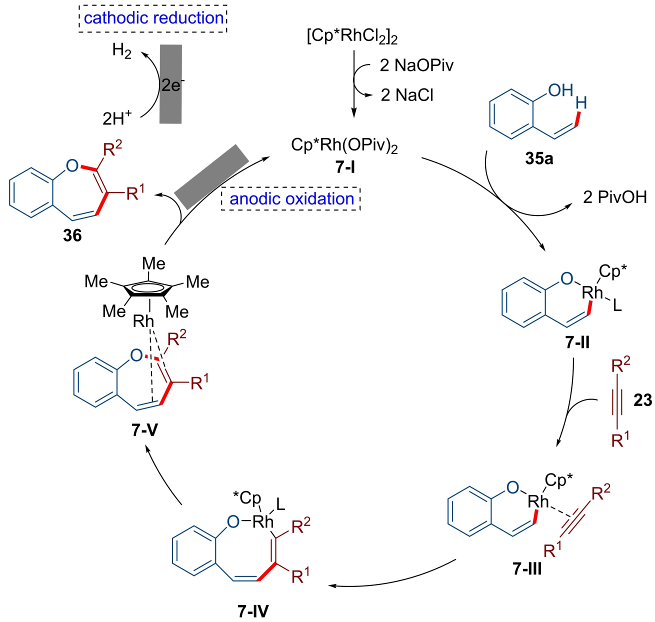
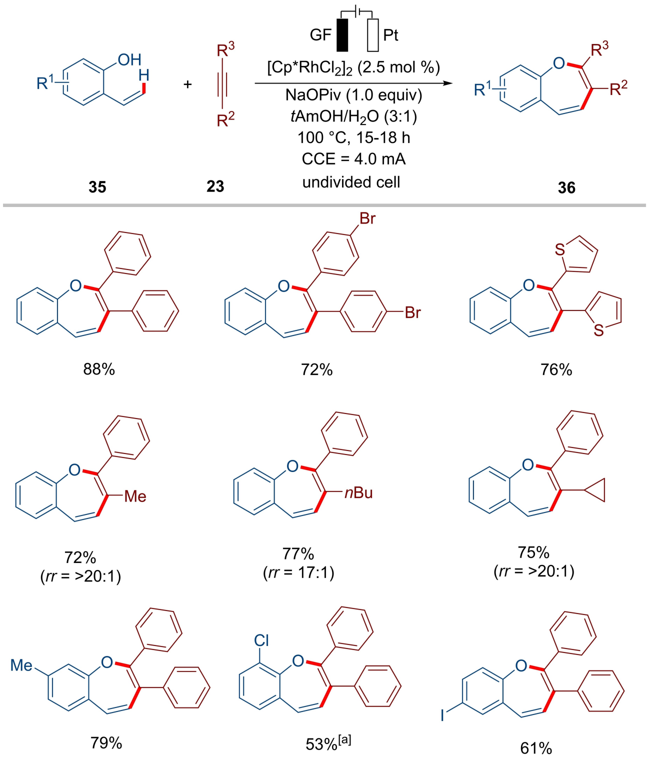
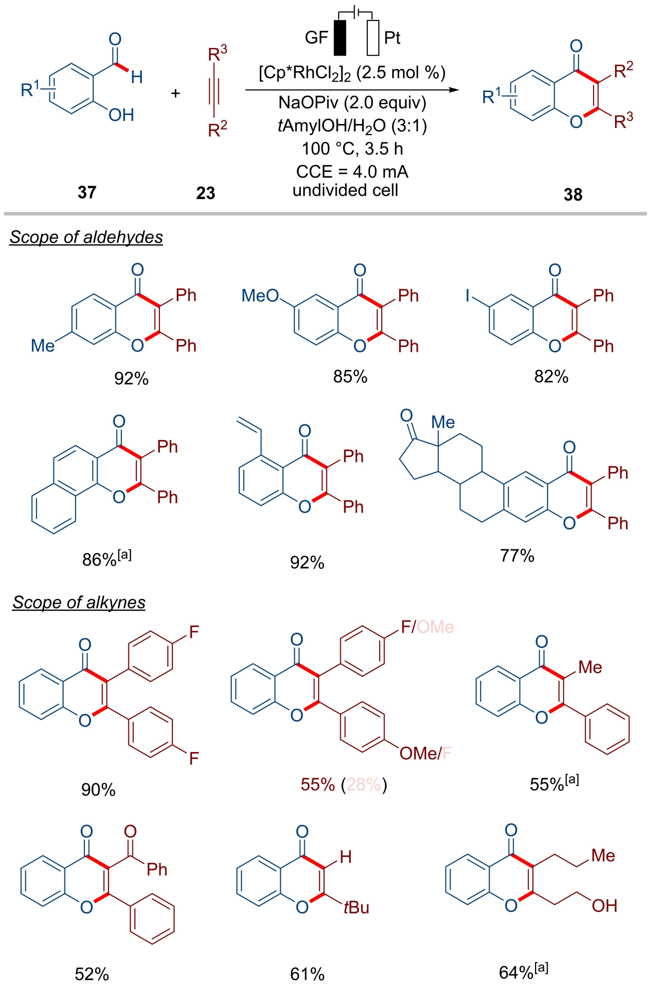


Figure 7. Proposed catalytic cycle for rhodaelectro-catalyzed [5+2] cycloaddition of 2-vinylphenols with alkynes.

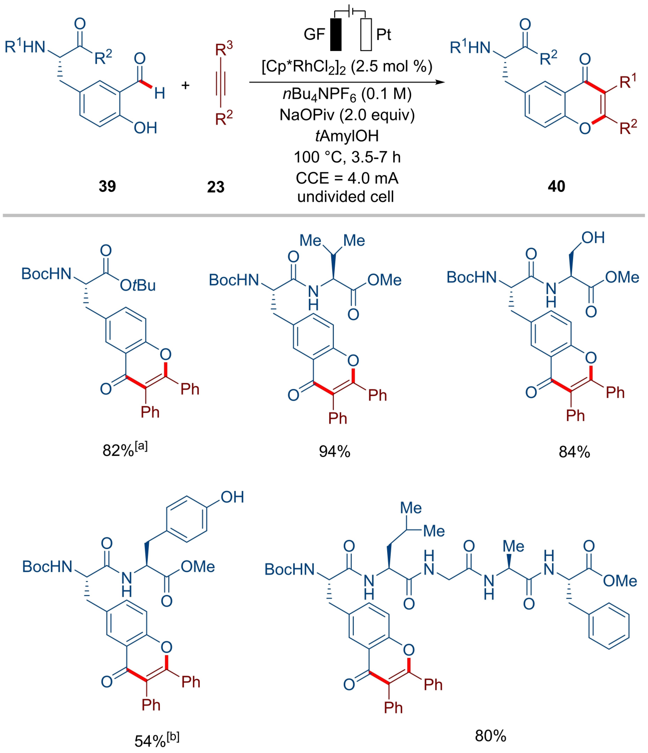


Scheme 18. Rhodaelectro-catalyzed [5+2] cycloaddition of 2-vinylphenols with alkynes. [a]5.0 mol% of $[Cp^*RhCl_2]_2$ used.



Scheme 19. Rhodium(III)-catalyzed electrochemical synthesis of chromones. [a] Reaction time: 7 h.

