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Enantioselective [5 + 1] cycloaddition of sulfur ylides and vinylolefin carbonates *via* synergistic palladium/chiral phosphonic acid catalysis†

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An effective method for the synthesis of dihydropyrans through synergistic palladium and chiral phosphonic acid catalysis was reported. This protocol proceeded under mild reactions and provided dihydropyrans in up to 87% yield and up to 97% ee. Meanwhile, various derivations such as oxidation, Wittig-reaction, reductions, nucleophilic substitution, and Baeyer–Villiger were accomplished to furnish interesting compounds. To gain insight into the reaction mechanism, nonlinear relationship experiments and Hammett plot experiments were carried out. In addition, a range of products (3i, 4b, 4f, 4g, and 4j) accessible from this method exhibit various anti-inflammatory activities on NO and ROS inhibition.

Introduction

Chiral di- or tetrahydropyrans are privileged scaffolds in natural product chemistry and pharmaceuticals (Fig. 1).^{1–6} For example, lovastatin is a lipid-regulating drug that can reduce blood cholesterol, low-density lipoprotein (LDL), and triglyceride concentrations, while increasing high-density lipoprotein (HDL) concentrations.⁷ Aspergillide C exhibits significant cytotoxicity against mouse lymphocytic leukemia cells (L1210) with LD₅₀ values of 2.0 μg mL⁻¹.³ Ambruticin exhibits potent anti-fungal activity against a range of fungal pathogens including *Coccidioides immitis* and *Blastomyces dermatitidis*.¹ Due to the importance of di- or tetrahydropyrans in natural products, human medicines, and other fields, many synthetic strategies and methodologies, including hetero-Diels–Alder reactions, Prins cyclizations, and intramolecular nucleophilic conjugate additions, have been developed for the synthesis of di- or tetrahydropyrans.^{8–13} The intramolecular asymmetric oxa-Michael reactions were also popular for the preparation of

substituted tetrahydropyrans. Zhu and co-workers reported palladium(II)-catalyzed, Selectfluor-mediated formal 6-*endo-trig* fluorocycloetherification of γ -hydroxyalkenes for the synthesis of functionalized tetrahydropyrans.¹⁴ Quintard and Kochem developed stereo-controlled oxa-Michael additions to generate a wide array of chiral tetrahydropyrans *via* borrowing hydrogen.⁸ Then, Scheidt reported an enantioselective cross-dehydrogenative coupling to furnish tetrahydropyrans *via* Lewis acid catalysis.¹⁰ Despite the recent progress, the attainment of high stereoselectivity through a ring-forming process in the synthesis of chiral di- or tetrahydropyrans continues to pose a significant synthetic hurdle.

The combination of two or more unsaturated structural units to form cyclic organic compounds is among the most useful synthetic constructions in organic chemistry.¹⁵ Vinylolefin carbonates (VECs), an important type of zwitterionic allylpalladium species precursor, not only acted as 1,3-dipoles, but also as 1,5-dipoles.^{16–19} The synthesis of diverse O-heterocycles from vinylolefin carbonates through [3 + 2],^{20–27} [5 + 2],^{28–31} [5 + 3],^{32,33} and [5 + 4]^{34–40} cycloadditions with different synthons is well

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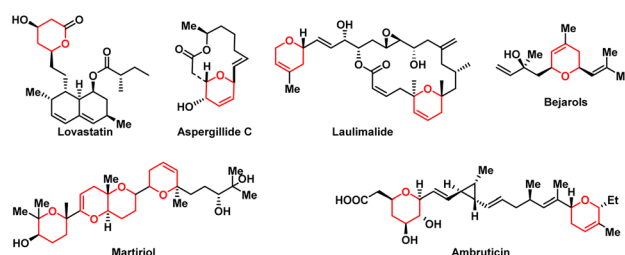
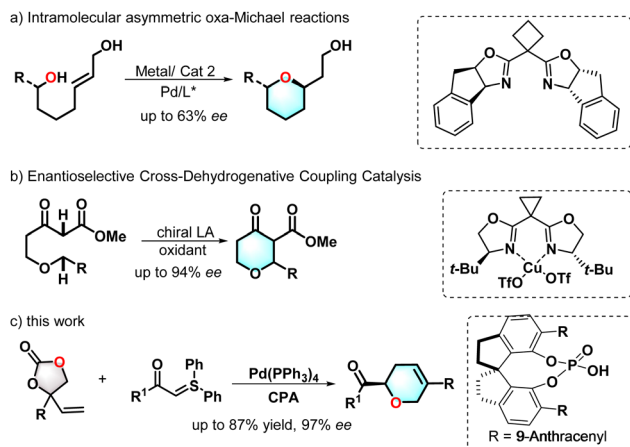


Fig. 1 Selected bioactive natural products and drugs bearing di- or tetrahydropyrans.





