

Cite this: *Chem. Sci.*, 2020, 11, 12533

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 13th June 2020
Accepted 17th September 2020

DOI: 10.1039/d0sc03297b

rsc.li/chemical-science

Chemo-selective cross reaction of two enals *via* carbene-catalyzed dual activation†

Xiaolin Peng,^a Jun Xu,^{bc} Tingting Li,^a Yonggui Robin Chi^{id} ^{ac} and Zhichao Jin^{id} ^{*a}

A dual catalytic chemo-selective cross-coupling reaction of two enals is developed. One enal (without α -substitution) is activated by an NHC catalyst to form an acylazolium enolate intermediate that undergoes Michael-type addition to another enal molecule bearing an alkynyl substituent. Mechanistic studies indicate that non-covalent interactions between the alkynyl enal and the NHC·HX catalyst play important roles in substrate activation and enantioselectivity control. Many of the possible side reactions are not observed. Our reaction provides highly chemo- and diastereo-selective access to chiral lactones containing functionalizable 1,3-enyn units with excellent enantioselectivities (95 to >99% ee).

The development of chemo-selective reactions of two or more substrates bearing similar functional groups remains a classic challenge in organic synthesis.¹ Enals (α,β -unsaturated aldehydes) are common building blocks that offer multiple useful modes of reactions. For instance, enals are readily used as Michael acceptors in many reactions including organic catalytic reactions mediated by amines.² In the area of N-heterocyclic carbene (NHC) organocatalysis,³ enals are used as precursors of several NHC-bound intermediates, including Breslow acyl anion intermediates,⁴ homoenolate intermediates,⁵ enolate intermediates,⁶ and acylazolium intermediates.⁷ Somewhat surprisingly, on the other hand, there is little success in using enals as Michael acceptors to react with any of these NHC-bound intermediates.⁸ Elegant studies in this direction are from Scheidt, in which they showed that in the presence of an NHC catalyst, a homo coupling reaction of enals (with one enal molecule as the Michael acceptor) occurred effectively (Fig. 1a, top side).^{8a,c} Berkessel reported an intramolecular reaction of two enal moieties (in one molecule) to form a bicyclic lactone adduct in the presence of an achiral NHC catalyst (Fig. 1a, bottom side).^{8b} To the best of our knowledge, the intermolecular Michael addition reaction of two different enal substrates mediated by NHC catalysts has not been reported.⁹ Possible reasons for the difficulties of enals to behave as effective

Michael acceptors likely include: (a) the relatively low electrophilicity of the α,β -unsaturated bonds of enals under the typical NHC catalytic conditions and (b) the presence of competing reactions involving both the alkene and aldehyde moieties of enals.

Here we disclose the first cross intermolecular reaction of two enals catalyzed by NHC catalysts (Fig. 1b). We envisioned that installation of an alkynyl substituent at the α -position of an enal can likely promote its reactivity as a Michael acceptor.¹⁰ The presence of an α -substituent can interrupt π -conjugations and thus minimize its reactivity *via* the corresponding enal-derived enolate/homoenolate intermediate formed with NHC, as shown by Bode, Glorius and others.^{6b,11} In addition, the alkynyl substituent can promote hydrogen-bonding interactions to increase the electrophilicity of the enal to react as a Michael acceptor, as observed in Jørgensen's amine-catalyzed reactions.¹² In our present study, a non-linear effect was observed regarding enantiomeric excesses of the NHC catalyst and the catalytic reaction product. The reaction enantioselectivity was also found to be sensitive to solvents and bases. These results suggested that the NHC and its azolium salt pre-catalyst (NHC·HX) played dual roles in our reaction: one is to activate the α -unsubstituted enal *via* the formation of the NHC-bound enolate intermediate,⁶ the other is to activate the α -alkynyl substituted enal *via* the acidic proton of the chiral NHC·HX (Fig. 1b, intermediate I & transition state TS-I).¹³ With respect to applications, carbon-carbon triple bonds are found in a good number of bioactive molecules such as cleviolide, (+)-prelaureatin, and oxamflatin (Fig. 1c).¹⁴ We demonstrated that our products containing these alkynyl units could be readily transformed into a diverse set of molecules.