A catalytic cycle was proposed to account for the possible reaction pathway (Figure 7).[110] The reaction of *in situ* formed $Cp^*Rh(OPiv)_2$ with 2-vinyl phenol substrate **35a** via a facile O–H/C–H activation resulted a six-membered rhodacycle **7-II**. Subsequently, alkyne **23** coordination followed by migratory insertion provided eight-membered intermediate **7-IV**. Reductive elimination of **7-IV** delivers the rhodium(I) complex **7-V**.



Scheme 20. Rhodaelectro-catalyzed late-stage functionalization of peptides. [a] With *t*AmylOH/H_2O (3:1). [b] With 5.0 mol% of $[Cp^*RhCl_2]_2$.

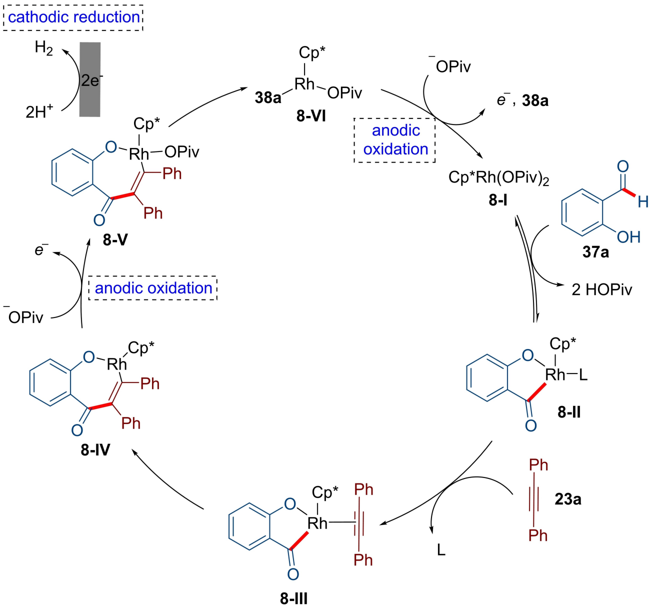
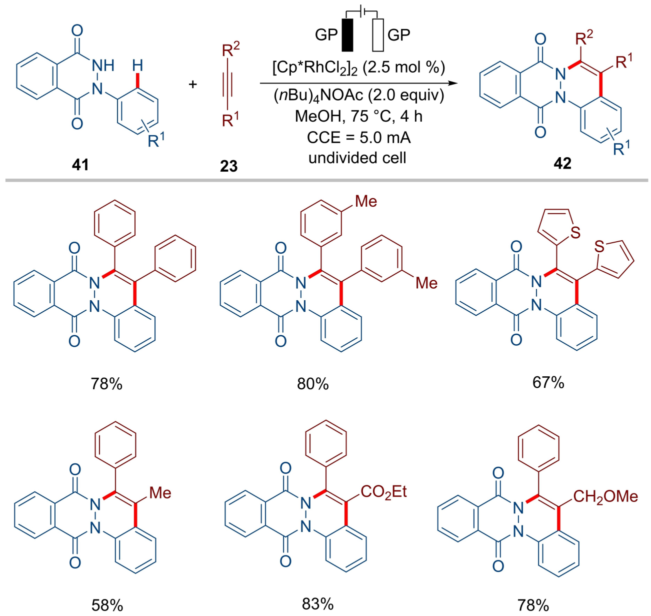


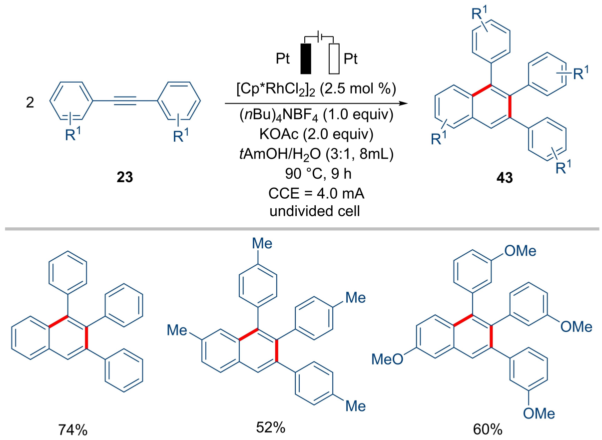
Figure 8. Proposed mechanism for rhodaelectro-catalyzed synthesis of chromones.

The authors mechanistic studies suggested that the rhodium(I) complex **7-V** was likely the catalyst resting state. Finally, anodic oxidation of **7-V** releases the desired product **36** and active catalytic species **7-I** for the next catalytic cycle.

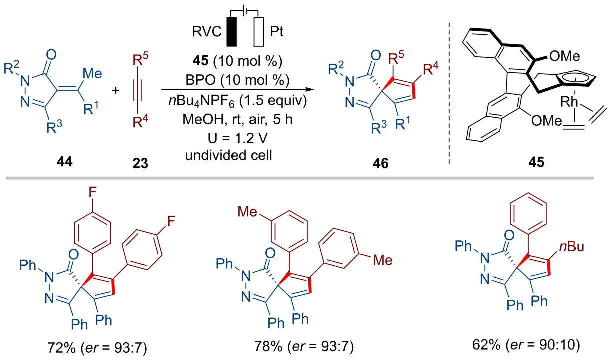
Rhodaelectro catalysis was not limited for activation of aryl and vinylic C–H bonds. Chelation-assisted formyl C–H activation



Scheme 21. Rhodium-catalyzed annulation of alkynes with arylhydrophthalazinediones.



Scheme 22. Electrochemical rhodium-catalyzed synthesis of naphthalenes.



Scheme 23. Rhodium-catalyzed electrochemical enantioselective C–H annulation with alkynes.

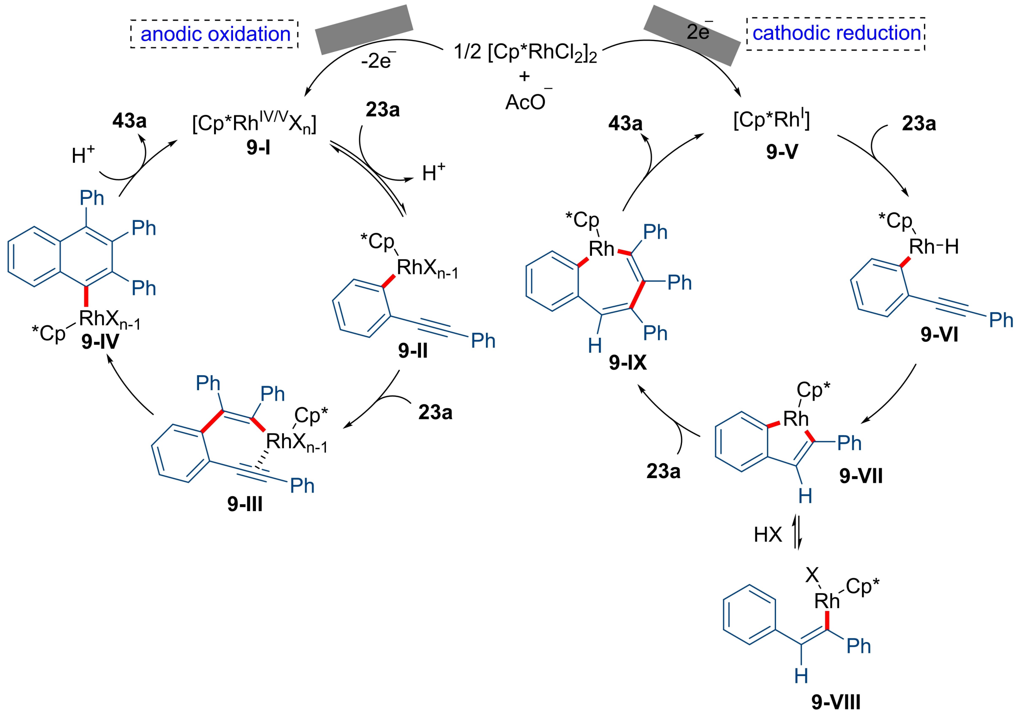


Figure 9. Proposed catalytic cycle for the electrochemical rhodium-catalyzed synthesis of naphthalenes.