Scheme 1 The construction of di- or tetrahydropyran.

known *via* metal-catalyzed ring-opening strategies. Despite the progress, utilizing vinyl ethylene carbonates as 1,5-dipoles to participate in the enantioselective [5 + 1] cycloaddition is yet to be disclosed, probably due to other competitive reactions, thus making enantiocontrol difficult. To make TM-catalyzed dipolar [5 + 1] cycloadditions more powerful and general in the synthesis of six-membered cyclic compounds, new strategies for achieving these transformations in high efficiency and selectivity are required. On the other hand, development of suitable C1 partners in the assembly with vinyl ethylene carbonates is also crucial for the creation of some unique frameworks. Sulfur ylides have gained popularity for use as potential synthetic building blocks in transition-metal-catalyzed reactions as they could be easily used as carbene precursors, which are commonly effective C1 partners.⁴¹ In continuation of our research work on synergistic double metal-catalyzed organic transformations,^{42–45} herein, we disclose a novel [5 + 1] annulation reaction of vinyl ethylene carbonates and sulfur ylides *via* synergistic palladium/chiral phosphonic acid catalysis (Scheme 1).

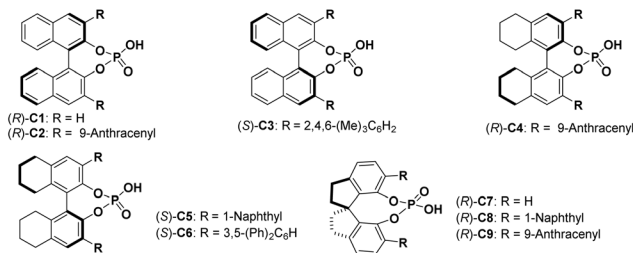
Results and discussion

Reaction discovery and optimization

Our study initiated the investigation of the model reaction between vinyl ethylene carbonate **1a** and sulfur ylide **2a** catalyzed by synergistic Pd(PPh₃)₄/chiral phosphonic acid to validate the feasibility of the above hypothesis. Sulfur ylide **2a** was initially chosen to avoid the complex stereoselectivity control caused by the simultaneous formation of one point. Regrettably, the targeted dihydropyran product was not observed under the Pd/CPA catalytic conditions. Instead, the rearrangement product **3a'** was formed (Table 1, entry 1). When substrate **2b** was employed, the desired product **3a** was still not achieved under the existing reaction conditions (entry 2). In an attempt to enhance the steric hindrance of the sulfur ylide, the desired product **3a** was obtained in 59% yield, albeit with poor enantioselectivity (entry 3). Afterward, diversely substituted and other scaffold-based CPA catalysts were investigated (entries 4–11). When 2,4,6-trimethylphenyl CPA **C2** was used, the product was obtained in 66% yield with 16% ee (entry 4). 9-Anthracenyl

Table 1 The screening of reaction conditions^a

Entry	2	CPA	Solvent	Yield 3a/3a' (%)	ee of 3a' ^c
1	2a	C1	DCE	ND/30	—
2	2b	C1	DCE	ND/33	—
3	2c	C1	DCE	59/—	2
4	2c	C2	DCE	66/—	16
5	2c	C3	DCE	64/—	64
6	2c	C4	DCE	72/—	12
7	2c	C5	DCE	60/—	18
8	2c	C6	DCE	58/—	31
9	2c	C7	DCE	31/	6
10	2c	C8	DCE	62/	86
11	2c	C9	DCE	76/	92
12	2c	C9	THF	46/—	89
13	2c	C9	DCM	57/—	93
14	2c	C9	1,4-Dioxane	65/—	94
15 ^d	2c	C9	DCE	82 (78)/—	93
16 ^e	2c	C9	DCE	88 (80)/—	92