Cinnamaldehyde **1a** and α -alkynyl enal **2a** were chosen as the model substrates to search for suitable cross coupling reaction conditions (Table 1). The reactions were first carried out with Et₃N as the base and THF as the solvent. When aminoindanol

^aLaboratory Breeding Base of Green Pesticide and Agricultural Bioengineering, Key Laboratory of Green Pesticide and Agricultural Bioengineering Ministry of Education, Guizhou University, Huaxi District, Guiyang 550025, China

^bSchool of Pharmacy, Guiyang College of Traditional Chinese Medicine, Huaxi District, Guiyang 550025, China

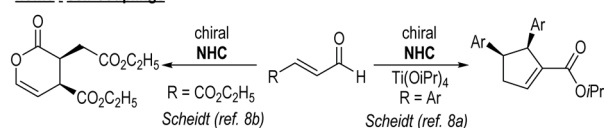
^cDivision of Chemistry & Biological Chemistry, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore. E-mail: zcjin@gzu.edu.cn

† Electronic supplementary information (ESI) available. CCDC 1980067. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d0sc03297b

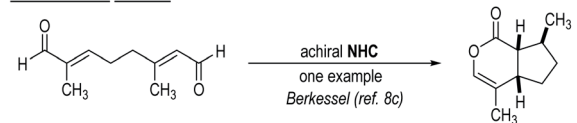


a) NHC-catalyzed reactions with enals as Michael acceptors (literature)

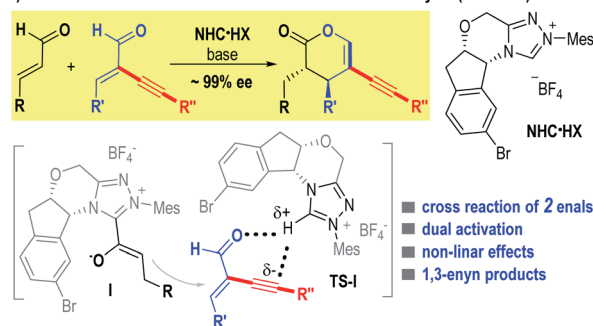
homo / self-couplings



intramolecular reaction



b) cross intermolecular reactions of two enals via NHC catalysis (this work)



c) alkyne-containing bioactive molecules

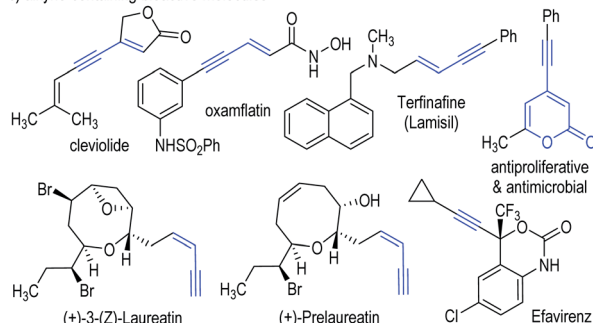


Fig. 1 NHC-catalyzed reactions (a) with enals as Michael acceptors, (b) via cross intermolecular reactions of two enals, and (c) bio-active molecules bearing alkyne units.

derived azolium salt **A**¹⁵ was used as the NHC pre-catalyst, the desired formal [4 + 2] product (**3a**) was obtained in a very encouraging yield (52%) with excellent ee and dr values (entry 1). The reactions appeared to be very sensitive to the structure of the NHC pre-catalysts, as similar azolium salts with *N*-phenyl or *N*-C₆F₅ substituents (**B**¹⁶ and **C**¹⁷) were completely ineffective, leading to no product formation (entries 2 & 3). Additional studies on the NHC pre-catalysts finally revealed that introduction of a Br substituent in the indane phenyl ring of the catalyst (**D**)¹⁸ led to **3a** in 85% yield with 99% ee as nearly a single diastereomer (entry 4). Replacing Et₃N with DIEA led to similar results (entry 5). Very interestingly, when the bases were replaced with DABCO or K₃PO₄, a significant drop in the enantioselectivity was observed (entries 6 & 7; see the ESI† for more details). Changing the solvent from THF to CHCl₃ or EtOAc has moderate effects on reaction yields (entries 8 & 9).

Our reactions are highly chemo-selective. Under all these conditions (Table 1), several possible side products were not formed. For example, possible adducts with enal **2a** as the

Table 1 Optimization of reaction conditions^a

possible competing reactions (not observed)

3a' cross (2a → 1a)

3a'' homo (1a / 1a)

3a''' homo (2a / 2a)

Entry NHC Base Solvent Yield^b (%) Ee^c (%) Dr^d

1	A	Et ₃ N	THF	52	99	>20 : 1
2	B	Et ₃ N	THF	0	—	—
3	C	Et ₃ N	THF	0	—	—
4	D	Et ₃ N	THF	85	99	>20 : 1
5	D	DIEA	THF	83	98	>20 : 1
6	D	DABCO	THF	72	67	>20 : 1
7	D	K ₃ PO ₄	THF	80	79	>20 : 1
8	D	Et ₃ N	CHCl ₃	64	97	>20 : 1
9	D	Et ₃ N	EtOAc	68	99	>20 : 1

^a Unless otherwise specified, the reactions were carried using **1a** (0.15 mmol), **2a** (0.1 mmol), NHC (0.02 mmol), base (0.05 mmol) and solvent (1.0 mL) at rt for 24 h. ^b Isolated yield of **3a**. ^c The ee values were determined via HPLC on a chiral stationary phase. ^d Dr values were determined via ¹H NMR of the crude reaction mixture.