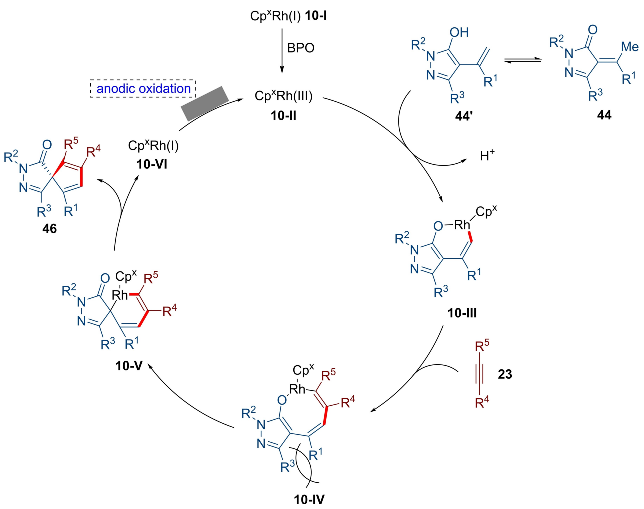
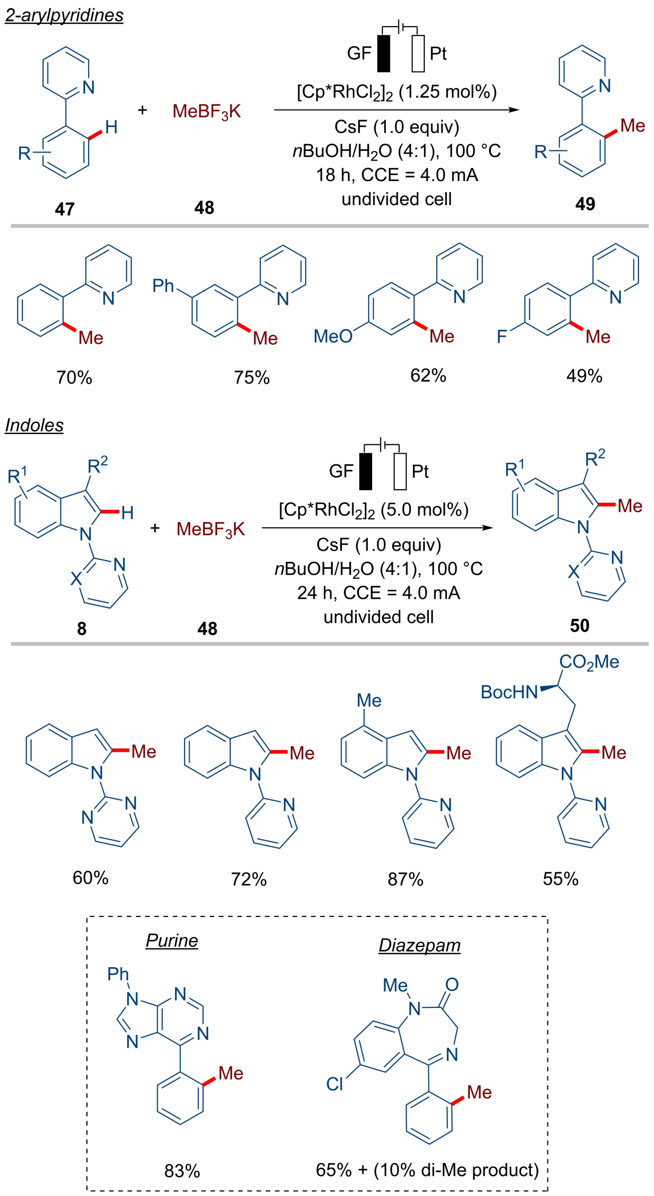


Figure 10. Proposed mechanism for rhodium-catalyzed electrochemical enantioselective C–H annulation with alkynes.

also viable as was reported by the Ackermann group.[111] This method provide access to chromones **38** from *ortho* hydroxybenzaldehydes **37** and alkynes **23** via formyl C–H activation and annulation (Scheme 19).[111] The reaction exhibited ample scope with respect to both aldehydes **37** and alkynes **23**. Interestingly, unsymmetrical and terminal alkynes provided products with excellent regioselectivities. The synthetic utility was further explored for the late stage modifications of amino acids and peptides **39** (Scheme 20).[111] The detailed experimental and computational studies supported for the oxidatively induced reductive elimination via Rh(III/IV/II) (Figure 8).[111]

Recently, Roy and coworkers have exploited the rhodium-catalyzed electrochemical C–H activation strategy for the annulation of alkynes **23** with arylhydrophthalazinediones **41** (Scheme 21).[112] Here, the reactions were performed in an undivided cell setup using graphite plate (GP) as both anode and cathode under CCE 5.0 mA. The annulation was proved viable for a range of symmetrical and unsymmetrical alkynes to give the desired annulation products **42**. In the case of unsymmetrical alkynes, excellent regioselectivity was observed. The authors have proposed a mechanism like Figure 5 (vide supra).

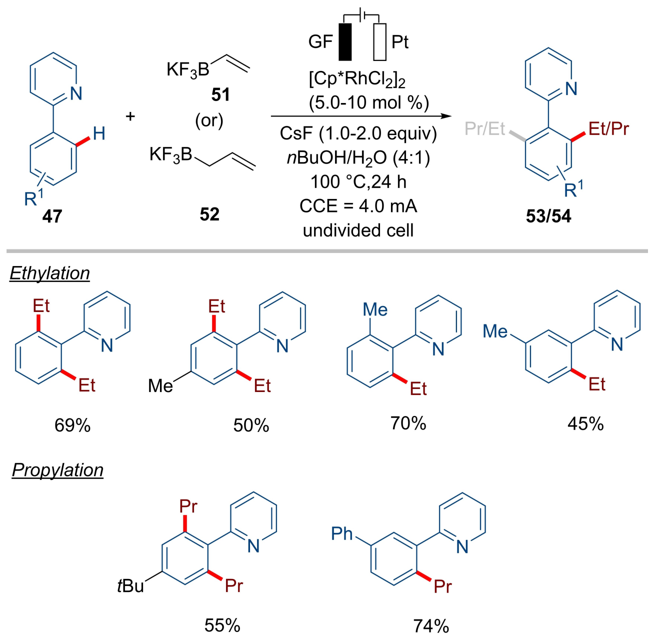
Transition metal-catalyzed C–H activation directed by π-chelation has been well established.[95,113–115] Recently, Zhang, Xie, and coworkers exploited this strategy for cyclodimerization of alkynes **23** to provide substituted naphthalenes **43** (Scheme 22).[116] This rhodium-catalyzed transformation was smoothly realized in an undivided cell setup using platinum as both anode and cathode under CCE 4.0 mA. Based on the mechanistic studies, a possible mechanism involving rhodium(IV)/(V) and rhodium(I) dual catalysis was proposed (Figure 9).[116] Thus, anodic oxidation of $[Cp^*RhCl_2]_2$ to high-valent rhodium(IV/V) complex **9-I** followed by electrophilic metalation resulted aryl-rhodium species **9-II**. Migratory insertion of two alkynes one after another gives intermediate **9-IV**. Then, protodemetallation release the product **43a** and active catalyst **9-I**. Meanwhile, cathodic reduction of $[Cp^*RhCl_2]_2$ produces rhodium(I) species **9-V**, which undergoes C–H metallation via oxidative addition to form intermediate **9-VI**. Then, consecutive alkyne migratory insertion gives a seven-membered intermediate **9-IX** which undergo reductive elimination