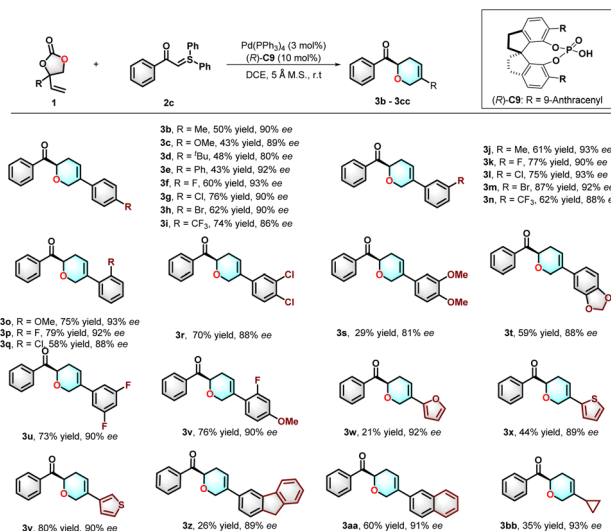
^a Reaction conditions: **1a** (0.06 mmol, 1.2 equiv.), **2** (0.05 mmol, 1.0 equiv.), Pd(PPh₃)₄ (5 mol%), CPA (10 mol%), solvent (0.5 mL), N₂, 24 h. ^b Determined by ¹H NMR using CH₂Br₂ as the internal standard. ^c Determined by HPLC. ^d 50 mg of 5 Å molecular sieves were added. Isolated yield is listed in parentheses. ^e **1a** (0.15 mmol, 1.5 equiv.), **2c** (0.1 mmol, 1.0 equiv.), Pd(PPh₃)₄ (3 mol%), DCE (1.0 mL), 18 h.

CPA **C3** gave an acceptable result (entry 5). Other tetrahydro BINOL-based CPAs **C4–C6** did not give satisfactory results (entries 6–8). The less sterically hindered spiro CPA **C7** afforded the tetrahydropyran in 71% yield and 6% ee (entry 9). The use of spiro skeleton-based CPAs **C8–C9** bearing bulky groups increased the enantioselectivity (entries 10 and 11), and the best result was obtained in 57% yield with 92% ee. Further screening of the solvents indicated that DCE was still the best choice compared to the other solvents (entries 12–14). The addition of 5 Å molecular sieves dramatically improved the yield to 88% with 93% ee (entry 15). The optimal conditions involved the use of **1a** (1.5 mmol, 1.5 equiv.), Pd(PPh₃)₄ (3 mol%), and **C9** (10 mol%) as the catalyst and 5 Å molecular sieves (100 mg) as the additive in DCE (1.0 mL) at 25 °C for 18 hours (entry 16).

Substrate scope

With the optimized reaction conditions established, we turned to investigate the scope and limitations of this new [5 + 1]

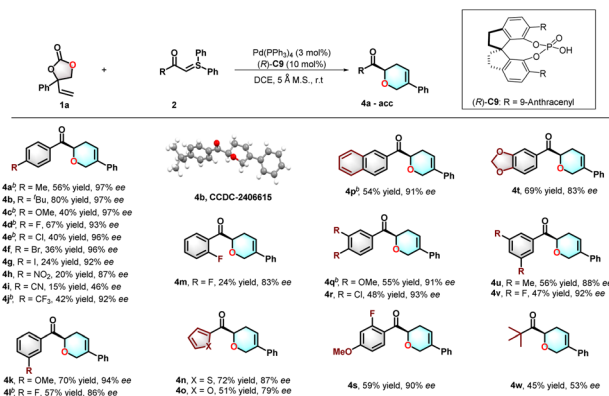




Scheme 2 Substitution scope of VMCCS.^a Reaction conditions: **1** (0.15 mmol), **2c** (0.1 mmol), Pd(PPh₃)₄ (3 mol%), (*R*)-**C9** (10 mol%), DCE (1 mL), 5 Å MS (100 mg), r.t., N₂, 18 h.

