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Rhodaelectro-catalyzed chemo-divergent C–H activations with alkylidenecyclopropanes for selective cyclopropylations†

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Herein, we report on selectivity control in C–H activations with alkylidenecyclopropanes (ACPs) for the chemo-selective assembly of cyclopropanes or dienes. Thus, unprecedented rhodaelectro-catalyzed C–H activations were realized with diversely decorated ACPs with a wide substrate scope and electricity as the sole oxidant.

Throughout the last decade, C–H activation has emerged as an increasingly powerful tool in molecular syntheses.¹ In sharp contrast, strategies for transition metal-catalyzed C–C activation remain comparably underdeveloped.² In recent years, major advances, in particular in ring-strain release-promoted C–C cleavages, have been achieved by Dong,³ Bower,⁴ and Marek,⁵ among others.⁶ Alkylidenecyclopropanes⁷ (ACPs) have previously been recognized as a versatile platform for C–H/C–C functionalizations. However, their application within a bifurcated mechanistic manifold for the selective introduction of cyclopropane⁸ or 1,3-dienes⁹ motifs has thus far proven elusive, although they represent crucial structural scaffolds in a variety of pharmaceuticals, biologically active molecules and natural products. While a single example of rhodium-catalyzed dienylation was realized with chemical oxidants,¹⁰ cyclopropylations are as of yet not available.

The use of electricity to drive chemical reactions has recently witnessed a remarkable renaissance.¹¹ Significant momentum was particularly gained by the merger of mettallaelectrocatalysis and QJ;C–H activation to avoid often toxic and expensive oxidants.^{1b,12} With our continued interest in rhodaelectro-catalyzed C–H activation,¹³ we have now developed a bifurcated C–H activation with alkylidenecyclopropanes that can be conducted under

sustainable and operationally-simple electrochemical conditions. Salient features of our strategy include (a) full control of selectivity within a bifurcated manifold for C–H cyclopropylations *versus* dienylation *via* β -H over β -C elimination, (b) detailed mechanistic insights by means of experiment and computation, (c) absence of external chemical oxidants, (d) water as the reaction medium, and (e) a user-friendly undivided cell setup without additional electrolyte (Fig. 1).

We initiated our studies with indole **1a** and ACP **2a** to evaluate C–H dienylation and cyclopropylations in a user-friendly undivided cell setup with a graphite felt (GF) anode and a platinum cathode (Table 1). The dienylated product **3aa** was obtained in 72% yield in the presence of 2.5 mol% $[\text{Cp}^*\text{RhCl}_2]_2$, using 1,4-dioxane/H₂O (1 : 1) as the solvent. After examination of different bases, NaO₂CaD led to the best result, delivering diene **3aa** in 85% yield with an *Z/E* ratio of 4.5/1 (entries 1–5). The indispensable roles of electricity and the rhodium catalyst were further confirmed by control experiments (entries 6 and 7). A variation of the current did not result in an improved performance (entries 8 and 9). We also tested different acids and found that cyclopentanecarboxylic acid proved beneficial (entries 10 and 11). With an increased amount of NaO₂CaD, the product was obtained in a higher *Z/E* ratio, albeit with a small decrease in efficiency (entry 12).

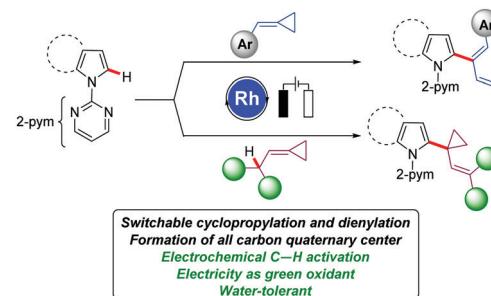


Fig. 1 Cyclopropylation and dienylation enabled by rhodaelectro-catalysis.

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† Electronic supplementary information (ESI) available. CCDC 2025011 (**3ap**) and 2025012 (**5pa**). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0cc08123j



Table 1 Electrochemical C–H dienylation of indole^a

Entry	Base	Acid	Yield (%)	Z/E
1	NaOAc	CypCO ₂ H	72	3.9/1
2	NaOPiv	CypCO ₂ H	78	3.5/1
3	NaO ₂ CMes	CypCO ₂ H	60	4.0/1
4	NaO ₂ CPh	CypCO ₂ H	82	3.6/1
5	NaO ₂ CAd	CypCO ₂ H	85	4.5/1
6 ^b	NaO ₂ CAd	CypCO ₂ H	24	2.4/1
7 ^c	NaO ₂ CAd	CypCO ₂ H	—	—
8 ^d	NaO ₂ CAd	CypCO ₂ H	87	3.8/1
9 ^e	NaO ₂ CAd	CypCO ₂ H	72	3.2/1
10	NaO ₂ CAd	MesCO ₂ H	78	3.8/1
11	NaO ₂ CAd	PivOH	82	3.3/1
12 ^f	NaO ₂ CAd	CypCO ₂ H	82	6.0/1
13 ^{fg}	NaO ₂ CAd	CypCO ₂ H	87	6.5/1
14 ^{gh}	NaO ₂ CAd	CypCO ₂ H	89	7.0/1
15 ⁱ	NaO ₂ CAd	CypCO ₂ H	95 (5aa)	<1/20