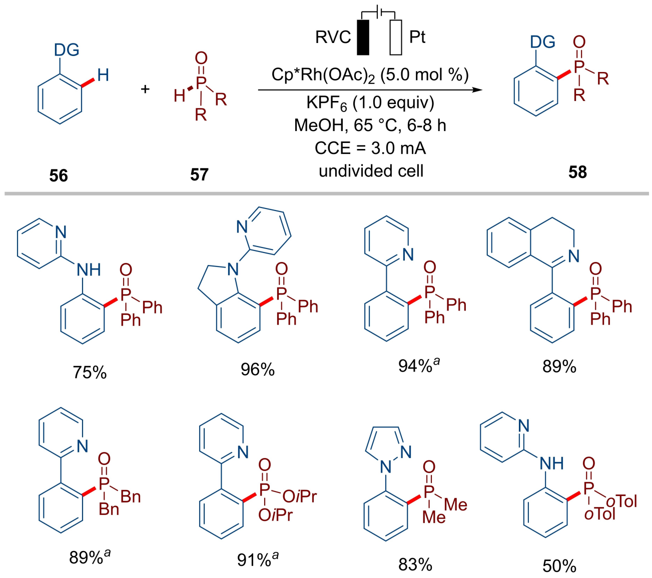
Scheme 24. Rhodaelectro-catalyzed C–H methylation of (hetero)arenes using potassium methyltrifluoroborate.

to afford the desired product **43 a** and regenerate the rhodium(I) species **9-V.**

The preparation of biologically relevant spiropyrazolones has been achieved via a rhodium-catalyzed enantioselective C–H activation and annulation with alkynes.[117] Thus, the reaction of α-arylidene pyrazolones **44** with alkynes **23** in the presence of catalytic amounts of chiral rhodium catalyst **45**, benzoyl peroxide (BPO), and $n\mathrm{Bu_4NPF_6}$ in methanol provided the desired product **46** in good yields and enantioselectivities (Scheme 23). The reaction was realized in an undivided cell setup using reticulated vitreous carbon (RVC) anode and Pt cathode under constant potential of 1.2 V. The controlled experiments showed that no desired product formed in the absence of electric current or BPO. The authors proposed a catalytic cycle involving cyclometalated rhodium intermediate



Scheme 25. Rhodaelectro-catalyzed C–H ethylation and propylation of 2-arylpyridines.



Scheme 26. Rhodium-catalyzed electrochemical C–H phosphorylation. [a]Reaction with CCE = 10 mA.

10-III formed by the reaction of *in situ* generated rhodium(III) species **10-II** and substrate **44'** (Figure 10).[117] Then, migratory insertion of alkyne **23** leads to eight-membered intermediate **10-IV**, which readily undergoes isomerization to intermediate **10-V** due to the unfavorable steric interactions of R[1] and R[3] in **10-IV**. The reductive elimination of **10-V** released the desired product **46**. The anodic oxidation of rhodium(I) species **10-VI** regenerates the active rhodium(III) catalytic species **10-II** for the next cycle.

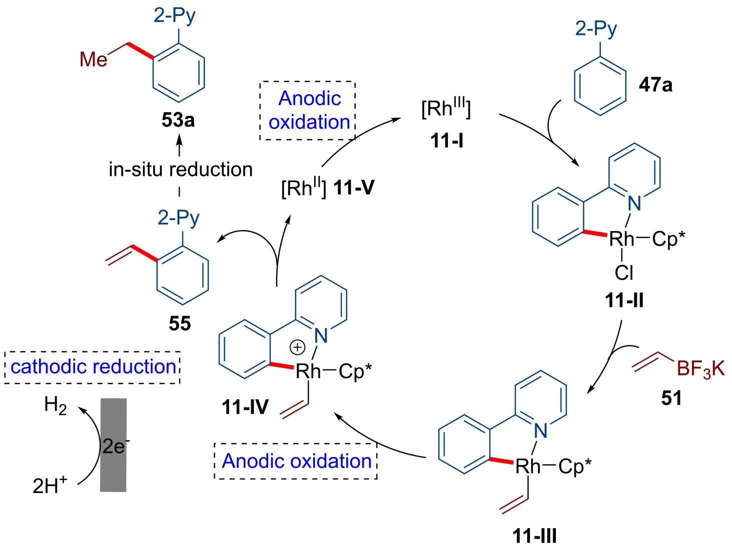


Figure 11. Proposed catalytic cycle for C–H ethylation of arenes with vinyltrifluoroborate.

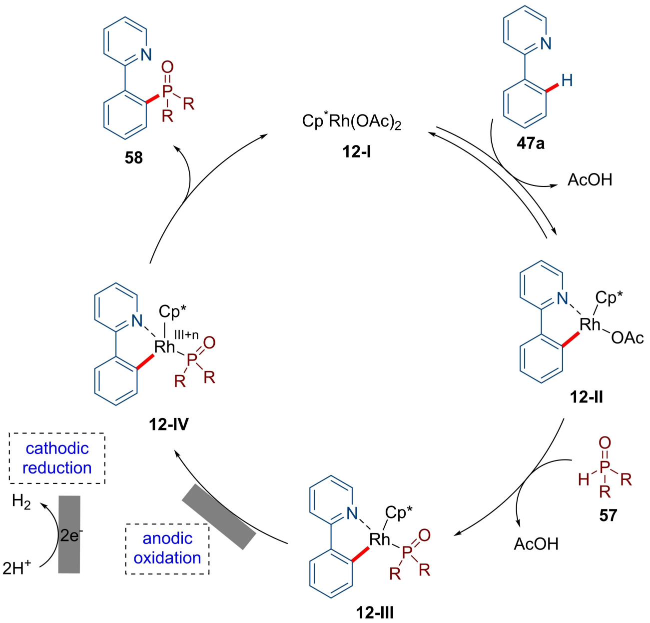
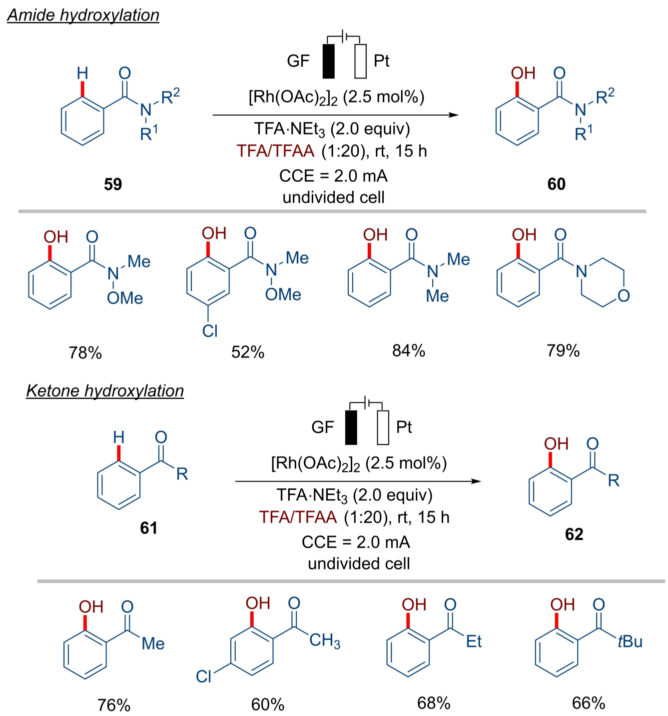


Figure 12. Proposed reaction pathway for rhodium-catalyzed electrochemical C–H phosphorylation.