annulation reaction. Initially, we investigated the substitution patterns of vinyl ethylene carbonates **1** in their reactions with sulfur ylide **2c**. As depicted in Scheme 2, we probed the incorporation of various groups onto the *para*-position of the phenyl ring in vinyl ethylene carbonates, and the corresponding products **3b–3i** were obtained in good yields and high enantioselectivities. Notably, substrates bearing electron-withdrawing groups exhibited enhanced reactivity, yielding the corresponding products in 60–76% yield with enantioselectivity ranging from 86% to 92%. In contrast, substrates with substituents at the *meta*- and *ortho*-positions also underwent the reaction successfully, producing dihydropyrans **3j–3q** with good yields and enantioselectivity. We were pleased to discover that disubstituted vinyl ethylene carbonates were well tolerated, affording the desired products **3r–3v** in yields of 29–76% with enantioselectivities of 81–90% ee. Interestingly, heteroaryl (thienyl-, furyl-) substituted vinyl ethylene carbonates proved to be good substrates, yielding products in 21–80% yield with commendable enantioselectivities. Additionally, fluorenyl- and naphthyl-substituted vinyl ethylene carbonates were also competent in the reaction, providing the targeted products in 26–60% yield with good enantioselectivities. The reaction conditions were also compatible for alkyl-substituted substrates, but a low yield was obtained, offering the dihydropyran **3bb** in 35% yield with 93% ee.

After examining the vinyl ethylene carbonate scope, we examined a range of sulfur ylides under the optimized conditions (Scheme 3). Gratifyingly, the sulfur ylides bearing various functional groups were compatible with our reaction conditions, including some sensitive groups (bromide, and iodide). Substitution patterns on the *para* position of sulfur ylides, including electron-donating groups (**4a–4c**), halides (**4d–4g**), and electron-withdrawing groups (**4h–4j**), are well tolerated to give the corresponding chiral dihydropyrans with 46–97% ee. Notably, the *para*-CN substituent resulted in slightly lower enantiomeric

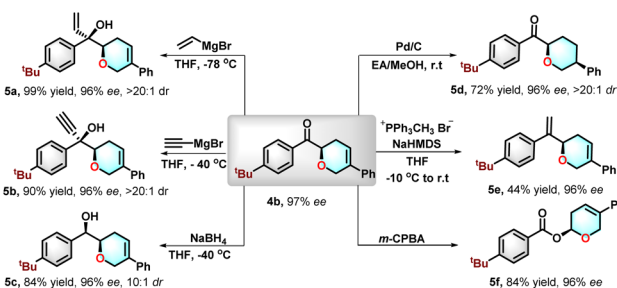


Scheme 3 Substitution scope of sulfur ylides.^a Reaction conditions: **1a** (0.15 mmol), **2** (0.1 mmol), Pd(PPh₃)₄ (3 mol%), (*R*)-**C9** (10 mol%), DCE (1 mL), 5 Å MS (100 mg), r.t., N₂, 18–36 h. ^b**1a** (0.12 mmol), Pd(PPh₃)₄ (5 mol%), 36 h.

excesses (46% ee) and reduced yields (15%). Additionally, sulfur ylides with *meta* substituents were also investigated, leading to the formation of enantioenriched dihydropyrans **4k–4l** in moderate yields of 57–70% with outstanding enantioselectivity. *Ortho*-substituted substrates could transform the target product **4m** in 24% yield with 84% ee. Furthermore, the enantioselective [5 + 1] annulation of hetero-substituted sulfur ylides was successfully accomplished, yielding the corresponding dihydropyrans **4n–4o** in moderate yields of 51–72% and with good enantiomeric excesses of 79–87%. The reaction also accommodated a naphthyl-substituted sulfur ylide, affording tetrahydropyran **4p** in 54% yield with 91% ee. The catalytic system also proved effective for disubstituted sulfur ylides, producing dihydropyrans **4q–4t** with high enantiomeric excesses. Alkyl-substituted sulfur ylide could tolerate standard conditions to provide the corresponding product **4w** in 45% yield with 53% ee. The absolute configuration of **4b** was assigned to be *R* configuration, as unambiguously confirmed by X-ray diffraction.