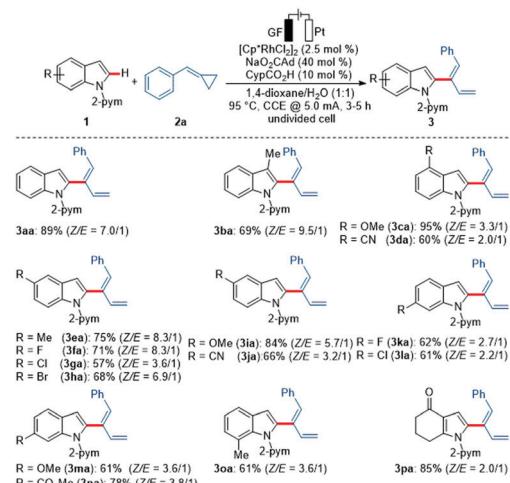
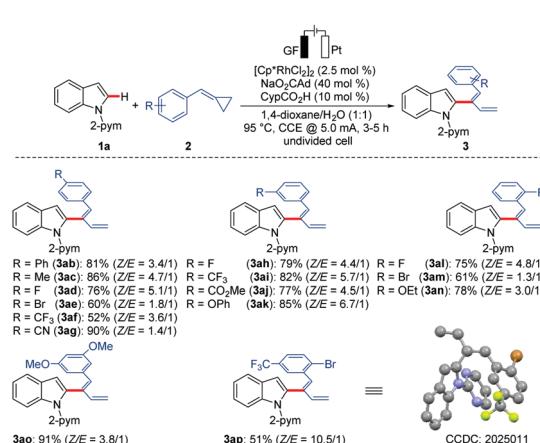
^a Undivided cell, graphite felt anode (GF), platinum plate cathode (Pt), **1a** (0.1 mmol) **2a** (0.16 mmol), [Cp*RhCl₂]₂ (2.5 mol%), base (20 mol%), acid (10 mol%), 1,4-dioxane/H₂O (1:1, 4.0 mL), 85 °C, CCE @ 3.0 mA, under air, 4.0 h, yield of isolated product, Z/E ratio determined by ¹H NMR spectroscopy, CypCO₂H = cyclopentanecarboxylic acid. ^b Without electricity, 12 h. ^c Without [Cp*RhCl₂]₂. ^d CCE @ 2.0 mA, 6.0 h. ^e CCE @ 4.0 mA, 3.0 h. ^f NaO₂CAd (40 mol%). ^g 0.2 mmol scale, 1,4-dioxane/H₂O (1:1, 8.0 mL), CCE @ 5.0 mA, 3.0 h. ^h 95 °C. ⁱ **4a** instead of **2a** under the conditions of entry 14.

A higher reaction temperature improved the efficacy. Importantly, the novel cyclopropylated product **5aa** was obtained in high yield when using benzyl ACP **4a**.¹⁴

With the optimized reaction conditions for the electrochemical C–H dienylation in hand, its versatility was explored with substituted indoles **1** (Scheme 1). 3-, 5- or 7-Methyl indoles **1** delivered the desired products **3ba**, **3ea** and **3oa**, while the 3-methyl indole **1b** gave an improved selectivity. Fluorine- and methoxy-substituted indoles **1** were efficiently transformed, but 6-substituted indoles **1k** and **1m** displayed a slightly lower efficiency. Various functional groups were tolerated by the rhodium electrocatalyst, such as chloro, bromo and cyano substituents. Interestingly, indole **1n** with an ester functionality at the 6-position delivered diene **3na** in high yield. The dienylation protocol was also amenable to pyrrole **3pa**.¹⁵

Next, the robustness of the rhodaelectro-catalyzed C–H dienylation was evaluated with a variety of functionalized cyclopropanes (Scheme 2). Substrates containing bromide groups delivered chemo-selectively the products **3ae** and **3am**. In contrast to previous studies, electron-deficient heteroarenes showed an inherent high reactivity.¹³ However, electron-rich substrates also performed well in the electrocatalysis. The connectivity of diene **3ap** was unambiguously confirmed by single-crystal X-ray analysis.[‡] It is noteworthy that, 2-phenyl pyridine could also be employed for the electrocatalysis to deliver arene **5qa**. The tryptamine-derived substrate **1r** delivered the challenging ring-opening product **5ra'**.