enolate precursor (to form **3a'** or **3a'''**) were not observed. This is not a complete surprise as α -substituted enals are unreactive azolium enolate intermediate precursors under NHC catalysis.¹¹ Our results showed that mixing of enal **2a** with highly reactive electrophiles (such as alkylidene diketone; see the ESI† for more details) did not lead to any formal [2 + 4] addition product. Interestingly, the simple enal **1a** did not behave as a Michael acceptor under our conditions, as homo-coupling adduct **3a''** was not observed. In Scheidt's elegant study, the introduction of a Lewis acid additive is necessary to activate one molecule of the enal to react as a Michael acceptor.^{8a}

Our further control experiments showed that when the α -alkynyl substituent of **2a** was replaced with an alkyl (e.g., Fig. 2, **2a1**), vinyl (**2a2**), phenyl (**2a3**) or cyano (**2a4**) unit, the corresponding cross [2 + 4] reactions were not observed, with most of the starting materials remaining unchanged (for more details, see the ESI†). It is clear that the alkynyl unit present in enal **2a** played more important roles than simply blocking the enal α -

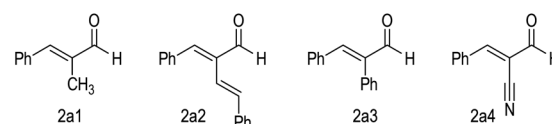


Fig. 2 Unsuccessful α -substituted enal substrates for the NHC catalytic chemo-selective cross [2 + 4] reactions.



carbon to interrupt the π -conjugations. Although attempts to identify key intermediates (and possible non-covalent interactions) between the NHC catalysts and the two enals did not lead to conclusive mechanistic pictures, our experiments did show strong non-linear effects with respect to the optical purities of the NHC pre-catalyst and the reaction product (Fig. 3, see the ESI† for more details).

Specifically, the reaction of **1a** and **2a** was studied by varying the enantiomeric purities of the NHC pre-catalyst **D** under the optimized reaction conditions as indicated in Table 1, entry 4 (Fig. 3). The ee values of the products and the ee values of the catalysts showed an obvious negative nonlinear effect (Fig. 3a). This nonlinear effect suggests that at least two catalysts are involved in the enantio-differentiating step of our reaction.¹⁹ It appears both of the enals (**1a** and **2a**) are activated by NHC and/or its salt (NHC·HX) in our formal [2 + 4] reaction. It is well established that cinnamaldehyde (**1a**) can be activated by NHC to form an acylazolium enolate intermediate.⁶ We therefore propose that the other enal (**2a**) bearing an alkynyl unit is activated by the acidic proton from NHC·HX *via* non-covalent

interactions. These non-covalent interactions between **2a** and NHC·HX could be further supported by the “linear-effect” shown by the ee values of the products and the catalysts when using DABCO as the base (Fig. 3b). In this case, only one catalyst was involved in the enantio-differentiating step of our reaction, since the non-covalent H-bonding interactions between **2a** and NHC·HX could be broken by a stronger base (*e.g.*, DABCO, K₃PO₄, see the ESI† for details) existing in the catalytic system. Similar activation of the α -alkynyl enal by a proton was proposed in Jørgensen’s amine-catalyzed reaction.¹¹ In the field of NHC related catalysis, the use of NHC·HX as a H-bond donating catalyst has been demonstrated by Huang, Scheidt, Guin, and others.¹³

The non-covalent interactions between the NHC pre-catalyst **D** and the alkynyl enal **2a** can also be supported by ¹H NMR analysis (Fig. 4). In the presence of the weak base Et₃N, the acidic proton of the NHC pre-catalyst **D** shows an obvious change in the chemical shift after mixing with the alkynyl enal **2a** (Fig. 4, *a vs. b*). Meanwhile, the chemical shift of the aldehyde proton of the substrate **2a** is not changed in the same reaction system (*a vs. c*). These results support the existence of a non-covalent interaction between the NHC pre-catalyst **D** and the alkynyl enal **2a** in our NHC organocatalytic reaction system (for more details, see the ESI†).

We then examined the substrate scope using different enals (**1**) to react with **2a** under the optimized reaction conditions indicated in Table 1, entry 4 (Scheme 1). Substituents could be installed at each position of the phenyl ring of the cinnamaldehyde **1a**, with all the products afforded in moderate to excellent yields with excellent chemo-, enantio- and diastereoselectivities (**3b** to **3p**). The β -phenyl rings of the enal substrates (**1**) could also be switched to a naphthyl group or heteroaromatic groups. The corresponding products were afforded in excellent enantioselectivities, although the yields or dr values dropped in these cases (**3q** to **3s**). To our delight, aliphatic enals could also be used as the enolate precursors for this NHC catalyzed chemoselective reaction, with the desired products afforded in moderate yields with excellent dr and ee values (**3t** & **3u**).