Diverse synthetic application

A 1 mmol scale reaction was conducted to provide product **3a** in 81% yield with 97% ee, which demonstrates the practical applicability of this asymmetric catalysis (Scheme 4). Then, we carried out several transformations of the tetrahydropyran **4b**. First, addition of organometallic reagents afforded the corresponding α -hydroxyl dihydropyrans **5a** and **5b** with a high



Scheme 4 Derivation of the compound **4b**.



efficiency, good enantioselectivities and diastereoselectivities. The C=O double bond could be reduced to alcohol **5c** in 84% yield with 96% ee and 10 : 1 dr. Also, the C=C double bond of **4b** could be efficiently reduced to tetrahydropyran **5d** without erosion of enantioselectivity in the presence of Pd/C, albeit with good diastereoselectivities (>20 : 1). The Wittig reaction of **4b** using commercial methyltriphenylphosphonium bromide could proceed to deliver the product **5e** in 44% yield with 96% ee. Finally, Baeyer–Villiger oxidation could smoothly convert **4b** to the corresponding ester **5f** in 84% yield with 96% ee in the presence of *m*-CPBA as an oxidant. These transformations bearing diverse functional groups while maintaining the optical purity established the potential application and versatility of the methodology in organic synthesis.

Biological studies

Anti-inflammatory assay. In the evaluation of the anti-inflammatory activity of the synthesized compounds, the levels of inflammatory factors were assessed in RAW264.7 cells. The concentrations of two key pro-inflammatory mediators, nitric oxide (NO) and reactive oxygen species (ROS), are critical for the organism's response to inflammatory stimuli. Elevated levels of NO and ROS have been shown to significantly influence the pathogenesis of various inflammatory diseases. Therefore, the concentrations of these two key pro-inflammatory mediators were detected in RAW264.7 cells. The collected data revealed that compounds **3i**, **4b**, **4f**, **4g**, and **4j** exhibit moderate concentration-dependent inhibitory activity against NO production (Fig. 2A). In the subsequent anti-inflammatory assay, compounds **3i** and **4g** demonstrated weak inhibition of ROS secretion in a dose-dependent manner, indicating their effectiveness in suppressing ROS (Fig. 2B).

Next, we carried out some additional studies to gain insights into the mechanism, particularly on the mode of catalyst function. We were curious about whether the chiral phosphonic acid activated the vinyl ethylene carbonates or the sulfur ylide

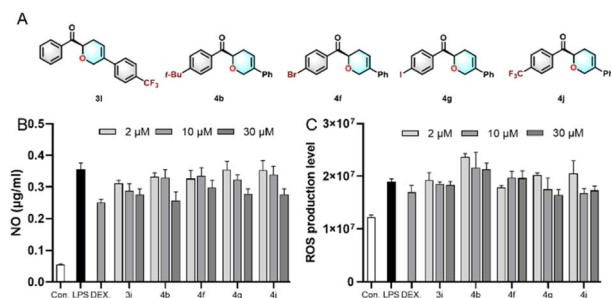
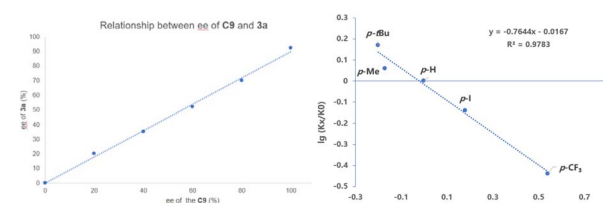


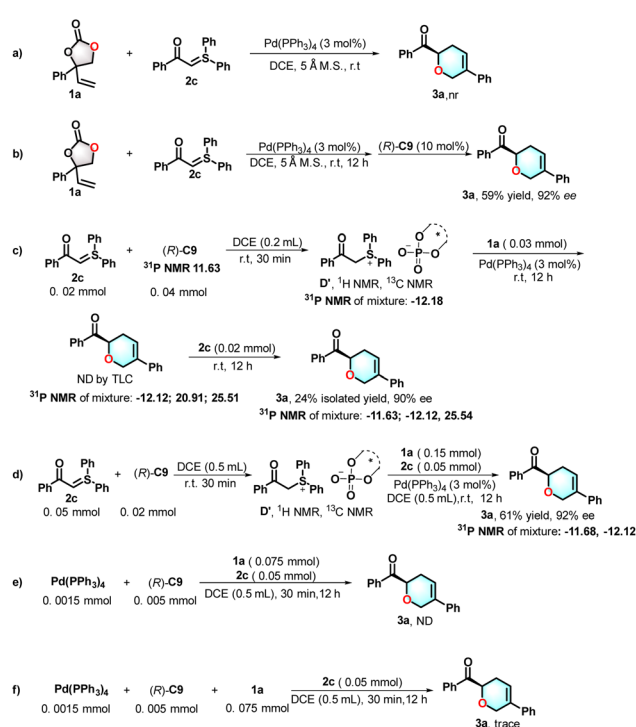
Fig. 2 (A) Chemical structures of tested compounds **3i**, **4b**, **4f**, **4g**, and **4j**. Effects of compound **3i** at 2 µM, 10 µM, and 30 µM on the production of (B) nitric oxide (NO) and (C) reactive oxygen species (ROS) in LPS-induced RAW264.7 macrophages. The cells were pre-treated with different concentrations of compounds for 1 h and then treated with LPS. NO concentration (LPS, 25 ng mL⁻¹, 24 h) in the medium was determined by the Griess method. The fluorescence intensity of ROS (LPS, 1 µg mL⁻¹, 24 h) was quantified by using a fluorescence microplate reader. Dexamethasone (DEX) was employed as a positive control (10 µM). The results shown are representative of three independent experiments.