Scheme 27. Rhodium-catalyzed electrochemical C–H oxygenation of amides and ketones.

2.3. C–H Alkylation

Derivatization of aryl- and heteroaryl bio-relevant molecules with alkyl groups are of great interest due to specific roles of alkyl groups in modulation of molecular properties.[118–121] In this context, recently, the Ackermann group was successfully applied rhodaelectro catalysis for the challenging methylation, ethylation and propylation of (hetero)arenes using trifluoroborates as alkylating agents.[122] The reaction conveniently performed in an undivided cell setup using *n*BuOH/H_2O as the reaction media. The optimization studies showed that catalysts based on other transition metals such as cobalt, iridium, and ruthenium are ineffective. As to the scope, the reaction nicely worked for methylation of 2-arylpyridines **47**, indoles **8**, purines and diazepam (Scheme 24).[122] Furthermore, the authors achieved C–H ethylation using vinyltrifluoroborate **50** via an unprecedented paired vinylation/reduction (Scheme 25).[122] Here, unsubstituted or *para* substituted 2-phenylpyridines gave dialkylated products, whereas *ortho*- or *meta*-substituted 2-phenylpyridines resulted mono-alkylated products due to the steric factor. In addition, potassium allyltrifluoroborate **51** was also proved viable alkyl source, providing propylated arenes **53** (Scheme 25).[122]

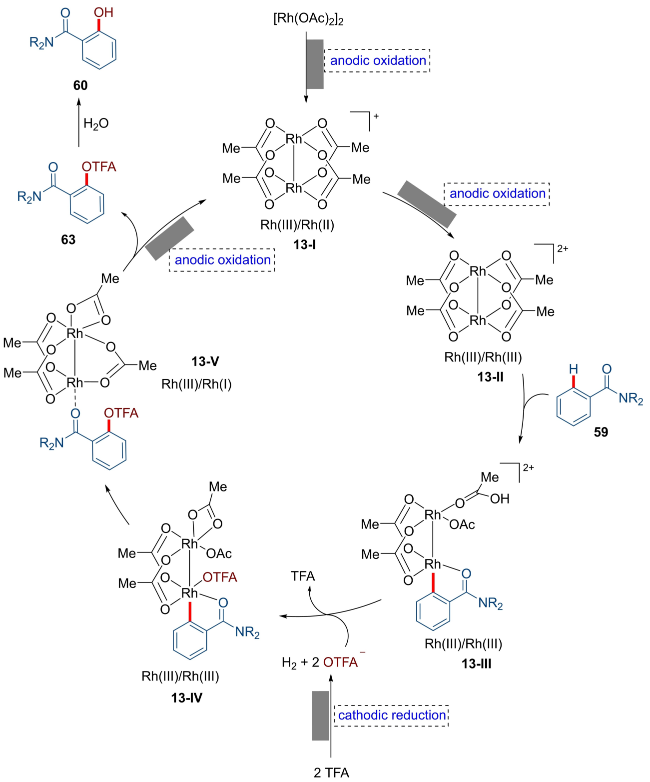


Figure 13. Proposed mechanism for rhodium-catalyzed electrochemical C–H oxygenation of amides.

The authors proposed a plausible reaction mechanism to account the mode of operation (Figure 11).[122] The initial chelation-assisted *ortho* C–H metalation resulted five-membered rhodacycle **11-II**. Subsequent transmetalation and anodic oxidation resulting in the rhodium(IV) intermediate **11-IV**, which readily undergo reductive elimination to give vinylated product **55** and rhodium(II) species **11-V**. The vinylated arenes undergo *in situ* reduction to provide the ethylated product **53 a**. Catalytically active rhodium(III) species **11-I** is regenerated by anodic oxidation.

3. C–Heteroatom Bond Formation

3.1. C–P Bond Formation

Rhodium-catalyzed electrochemical C–H activation was not limited to C–C bond formation. In 2019, Wen/Zhang/Xu and coworkers demonstrated the potential of electrochemical rhodium catalysis for direct aryl C–H phosphorylation (Scheme 26).[123] A wide variety of arenes bearing various directing groups (DGs) smoothly functionalized with phosphine oxides **57**. The reaction was performed using catalytic amounts of $Cp^*Rh(OAc)_2$ as the catalyst and KPF_6 as an additive in an undivided cell setup under constant current electrolysis (CCE = 3.0 mA). Based on their mechanistic studies, the authors proposed a catalytic cycle involving oxidation-induced reductive elimination for C–P bond formation (Figure 12).[123]

3.2. C–O Bond Formation

Recently, Ackermann and coworkers reported an elegant approach for electrochemical C–H oxygenation of amides **59** and ketones **61** (Scheme 27).[124] Here, $[Rh(OAc)_2]_2$ was identified as the suitable catalyst, and trifluoroacetic acid (TFA)/trifluoroacetic anhydride (TFAA) (1:1) as the solvent. The reactions were performed using graphite felt (GF) anode and platinum cathode under CCE (2.0 mA) at room temperature. The use of $TFA{\cdot}NEt_3$ as electrolyte was found to be beneficial for the desired product formation. As to the scope, a wide range of Weinreb amides and N-dialkyl amides **59** were found compatible to give the expected oxygenated products **60** in good yields. Notably, under similar reaction conditions, aromatic ketones **61** also underwent the C–H activation reaction afforded the ortho-hydroxylated aryl ketones **62** in satisfactory yields.

A plausible catalytic cycle was proposed based on detailed experimental and computational mechanistic studies (Figure 13).[124] The catalytic cycle is commenced by the formation of bimetallic rhodium(III) species **13-II** from $[Rh(OAc)_2]_2$ by anodic oxidations. Then, substrate **59** coordination followed by *ortho* C–H rhodation resulted intermediate **13-III**. In subsequent steps, coordination of trifluoroacetates, and reductive elimination resulted **13-V**, which released the product upon decoordination. The active catalytic species **13-I** regenerated by anodic oxidation.