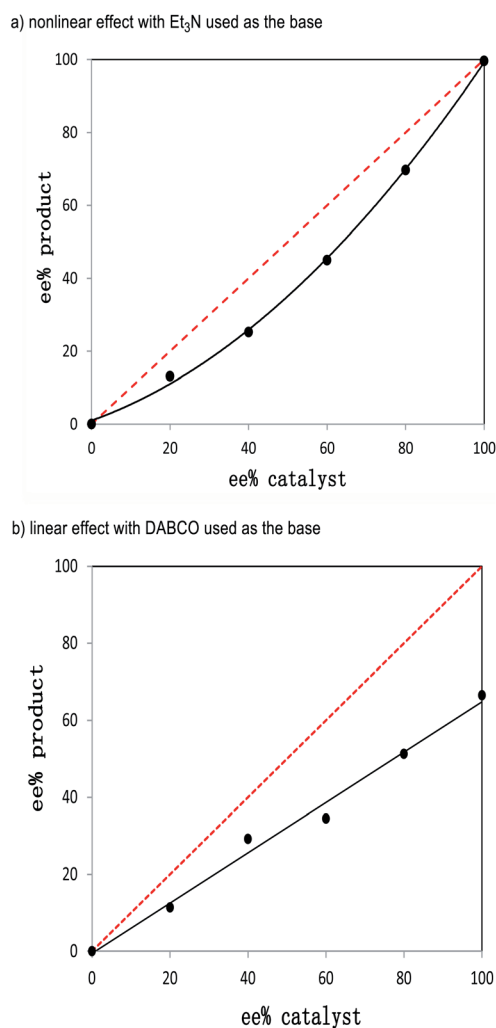


Fig. 3 Nonlinear effects with respect to the product ee and the catalyst ee values using different bases: (a) Et₃N and (b) DABCO.

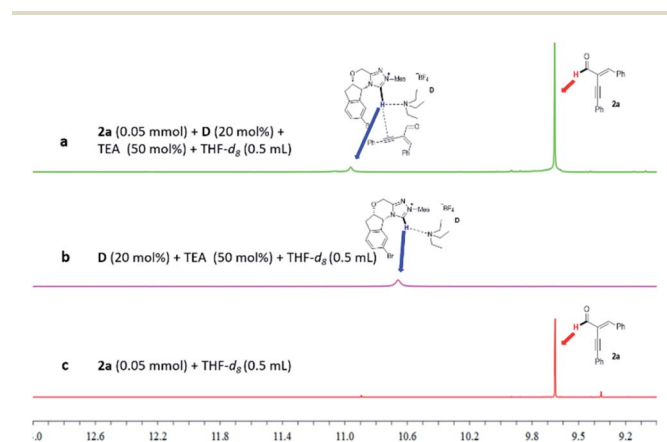
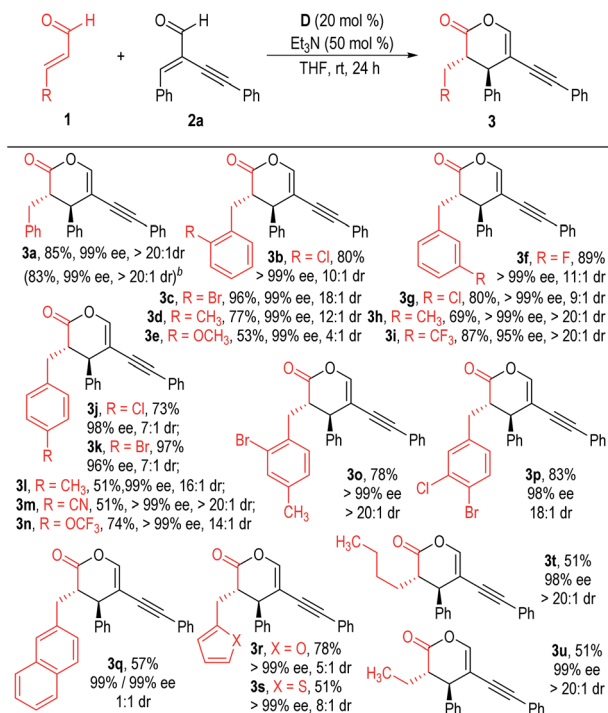


Fig. 4 Chemical shift of the acidic proton of the NHC pre-catalyst **D** under various conditions.