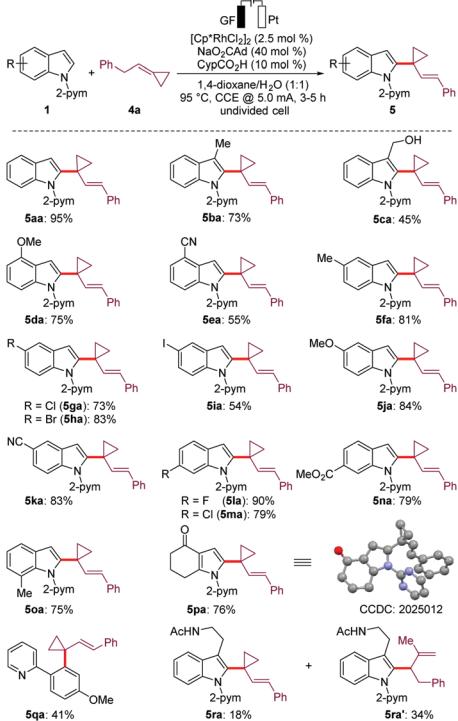
Thereafter, we turned our attention to the versatility of the unprecedented electrochemical C–H cycloproylation of indoles **1**

Scheme 1 Electrochemical C–H dienylation of indoles **1**.Scheme 2 Electrochemical C–H dienylation with ACPs **2**.

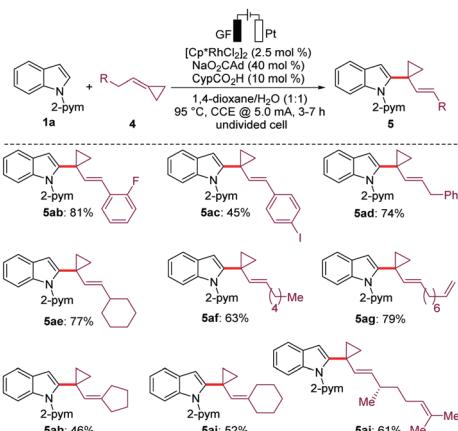
(Scheme 3). We found that an otherwise reactive hydroxyl was fully tolerated, despite being in close proximity (**5ca**). Halogen-containing indoles, even the reactive iodo-substituent, were likewise viable substrates. Indoles containing electron-withdrawing or electron-donating groups selectively underwent this transformation. For 7-methyl indole, the cycloproylation showed a higher efficiency as compared to the dienylation (**5oa** versus **3oa**). The rhodaelectrocatalysis proved also applicable to pyrroles, while the structure of the cyclopropylated product **5pa** was confirmed by single-crystal X-ray analysis.[‡] It is noteworthy that, 2-phenyl pyridine could also be employed for the electrocatalysis to deliver arene **5qa**. The tryptamine-derived substrate **1r** delivered the challenging ring-opening product **5ra'**.

Next, we explored the C–H cycloproylation with differently substituted ACPs **4** (Scheme 4). Substrate **4c** bearing an iodine substituent gave the desired product **5ac** with a small amount of the deiodinated product (**5aa**:**5ac** 1/3). The aqueous conditions were compatible with linear or branched alkyl-derived cyclopropanes (**5ad**–**5af**). The challenging cyclopropane **4g** bearing a terminal alkene was also found to be a viable





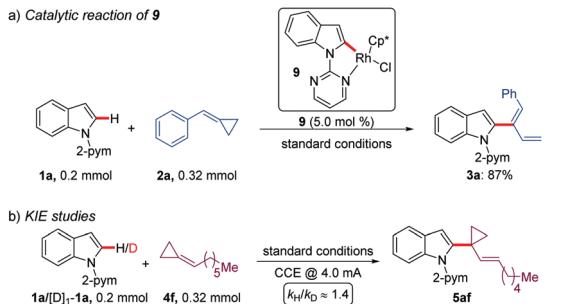
Scheme 3 Electrocatalyzed C–H cyclopropanation of indoles **1**, arenes and pyrroles.



Scheme 4 Rhodaelectro-catalyzed C–H cyclopropanation with ACPs **4**.

substrate, affording product **5ag** in 79% yield. The transformation was also tolerant to changes in the backbone of the cyclic alkanes and generated the desired products **5ah** and **5ai**. Indeed, the structurally more complex, natural product citronellol-derived starting material **4j** was chemo-selectively converted to the desired product **5aj**.