4. Summary and Outlook

In this review, we have summarized rhodium-catalyzed electrochemical C–H activation reactions. The electrochemical approach enabled many oxidative transformations devoid of toxic and expensive chemical oxidants. Thus, this strategy represents an environmentally friendly organic synthesis. Thus far, rhodaelectrocatalysis was successfully realized for several oxidative alkenylations and alkyne annulation reactions. On the other hand, carbon-heteroatom bond formations were limited to C–P and C–O bond formations. Despite the significant advances, there are several exciting areas remain to be developed, including (i) non-directed regioselective C–H activation, (ii) rhodium-catalyzed direct C(sp^3)–H functionalization, (iii) expansion of the scope of C–heteroatom bond formation reactions, and (iv) enantioselective C–H activations. Overall, rhodaelectrochemical C–H activation has already enabled several transformations in a sustainable manner; further exciting developments will continue to provide an amicable solution to challenging molecular synthesis.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: C–H activation · electrocatalysis · electrochemical synthesis · organic synthesis · rhodium

[1] D. C. Blakemore, L. Castro, I. Churcher, D. C. Rees, A. W. Thomas, D. M. Wilson, A. Wood, *Nat. Chem.* **2018**, *10*, 383–394.
[2] K. C. Nicolaou, *Proc. R. Soc. A* **2014**, *470*.
[3] K. C. Nicolaou, *Isr. J. Chem.* **2018**, *58*, 104–113.
[4] C. C. C. Johansson Seechurn, M. O. Kitching, T. J. Colacot, V. Snieckus, *Angew. Chem. Int. Ed.* **2012**, *51*, 5062–5085; *Angew. Chem.* **2012**, *124*, 5150–5174.
[5] J. Magano, J. R. Dunetz, *Chem. Rev.* **2011**, *111*, 2177–2250.
[6] M. J. Buskes, M.-J. Blanco, *Molecules* **2020**, *25*, 3493.
[7] D. G. Brown, J. Boström, *J. Med. Chem.* **2016**, *59*, 4443–4458.
[8] P. Knochel, *Handbook of Functionalized Organometallics: Applications in Synthesis*, Wiley-VCH, Weinheim, **2005**.
[9] A. d. Meijere, F. Diederich, *Metal-catalyzed cross-coupling reactions*, 2nd ed., Wiley-VCH, Weinheim **2004**.
[10] F. Diederich, P. J. Stang, *Metal-Catalyzed Cross-Coupling Reactions*, Wiley-VCH, New York, **1998**.
[11] R. Logeswaran, M. Jeganmohan, *Adv. Synth. Catal.* **2022**, *364*, 2113–2139.
[12] S. K. Sinha, S. Guin, S. Maiti, J. P. Biswas, S. Porey, D. Maiti, *Chem. Rev.* **2021**, *122*, 5682–5841.
[13] T. Rogge, N. Kaplaneris, N. Chatani, J. Kim, S. Chang, B. Punji, L. L. Schafer, D. G. Musaev, J. Wencel-Delord, C. A. Roberts, R. Sarpong, Z. E. Wilson, M. A. Brimble, M. J. Johansson, L. Ackermann, *Nat. Rev. Methods Primers* **2021**, *1*, 43.
[14] B. Liu, A. M. Romine, C. Z. Rubel, K. M. Engle, B.-F. Shi, *Chem. Rev.* **2021**, *121*, 14957–15074.
[15] L. Guillemard, N. Kaplaneris, L. Ackermann, M. J. Johansson, *Nat. Chem. Rev.* **2021**, *5*, 522–545.
[16] T. Dalton, T. Faber, F. Glorius, *ACS Cent. Sci.* **2021**, *7*, 245–261.
[17] P. Gandeepan, T. Müller, D. Zell, G. Cera, S. Warratz, L. Ackermann, *Chem. Rev.* **2019**, *119*, 2192–2452.
[18] Y. Park, Y. Kim, S. Chang, *Chem. Rev.* **2017**, *117*, 9247–9301.
[19] J. He, M. Wasa, K. S. L. Chan, Q. Shao, J.-Q. Yu, *Chem. Rev.* **2016**, *117*, 8754–8786.
[20] H. M. L. Davies, D. Morton, *Chem. Soc. Rev.* **2011**, *40*, 1857–1869.
[21] T. W. Lyons, M. S. Sanford, *Chem. Rev.* **2010**, *110*, 1147–1169.
[22] I. A. I. Mkhalid, J. H. Barnard, T. B. Marder, J. M. Murphy, J. F. Hartwig, *Chem. Rev.* **2009**, *110*, 890–931.
[23] O. Baudoin, *Angew. Chem. Int. Ed.* **2020**, *59*, 17798–17809; *Angew. Chem.* **2020**, *132*, 17950–17961.
[24] S. K. Sinha, G. Zanoni, D. Maiti, *Asian J. Org. Chem.* **2018**, *7*, 1178–1192.
[25] D. J. Abrams, P. A. Provencher, E. J. Sorensen, *Chem. Soc. Rev.* **2018**, *47*, 8925–8967.
[26] Y. Qiu, S. Gao, *Nat. Prod. Rep.* **2016**, *33*, 562–581.
[27] J. Yamaguchi, A. D. Yamaguchi, K. Itami, *Angew. Chem. Int. Ed.* **2012**, *51*, 8960–9009; *Angew. Chem.* **2012**, *124*, 9092–9142.
[28] W. R. Gutekunst, P. S. Baran, *Chem. Soc. Rev.* **2011**, *40*, 1976–1991.
[29] K. Wang, J. Zhang, R. Hu, C. Liu, T. A. Bartholome, H. Ge, B. Li, *ACS Catal.* **2022**, *12*, 2796–2820.
[30] I. A. Stepek, K. Itami, *ACS Materials Lett.* **2020**, *2*, 951–974.
[31] J. B. Williamson, S. E. Lewis, R. R. Johnson Iii, I. M. Manning, F. A. Leibfarth, *Angew. Chem. Int. Ed.* **2019**, *58*, 8654–8668; *Angew. Chem.* **2019**, *131*, 8746–8761.
[32] P. Gandeepan, C.-H. Cheng, *Chem. Asian J.* **2016**, *11*, 448–460.
[33] D. Basu, S. Kumar, S. S. V, R. Bandichhor, *J. Chem. Sci.* **2018**, *130*, 71.
[34] J. Genovino, D. Sames, L. G. Hamann, B. B. Touré, *Angew. Chem. Int. Ed.* **2016**, *55*, 14218–14238; *Angew. Chem.* **2016**, *128*, 14430–14451.