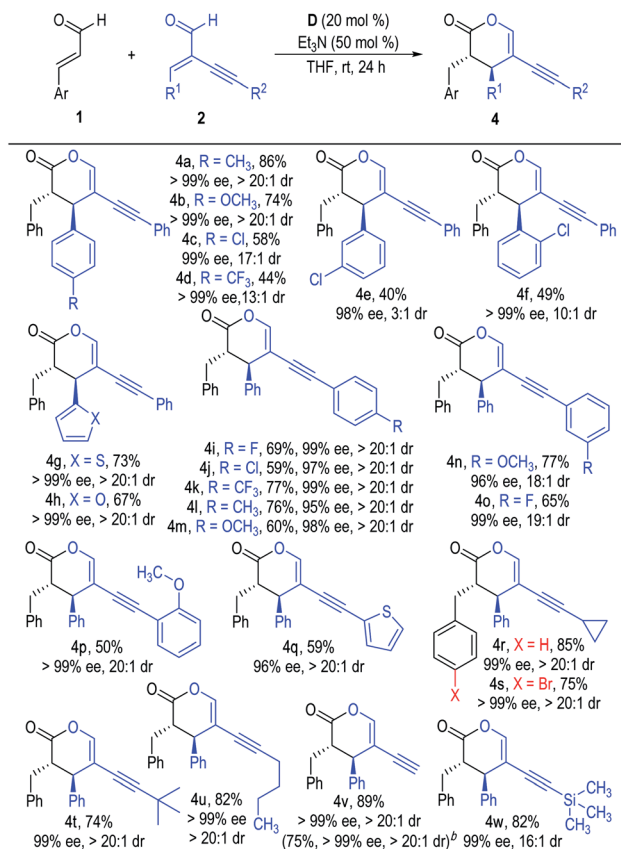


Scheme 1 Scope of enals **1**. ^aReaction conditions as stated in Table 1, entry 4. Yields are isolated yields after purification by column chromatography. Er values were determined via HPLC on a chiral stationary phase. ^bThe reaction was carried out on a 1.0 mmol scale based on **2a**.

The scope of the α -alkynyl enal substrates (**2**) was also examined (Scheme 2). Electron-donating substituents could be well tolerated on the β -phenyl rings of the α -alkynyl enals, with the desired products afforded in good yields with excellent ee values as single diastereomers (**4a** & **4b**). The yields of the [2 + 4] products decreased when installing electron-withdrawing groups at any position of the β -phenyl rings, although the enantioselectivities were not affected (**4c** to **4f**). The β -phenyl rings of the α -alkynyl enal substrates (**2**) could also be replaced with various heteroaromatic groups without obvious reduction in the product yields or stereoselectivities (**4g** & **4h**). Substituents were also well tolerated on the phenyl rings attached to the alkynyl units of the enal substrates **2**, with all the corresponding products afforded in moderate to good yields with excellent optical purities as single diastereomers (**4i** to **4p**). Enal substrates **2** bearing heteroaromatic, aliphatic or terminal α -alkynyl groups also worked well in this reaction and gave the target products in moderate to good yields with excellent enantio- and diastereoselectivities (**4q** to **4w**).

As a technical note, this chemo-selective reaction of α,β -unsaturated enals could be carried out on a large scale without reduction of the product ee or dr values, although the yields of the final products slightly dropped (e.g., Scheme 1, **3a** & Scheme 2, **4v**).

Having examined the reaction scope with both of the enal reactants, we next seek to get additional insights into the reaction mechanism. Hammett studies²⁰ were carried out using alkynyl enal substrates **2** bearing various *p*-substituents on the phenyl



Scheme 2 Scope of α -alkynyl enals **2**. ^aReaction conditions as stated in Table 1, entry 4. Yields are isolated yields after purification by column chromatography. Er values were determined via HPLC on a chiral stationary phase. ^bThe reaction was carried out on a 6.4 mmol scale based on **2v** (1.0 g).

groups of the alkynyl units (Fig. 5). Alkynyl enal substrates **2** bearing 4-F (**2i**), 4-Cl (**2j**), 4-CF₃ (**2k**), 4-CH₃ (**2l**), and 4-OCH₃ (**2m**) groups were chosen as the target substrates to evaluate their relative reaction rates compared with the alkynyl enal **2a**. Kinetic studies showed that the substrates **2** bearing electron-withdrawing groups reacted faster than those bearing electron-donating groups (Fig. 5a). The Hammett plot of the relative reaction rates of the substrates **2i** to **2m** gave a positive slope ($\rho = 1.0128$). Therefore, a negatively charged transition state should be built up in the rate determining step of this [2 + 4] cycloaddition process. This is in accordance with the non-covalent H-bonding interactions that we have proposed to exist between the acidic proton of the NHC-precatalyst **D** and the alkynyl unit of the enal substrate **2** (Fig. 1b, **TS-I**, see the ESI[†] for more details).

Additionally, substrates **2x** and **2y** bearing steric bulky substituted phenyl groups on the alkynyl units were further examined for this NHC dual catalytic [2 + 4] cycloaddition reaction (Fig. 6). It is not surprising that the corresponding reaction products **4x** and **4y** were only afforded in poor yields with moderate ee values. Because the alkynyl groups of the substrates **2x** and **2y** were shielded by the bulky mesityl and 2,6-diisopropylphenyl groups, the H-bonding interactions between the NHC pre-catalyst **D** and the alkynyl groups cannot be efficiently formed in these cases.