To gain insights into the reaction mechanism, control experiments were performed. The independently prepared cyclometalated complex **9**¹⁶ was found to serve as a catalytically competent species (Scheme 5a). Under the standard conditions but without electricity, H/D exchange of indole **1a** with D₂O was



Scheme 5 Summary of key mechanistic findings.

observed with significant deuterium incorporation at the position C2 (Scheme S2 in the ESI†). However, a significant deuterium-incorporation into product **3aa** was not observed, when **1a** was reacted with **2a** under the electrochemical conditions using D₂O as the cosolvent (Scheme S3 in the ESI†). A kinetic isotope effect (KIE) study was next conducted. Parallel independent reactions resulted in a value of $k_H/k_D \approx 1.4$ (Scheme 5b), indicating that the C–H cleavage step is likely not involved in the rate-determining step.¹⁴

In order to further understand the catalyst's mode of action, we became interested in studying the rhodaelectro-catalyzed C–H cyclopropanation of indole **1a** with ACP **4a** by density functional theory (DFT). Geometry optimizations and frequency calculations were performed at the TPSS-D3(BJ)/def2-SVP level of theory, while single point energies were calculated at the PW6B95-D3(BJ)/def2-TZVP+SMD(1,4-dioxane) and PBE0-D3(BJ)/def2-TZVP+SMD(1,4-dioxane) level of theory.¹⁴ All energies reported here were calculated at the PW6B95-D3(BJ)/def2-TZVP+SMD(1,4-dioxane)/TPSS-D3(BJ)/def2-SVP level of theory.¹⁴ Our calculations indicated that after the migratory insertion of ACP **4a**, β -H elimination occurs from the intermediate **D** via **TS(D-E)** (Fig. S1, ESI†) with a barrier of 1.1 kcal mol⁻¹. Moreover, β -H elimination from the intermediate **D** results in the regioselective formation of the *E*-isomer as the major product, while the generation of *Z*-isomer is energetically not favourable.¹⁴

Based on our studies, we propose a plausible catalytic cycle for the unprecedented rhodaelectro-C–H-cyclopropanation, which is initiated by the formation of a catalytically competent mononuclear cationic Cp*Rh(III) species. As shown in Fig. 2, coordination of indole **1a** to Cp*Rh(III) and facile subsequent cyclorhodation at the 2-position affords rhodacycle **A**. Then, the insertion of alkene **4a** occurs to furnish intermediate **D**, which undergoes β -H elimination to generate the cyclopropanated product **5aa** along with a rhodium(I) intermediate. Finally, the Cp*Rh(III) species is regenerated by rate-limiting reoxidation of rhodium(I) at the anode, while generating molecular hydrogen as the byproduct at the cathode and completing the catalytic cycle. In terms of the dienylation, intermediate **D** undergoes β -C elimination to form intermediate **G** (Fig. S10 in the ESI†). Final β -H elimination then delivers the dienylated indole **3aa**.

In conclusion, we have reported on a versatile rhodaelectro-catalyzed C–H activation with alkylidenecyclopropanes under

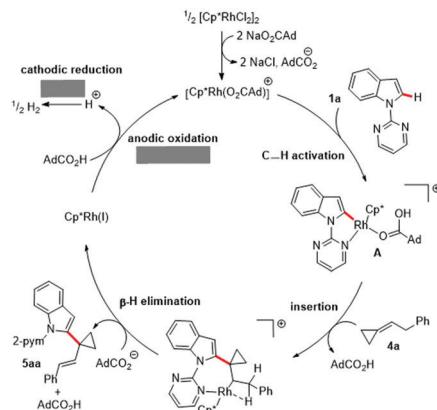


Fig. 2 Proposed mechanism for electro-C–H cyclopropanation with ACPs 4.

aqueous conditions, devoid of stoichiometric amounts of chemical oxidants. Our unique strategy allowed for the control of selectivity within a bifurcated mechanistic pathway by the judicious choice of β -H over β -C elimination. Detailed studies by experiment and calculation provided key insights into the catalyst's mode of action, revealing β -H elimination as the key selectivity-determining process for an unprecedented C–H cyclopropanation. The reactive catalyst can be regenerated in a sustainable manner by anodic oxidation, yielding hydrogen as the sole stoichiometric byproduct. Thereby, a wealth of heteroarenes was functionalized with excellent chemo-, position- and diastereoselectivity.

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Conflicts of interest

There are no conflicts to declare.

Notes and references

‡ Deposition numbers 2025011 (3ap) and 2025012 (5pa) contain the supplementary crystallographic data for this paper.

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