[35] E. J. E. Caro-Diaz, M. Urbano, D. J. Buzard, R. M. Jones, *Bioorg. Med. Chem. Lett.* **2016**, *26*, 5378–5383.
[36] J. Wencel-Delord, F. Glorius, *Nat. Chem.* **2013**, *5*, 369–375.
[37] B. Ye, N. Cramer, *Acc. Chem. Res.* **2015**, *48*, 1308–1318.
[38] T. Satoh, M. Miura, *Chem. Eur. J.* **2010**, *16*, 11212–11222.
[39] Y. Yang, K. Li, Y. Cheng, D. Wan, M. Li, J. You, *Chem. Commun.* **2016**, *52*, 2872–2884.
[40] G. Song, F. Wang, X. Li, *Chem. Soc. Rev.* **2012**, *41*, 3651–3678.
[41] G. Song, X. Li, *Acc. Chem. Res.* **2015**, *48*, 1007–1020.
[42] S. R. Waldvogel, S. Lips, M. Selt, B. Riehl, C. J. Kampf, *Chem. Rev.* **2018**, *118*, 6706–6765.
[43] S. Tang, Y. Liu, A. Lei, *Chem* **2018**, *4*, 27–45.
[44] E. J. Horn, B. R. Rosen, P. S. Baran, *ACS Cent. Sci.* **2016**, *2*, 302–308.
[45] S. Möhle, M. Zirbes, E. Rodrigo, T. Gieshoff, A. Wiebe, S. R. Waldvogel, *Angew. Chem. Int. Ed.* **2018**, *57*, 6018–6041; *Angew. Chem.* **2018**, *130*, 6124–6149.
[46] A. Wiebe, T. Gieshoff, S. Möhle, E. Rodrigo, M. Zirbes, S. R. Waldvogel, *Angew. Chem. Int. Ed.* **2018**, *57*, 5594–5619; *Angew. Chem.* **2018**, *130*, 5694–5721.
[47] M. Yan, Y. Kawamata, P. S. Baran, *Chem. Rev.* **2017**, *117*, 13230–13319.
[48] J.-i. Yoshida, K. Kataoka, R. Horcajada, A. Nagaki, *Chem. Rev.* **2008**, *108*, 2265–2299.
[49] B. H. Nguyen, A. Redden, K. D. Moeller, *Green Chem.* **2014**, *16*, 69–72.
[50] B. A. Frontana-Uribe, R. D. Little, J. G. Ibanez, A. Palma, R. Vasquez-Medrano, *Green Chem.* **2010**, *12*, 2099–2119.
[51] C. Amatore, C. Cammoun, A. Jutand, *Adv. Synth. Catal.* **2007**, *349*, 292–296.
[52] C. Amatore, A. Jutand, *Acc. Chem. Res.* **2000**, *33*, 314–321.
[53] A. Jutand, *Chem. Rev.* **2008**, *108*, 2300–2347.
[54] F. Kakiuchi, T. Kochi, *Chem. Rec.* **2021**, *21*, 2320–2331.
[55] F. Kakiuchi, T. Kochi, *Isr. J. Chem.* **2017**, *57*, 953–963.
[56] K.-J. Jiao, Y.-K. Xing, Q.-L. Yang, H. Qiu, T.-S. Mei, *Acc. Chem. Res.* **2020**, *53*, 300–310.
[57] J. E. Erchinger, M. Gemmeren, *Asian J. Org. Chem.* **2020**, *10*, 50–60.
[58] S. K. Zhang, R. C. Samanta, A. Del Vecchio, L. Ackermann, *Chem. Eur. J.* **2020**, *26*, 10936–10947.
[59] R. C. Samanta, T. H. Meyer, I. Siewert, L. Ackermann, *Chem. Sci.* **2020**, *11*, 8657–8670.
[60] N. Sauermann, T. H. Meyer, Y. Qiu, L. Ackermann, *ACS Catal.* **2018**, *8*, 7086–7103.
[61] N. Sauermann, T. H. Meyer, L. Ackermann, *Chem. Eur. J.* **2018**, *24*, 16209–16217.
[62] V. Dwivedi, D. Kalsi, B. Sundararaju, *ChemCatChem* **2019**, *11*, 5160–5187.
[63] C. Ma, P. Fang, T.-S. Mei, *ACS Catal.* **2018**, *8*, 7179–7189.
[64] Y. Budnikova, Y. Dudkina, M. Khrizanforov, *Inorganics* **2017**, *5*, 70.
[65] T. H. Meyer, L. H. Finger, P. Gandeepan, L. Ackermann, *Trends Chem.* **2019**, *1*, 63–76.
[66] P. Gandeepan, L. H. Finger, T. H. Meyer, L. Ackermann, *Chem. Soc. Rev.* **2020**, *49*, 4254–4272.
[67] Y. Qiu, C. Zhu, M. Stangier, J. Struwe, L. Ackermann, *CCS Chem.* **2021**, *3*, 1529–1552.
[68] W. Ma, P. Gandeepan, J. Li, L. Ackermann, *Org. Chem. Front.* **2017**, *4*, 1435–1467.
[69] P. Gandeepan, L. Ackermann, in *C-H Activation for Asymmetric Synthesis* (Ed.: F. C. J. Wencel-Delord), Wiley-VCH, **2019**, 239–274.
[70] R. Manikandan, M. Jeganmohan, *Chem. Commun.* **2017**, *53*, 8931–8947.
[71] W. Ali, G. Prakash, D. Maiti, *Chem. Sci.* **2021**, *12*, 2735–2759.
[72] J. L. Bras, J. Muzart, *Catalysts* **2020**, *10*, 571.
[73] A. Carral-Menoyo, N. Sotomayor, E. Lete, *Trends Chem.* **2022**, *4*, 495–511.
[74] S. Vivek Kumar, S. Banerjee, T. Punniyamurthy, *Org. Chem. Front.* **2020**, *7*, 1527–1569.
[75] Y. L. Tsang, P. Y. Choy, M. P. Leung, X. He, F. Y. Kwong, *Org. Chem. Front.* **2022**, *9*, 1992–2012.
[76] Y. Qiu, W.-J. Kong, J. Struwe, N. Sauermann, T. Rogge, A. Scheremetjew, L. Ackermann, *Angew. Chem. Int. Ed.* **2018**, *57*, 5828–5832; *Angew. Chem.* **2018**, *130*, 5930–5934.
[77] Y. Zhang, J. Struwe, L. Ackermann, *Angew. Chem. Int. Ed.* **2020**, *59*, 15076–15080; *Angew. Chem.* **2020**, *132*, 15188–15192.
[78] Z. Shen, I. Maksso, R. Kuniyil, T. Rogge, L. Ackermann, *Chem. Commun.* **2021**, *57*, 3668–3671.
[79] B. Sadowski, B. Yuan, Z. Lin, L. Ackermann, *Angew. Chem. Int. Ed.* **2022**, *61*, e202117188.
[80] T. Otsuka, I. Okamoto, E. Kotani, T. Takeya, *Tetrahedron Lett.* **2004**, *45*, 2643–2647.
[81] T. Takeya, T. Otsuka, I. Okamoto, E. Kotani, *Tetrahedron* **2004**, *60*, 10681–10693.
[82] M. Y. Abdelaal, *Int. J. Polym. Mater.* **2005**, *54*, 151–159.
[83] W.-J. Kong, L. H. Finger, A. M. Messinis, R. Kuniyil, J. C. A. Oliveira, L. Ackermann, *J. Am. Chem. Soc.* **2019**, *141*, 17198–17206.