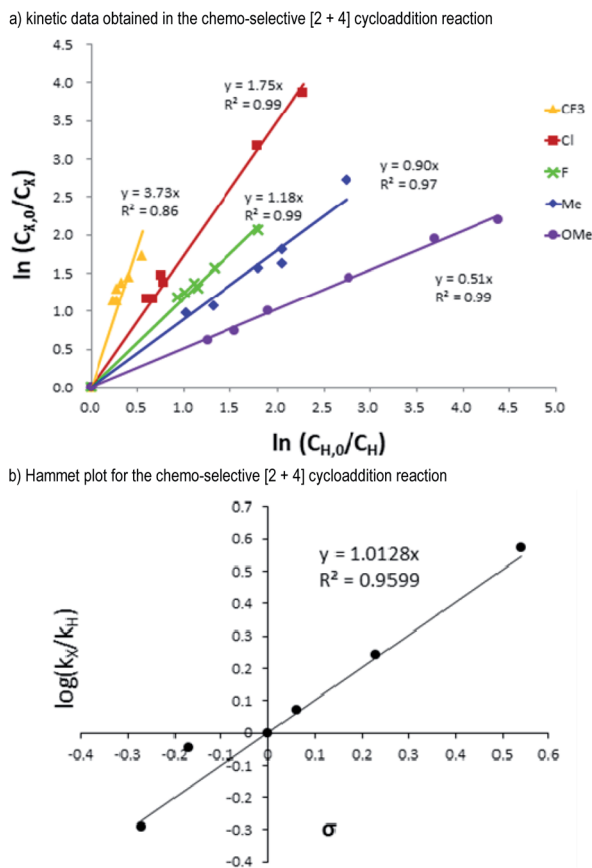


Fig. 5 (a) Kinetic data and (b) Hammett plot for the competitive [2 + 4] cycloaddition reactions based on the σ values.

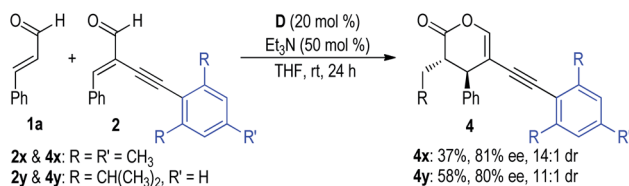


Fig. 6 Reactions with enals **2** bearing bulky alkyne substituents.

The chiral alkyne pyranone products obtained from this methodology are rich in functionalities for further synthetic transformations (Fig. 7). For instance, the alkyne group in **3a** could react with the adjacent phenyl group under the catalysis of $\text{Cu}(\text{OTf})_2$ to give tricyclic product **5** in a good yield without reduction of the optical purity.²¹ The terminal alkyne group in **4v** could participate in various addition reactions and afford a variety of multi-functionalized alkene products in moderate to excellent yields with excellent ee values as single diastereomers (e.g., **6**, **7**, **8**, **10**).²² A click reaction between the alkyne group in **4v** and benzyl azide led to the formation of the chiral triazole product **9** in almost quantitative yield with excellent optical purity as a single diastereomer.^{22d} The ethynyl group in **4v** could be selectively reduced to an ethyl group with a Pd/C and CaCO_3 catalyst in a hydrogen atmosphere (**11**). Pyranone **4w** bearing a 2-trimethylsilylethynyl group could be coupled with 2-