nucleophile. Experiments to probe the relationship between the enantio-purity of **C9** and that of product **3a** showed that the relationship fell within the experimental error of a linear association. To investigate the chiral phosphonic acid speciation, nonlinear effect (NLE) studies were carried out by variation of the enantiomeric excess of the chiral phosphonic acid catalyst. The ee of the product **3a** was linearly related to the ee of chiral phosphonic acid employed (Scheme 5). The linear relationship implies that a mono-chiral phosphonic acid molecule might participate in the stereo-determining step. The slope of a Hammett plot in Scheme 5 that reveals the effect of the electronic properties of the aryl group in the alkene electrophile on the reaction was negative ($\rho = -1.38$), indicating that a positive charge accumulates in the allyl group in the intermediate.

Control experiments were conducted as shown in Scheme 6. The absence of chiral phosphonic acid (eqn (a)) resulted in no detectable product formation. Furthermore, when chiral phosphonic acid was introduced into the reaction mixture after 12 hours of palladium catalysis, the desired product was obtained in 59% yield with 92% ee (eqn (b)). These findings suggest that the reaction is a step-wise cycloaddition. Sulfur ylide **2c** (0.02 mmol)



Scheme 5 Nonlinear relationship experiment and Hammett plot.



Scheme 6 Control experiments.

was treated with excess chiral phosphoric acid (CPA, 0.04 mmol) in dichloroethane (DCE) at ambient temperature (eqn (c)). Comprehensive characterization by ^1H NMR and ^{13}C NMR spectroscopy unambiguously confirmed the formation of intermediate **D'** through tautomerization of the initially generated unstable intermediate **D**. Subsequently, vinyl ethylene carbonate **1a** (0.03 mmol) and the $\text{Pd}(\text{PPh}_3)_4$ catalyst (0.0006 mmol, 3 mol%) were introduced into the pre-equilibrated reaction system. Notably, the reaction failed to proceed even after 12 hours of stirring. This observation strongly suggests that excess CPA coordinates with the $\text{Pd}(\text{PPh}_3)_4$ catalyst, thereby preventing the critical transformation of intermediate **C**. To verify this hypothesis, we reintroduced fresh sulfur ylide **2c** (0.02 mmol) into the stagnant reaction mixture. Remarkably, this intervention successfully liberated the Pd catalyst from the CPA–Pd complex, ultimately yielding the desired product **3a** in 24% yield with 90% ee. These controlled experimental results show that the CPA does not engage in permanent coordination with the $\text{Pd}(\text{PPh}_3)_4$ catalyst under productive catalytic conditions. To unambiguously establish the catalytic role of intermediate **D**, we conducted rigorously controlled mechanistic investigations. Initial treatment of sulfur ylide (0.04 mmol) with chiral phosphoric acid (CPA, 0.02 mmol) in anhydrous dichloroethane (DCE) at room temperature under an argon atmosphere led to the clean formation of intermediate **D'**, as evidenced by ^1H NMR spectroscopic analysis (eqn (d)). Crucially, the subsequent addition of vinyl ethylene carbonate **1a** (0.06 mmol) and $\text{Pd}(\text{PPh}_3)_4$ catalyst (0.0012 mmol, 3 mol%) to this preformed intermediate system for 12 hours afforded the desired product **3a** in 61% isolated yield with 92% ee. These results suggested that intermediate **D** could be the key transition state. To further ascertain whether $\text{Pd}(\text{PPh}_3)_4$ cooperated with the CPA, a mixture containing $\text{Pd}(\text{PPh}_3)_4$ (0.0015 mmol) and chiral phosphoric acid (CPA, 0.005 mmol) in anhydrous dichloroethane (DCE, 0.5 mL) was stirred for 30 minutes at room temperature under an argon atmosphere (eqn (e)). Subsequently, substrates **1a** (0.075 mmol) and **2c** (0.05 mmol) were added to this mixture. However, no desired product **3a** was observed. In a separate experiment, a mixture of $\text{Pd}(\text{PPh}_3)_4$ (0.0015 mmol), substrate **1a** (0.075 mmol), and CPA (0.05 mmol) in anhydrous DCE (0.5 mL) was similarly stirred for 30 minutes under argon at room temperature (eqn (f)), followed by the