[84] K. Naksomboon, J. Poater, F. M. Bickelhaupt, M. Á. Fernández-Ibáñez, *J. Am. Chem. Soc.* **2019**, *141*, 6719–6725.
[85] E. Tan, O. Quinonero, M. Elena de Orbe, A. M. Echavarren, *ACS Catal.* **2018**, *8*, 2166–2172.
[86] W. Ma, R. Mei, G. Tenti, L. Ackermann, *Chem. Eur. J.* **2014**, *20*, 15248–15251.
[87] H. Ito, Y. Segawa, K. Murakami, K. Itami, *J. Am. Chem. Soc.* **2018**, *141*, 3–10.
[88] Y. Koga, T. Kaneda, Y. Saito, K. Murakami, K. Itami, *Science* **2018**, *359*, 435–439.
[89] H. Kitano, W. Matsuoka, H. Ito, K. Itami, *Chem. Sci.* **2018**, *9*, 7556–7561.
[90] W. Matsuoka, H. Ito, K. Itami, *Angew. Chem. Int. Ed.* **2017**, *56*, 12224–12228; *Angew. Chem.* **2017**, *129*, 12392–12396.
[91] J. Yin, J. You, *Angew. Chem. Int. Ed.* **2019**, *58*, 302–306; *Angew. Chem.* **2019**, *131*, 308–312.
[92] V. D. Kadam, B. Feng, X. Chen, W. Liang, F. Zhou, Y. Liu, G. Gao, J. You, *Org. Lett.* **2018**, *20*, 7071–7075.
[93] C. Zhu, D. Wang, D. Wang, Y. Zhao, W.-Y. Sun, Z. Shi, *Angew. Chem. Int. Ed.* **2018**, *57*, 8848–8853; *Angew. Chem.* **2018**, *130*, 8986–8991.
[94] J. Jayakumar, K. Parthasarathy, Y.-H. Chen, T.-H. Lee, S.-C. Chuang, C.-H. Cheng, *Angew. Chem. Int. Ed.* **2014**, *53*, 9889–9892; *Angew. Chem.* **2014**, *126*, 10047–10050.
[95] P. Gandeepan, C.-H. Cheng, *Org. Lett.* **2013**, *15*, 2084–2087.
[96] C.-Z. Luo, P. Gandeepan, J. Jayakumar, K. Parthasarathy, Y.-W. Chang, C.-H. Cheng, *Chem. Eur. J.* **2013**, *19*, 14181–14186.
[97] W. J. Kong, L. H. Finger, J. C. A. Oliveira, L. Ackermann, *Angew. Chem. Int. Ed.* **2019**, *58*, 6342–6346; *Angew. Chem.* **2019**, *131*, 6408–6412.
[98] W.-J. Kong, Z. Shen, L. H. Finger, L. Ackermann, *Angew. Chem. Int. Ed.* **2020**, *59*, 5551–5556; *Angew. Chem.* **2020**, *132*, 5596–5601.
[99] B. Ramesh, M. Jeganmohan, *J. Org. Chem.* **2022**, *87*, 5668–5681.
[100] B. Liu, L. Yang, P. Li, F. Wang, X. Li, *Org. Chem. Front.* **2021**, *8*, 1085–1101.
[101] T. Zhu, S. Xie, P. Rojsitthisak, J. Wu, *Org. Biomol. Chem.* **2020**, *18*, 1504–1521.
[102] M. Maraswami, T.-P. Loh, *Synthesis* **2019**, *51*, 1049–1062.
[103] P. Gandeepan, P. Rajamalli, C.-H. Cheng, *Angew. Chem. Int. Ed.* **2016**, *55*, 4308–4311; *Angew. Chem.* **2016**, *128*, 4380–4383.
[104] C.-Z. Luo, J. Jayakumar, P. Gandeepan, Y.-C. Wu, C.-H. Cheng, *Org. Lett.* **2015**, *17*, 924-927.
[105] P. Gandeepan, P. Rajamalli, C.-H. Cheng, *Chem. Eur. J.* **2015**, *21*, 9198-9203.
[106] C.-Z. Luo, P. Gandeepan, C.-H. Cheng, *Chem. Commun.* **2013**, *49*, 8528-8530.
[107] Q.-L. Yang, Y.-K. Xing, X.-Y. Wang, H.-X. Ma, X.-J. Weng, X. Yang, H.-M. Guo, T.-S. Mei, *J. Am. Chem. Soc.* **2019**, *141*, 18970–18976.
[108] L. Yang, R. Steinbock, A. Scheremetjew, R. Kuniyil, L. H. Finger, A. M. Messinis, L. Ackermann, *Angew. Chem. Int. Ed.* **2020**, *59*, 11130–11135; *Angew. Chem.* **2020**, *132*, 11223–11229.
[109] Y.-K. Xing, X.-R. Chen, Q.-L. Yang, S.-Q. Zhang, H.-M. Guo, X. Hong, T.-S. Mei, *Nat. Commun.* **2021**, *12*, 930.
[110] Y. Wang, J. C. A. Oliveira, Z. Lin, L. Ackermann, *Angew. Chem. Int. Ed.* **2021**, *60*, 6419–6424; *Angew. Chem.* **2021**, *133*, 6490–6495.
[111] M. Stangier, A. M. Messinis, J. C. A. Oliveira, H. Yu, L. Ackermann, *Nat. Commun.* **2021**, *12*, 4736.
[112] P. P. Sen, R. Prakash, S. R. Roy, *Org. Lett.* **2022**, *24*, 4530–4535.
[113] Y. Minami, T. Hiyama, *Acc. Chem. Res.* **2015**, *49*, 67–77.
[114] P. Gandeepan, C.-H. Cheng, *Chem. Asian J.* **2015**, *10*, 824–838.
[115] P. Gandeepan, C.-H. Cheng, *J. Am. Chem. Soc.* **2012**, *134*, 5738–5741.
[116] Z. Guo, J. Zhang, J. Zhang, M. Xie, *Org. Lett.* **2022**, *24*, 7784–7789.
[117] Y.-Q. Huang, Z.-J. Wu, L. Zhu, Q. Gu, X. Lu, S.-L. You, T.-S. Mei, *CCS Chem.* **2022**, *4*, 3181–3189.
[118] D. Mandal, S. Roychowdhury, J. P. Biswas, S. Maiti, D. Maiti, *Chem. Soc. Rev.* **2022**, *51*, 7358–7426.
[119] D. Aynetdinova, M. C. Callens, H. B. Hicks, C. Y. X. Poh, B. D. A. Shennan, A. M. Boyd, Z. H. Lim, J. A. Leitch, D. J. Dixon, *Chem. Soc. Rev.* **2021**, *50*, 5517–5563.
[120] Z. Dong, Z. Ren, S. J. Thompson, Y. Xu, G. Dong, *Chem. Rev.* **2017**, *117*, 9333–9403.
[121] H. Schönherr, T. Cernak, *Angew. Chem. Int. Ed.* **2013**, *52*, 12256–12267; *Angew. Chem.* **2013**, *125*, 12480–12492.
[122] K. Kuciński, H. Simon, L. Ackermann, *Chem. Eur. J.* **2021**, *28*, e202103837.
[123] Z. J. Wu, F. Su, W. Lin, J. Song, T. B. Wen, H. J. Zhang, H. C. Xu, *Angew. Chem. Int. Ed.* **2019**, *58*, 16770–16774; *Angew. Chem.* **2019**, *131*, 16926–16930.
[124] X. Tan, L. Massignan, X. Hou, J. Frey, J. C. A. Oliveira, M. N. Hussain, L. Ackermann, *Angew. Chem. Int. Ed.* **2021**, *60*, 13264–13270; *Angew. Chem.* **2021**, *133*, 13373–13379.

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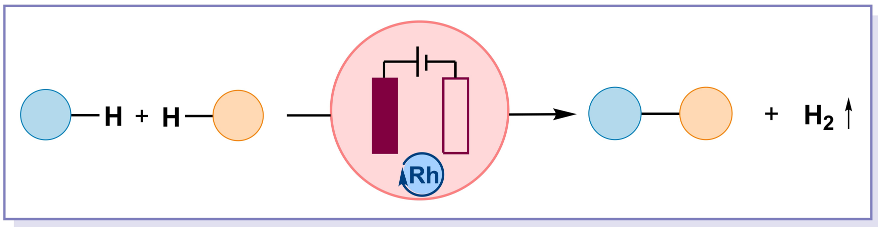

This review provides an overview of precedents and perspective on electrochemical rhodium-catalyzed C–H actiation strategies for organic synthesis.

*V. Kumar, R. Maayuri, L. Mantry, Dr. P. Gandeepan**

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Recent Advances in Rhodium-Catalyzed Electrochemical C–H Activation