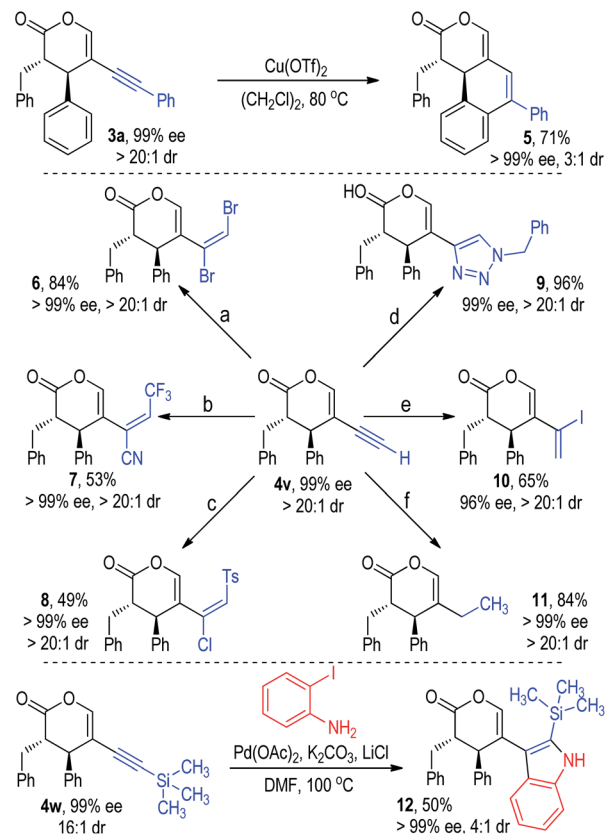


Fig. 7 Synthetic transformations of the chiral pyranone products. ^a CuBr_2 , CH_3CN , r.t., 1 h; ^bTogni reagent, TMS-CN, $\text{Cu}(\text{OAc})_2$, terpyridine, CH_3CN , 70 °C, 5 h; ^c TsNHNH_2 , FeCl_3 , TBHP, CH_3CN , 80 °C, 8 h; ^d BnN_3 , sodium L-ascorbate, DCM/ H_2O (v/v = 1/1), r.t., 12 h; ^eNaI, TMS-Cl, H_2O , CH_3CN , r.t., 4 h; ^fPd/C, CaCO_3 , H_2 (balloon), EtOH, r.t., 2 h.

iodoaniline to give the indole product **12** in a moderate yield and diastereoselectivity with an excellent ee value.²³

Conclusions

In summary, we have developed a chemo-selective intermolecular cross-coupling reaction of two different enals *via* a dual activation process. One of the enals is activated by NHC to form an acylazolium enolate intermediate. The other enal (α -alkyne substituted enal) is presumably activated by $\text{NHC} \cdot \text{HX}$ to behave as a Michael acceptor. Non-linear effects with respect to catalyst and product ee values suggest the involvement of more than one catalyst in the enantio-differentiation step of our reaction. Our reaction provides chiral lactones containing functionalizable 1,3-enyn units with excellent diastereo- and enantioselectivities. Synthetic transformations of our catalytic reaction products give a diverse set of functional molecules. Further studies in developing challenging chemo-selective reactions, as well as mechanistic studies, are being pursued in our laboratories.

Conflicts of interest

The authors declare no competing financial interests.



Acknowledgements

We acknowledge financial support from the National Natural Science Foundation of China (21772029, 21801051, and 21961006), The 10 Talent Plan (Shicengci) of Guizhou Province ([2016]5649), the Guizhou Province Returned Oversea Student Science and Technology Activity Program [(2014)-2], the Science and Technology Department of Guizhou Province ([2018]2802, [2019]1020), the Program of Introducing Talents of Discipline to Universities of China (111 Program, D20023) at Guizhou University, the Guizhou Province First-Class Disciplines Project [[Yiliu Xueke Jianshe Xiangmu]-GNYL(2017)008], Guizhou University of Traditional Chinese Medicine, Guizhou University (China), and the Singapore National Research Foundation under its NRF Investigatorship (NRF-NRFI2016-06), the Ministry of Education, Singapore, under its MOE AcRF Tier 1 Award (RG108/16, RG5/19, RG1/18), MOE AcRF Tier 3 Award (MOE2018-T3-1-003), the Agency for Science, Technology and Research (A*STAR) under its A*STAR AME IRG Award (A1783c0008, A1783c0010), GSK-EDB Trust Fund, and Nanyang Research Award Grant, Nanyang Technological University.