addition of substrate **2c** (0.05 mmol). The desired product **3a** was obtained in trace amounts. These findings indicate that CPA does not coordinate with the $\text{Pd}(\text{PPh}_3)_4$ catalyst under the catalytic process.

Based on our experimental results and the literature report, a plausible mechanism is listed in Scheme 7. Initially, the ring-opening of vinyl ethylene carbonate **1a** occurs in the presence of a palladium catalyst, yielding intermediate **B**.^{17–19} Concurrently, intermediate **B** may undergo isomerization to form intermediate **C**. This intermediate **C** is then subjected to a reaction with a chiral complex **D**, which is derived from sulfur ylides and chiral phosphonic acid,⁴⁶ to generate intermediate **E** and release species **A**. Subsequently, an intra-molecular nucleophilic substitution reaction proceeds smoothly, resulting in the formation of the desired product **3a**, while simultaneously regenerating chiral CPA.

Conclusions

In summary, we have devised a highly efficient protocol for the enantioselective synthesis of dihydropyrans, achieving high yields and exceptional enantioselectivities through the catalysis of synergistic palladium/chiral phosphonic acid. Mechanistic insights revealed that the pivotal step of the reaction entails the activation of challenging cyclic, aliphatic oxocarbenium ions. It is noteworthy that this reaction can be executed on one mmol scale, and the resultant product can be readily transformed into diverse and valuable chiral building blocks for the synthesis of enantio-enriched compounds. To assess the anti-inflammatory effectiveness of the synthesized compounds, we conducted evaluations of NO and ROS production levels in RAW264.7 cells. Notably, compounds **3i**, **4b**, **4f**, **4g**, and **4j** exhibited favorable anti-inflammatory activity by inhibiting NO production. In particular, compounds **3i** and **4g** also demonstrated mild inhibitory effects on ROS production. Moreover, we anticipate that our findings will stimulate further innovation among pharmaceutical chemists in adorning pharmacophores with enantio-enriched di- or tetrahydropyran motifs.

Data availability

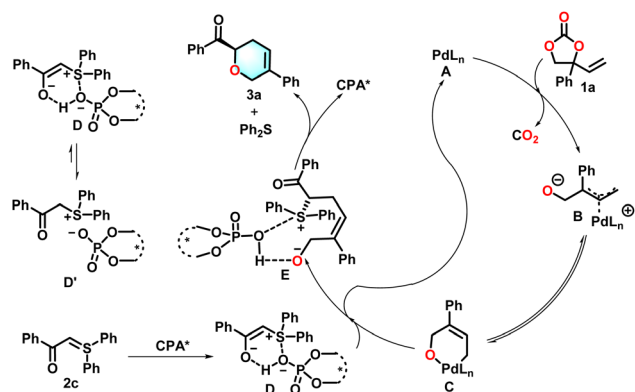
All the data supporting this article have been uploaded as part of the ESI.†

Author contributions

M. Ke and F. Chen designed the work. All the syntheses and characterization studies have been done by M. Ke, J. Zheng, J. Zong, J. Wang, G. Zheng, and B. Zhang. Bioactive experiments have been done by K. Tang, and Z. Ju and D. Cheng helped polish the article. The manuscript was written by M. Ke, Z. Ju and F. Chen. The overall work was supervised by Z. Ju and F. Chen. All authors have approved the final version of the article before submission.

Conflicts of interest

There are no conflicts to declare.



Scheme 7 A plausible mechanism.



Acknowledgements

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