Notes and references

- (a) A. H. Hoveyda, D. A. Evans and G. C. Fu, *Chem. Rev.*, 1993, **93**, 1307–1370; (b) R. A. Shenvi, D. P. O'Malley and P. S. Baran, *Acc. Chem. Res.*, 2009, **42**, 530–541; (c) I. S. Young and P. S. Baran, *Nat. Chem.*, 2009, **1**, 193–205; (d) E. Roulland, *Angew. Chem., Int. Ed.*, 2011, **50**, 1226–1227; (e) D. Kaiser, A. Bauer, M. Lemmerer and N. Maulide, *Chem. Soc. Rev.*, 2018, **47**, 7899–7925.
- For selected reviews, see: (a) A. Erkkilä, I. Majander and P. M. Pihko, *Chem. Rev.*, 2007, **107**, 5416–5470; (b) D. Enders, C. Grondal and M. R. M. Hüttl, *Angew. Chem., Int. Ed.*, 2007, **46**, 1570–1581; (c) D. MacMillan, *Nature*, 2008, **455**, 304–308; (d) E. Arceo and P. Melchiorre, *Angew. Chem., Int. Ed.*, 2012, **51**, 5290–5292; (e) P. Chauhan, S. Mahajan and D. Enders, *Acc. Chem. Res.*, 2017, **50**, 2809–2821; (f) L. Klier, F. Tur, P. H. Poulsen and K. A. Jørgensen, *Chem. Soc. Rev.*, 2017, **46**, 1080–1102; (g) L. Zhu, D. Wang, Z. Jia, Q. Lin, M. Huang and S. Luo, *ACS Catal.*, 2018, **8**, 5466–5484; (h) G. J. R. Rodríguez, N. M. Rezayee, A. V. Albalat and K. A. Jørgensen, *Chem. Rev.*, 2019, **119**, 4221–4260; (i) F. An, B. Maji, E. Min, A. R. Ofial and H. Mayr, *J. Am. Chem. Soc.*, 2020, **142**, 1526–1547.
- For selected recent reviews on NHC catalysis: (a) D. Enders and T. Balensiefer, *Acc. Chem. Res.*, 2004, **37**, 534–541; (b) D. Enders, O. Niemeier and A. Henseler, *Chem. Rev.*, 2007, **107**, 5606–5655; (c) A. T. Biju, N. Kuhl and F. Glorius, *Acc. Chem. Res.*, 2011, **44**, 1182–1195; (d) D. T. Cohen and K. A. Scheidt, *Chem. Sci.*, 2012, **3**, 53–57; (e) A. Grossmann and D. Enders, *Angew. Chem., Int. Ed.*, 2012, **51**, 314–325; (f) X. Bugaut and F. Glorius, *Chem. Soc. Rev.*, 2012, **41**, 3511–3522; (g) J. Douglas, G. Churchill and A. D. Smith, *Synthesis*, 2012, **44**, 2295–2309; (h) J. Izquierdo, G. E. Hutson, D. T. Cohen and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2012, **51**, 11686–11698; (i) H. U. Vora, P. Wheeler and T. Rovis, *Adv. Synth. Catal.*, 2012, **354**, 1617–1639; (j) S. J. Ryan, L. Candish and D. W. Lupton, *Chem. Soc. Rev.*, 2013, **42**, 4906–4917; (k) S. J. Connon, *Angew. Chem., Int. Ed.*, 2014, **53**, 1203–1205; (l) M. N. Hopkinson, C. Richter, M. Schedler and F. Glorius, *Nature*, 2014, **510**, 485–496; (m) J. Mahatthananchai and J. W. Bode, *Acc. Chem. Res.*, 2014, **47**, 696–707; (n) R. S. Menon, A. T. Biju and V. Nair, *Chem. Soc. Rev.*, 2015, **44**, 5040–5052; (o) D. M. Flanigan, F. Romanov-Michailidis, N. A. White and T. Rovis, *Chem. Rev.*, 2015, **115**, 9307–9387; (p) M. H. Wang and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2016, **55**, 14912–14922; (q) X. Y. Chen, Q. Liu, P. Chauhan and D. Enders, *Angew. Chem., Int. Ed.*, 2018, **57**, 3862–3873; (r) Z. Wang, D. Pan, T. Li and Z. Jin, *Chem.-Asian J.*, 2018, **13**, 2149–2163; (s) R. Song and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2019, **58**, 8628–8630; (t) X.-Y. Chen, Z.-H. Gao and S. Ye, *Acc. Chem. Res.*, 2020, **53**, 690–702; for a recent book on NHC organocatalysis, see: (u) A. T. Biju, *N-Heterocyclic carbenes in organocatalysis*, Wiley-VCH, Weinheim, Germany, 2019.
- For pioneering studies on the generation of Breslow intermediates, see: (a) T. Ukai, R. Tanaka and T. J. Dokawa, *Pharm. Soc. Jpn.*, 1943, **63**, 296–300; (b) R. Breslow, *J. Am. Chem. Soc.*, 1958, **80**, 3719–3726.
- For pioneering studies on the NHC-catalyzed homoenolate activation of enals, see: (a) C. Burstein and F. Glorius, *Angew. Chem., Int. Ed.*, 2004, **43**, 6205–6208; (b) S. S. Sohn, E. L. Rosen and J. W. Bode, *J. Am. Chem. Soc.*, 2004, **126**, 14370–14371.
- For pioneering studies on the NHC-catalyzed enolate activation of enals, see: (a) M. He, J. R. Struble and J. W. Bode, *J. Am. Chem. Soc.*, 2006, **128**, 8418–8420; (b) C. Burstein, S. Tschan, X. Xie and F. Glorius, *Synthesis*, 2006, **14**, 2418–2439.
- For pioneering studies on the NHC-catalyzed oxidative LUMO activation of enals, see: (a) K. Zeitler, *Org. Lett.*, 2006, **8**, 637–640; (b) S. J. Ryan, L. Candish and D. W. Lupton, *J. Am. Chem. Soc.*, 2009, **131**, 14176–14177; (c) S. D. Sarkar and A. Studer, *Angew. Chem., Int. Ed.*, 2010, **49**, 9266–9269. For selected reviews, see: (d) C. Zhang, J. F. Hooper and D. W. Lupton, *ACS Catal.*, 2017, **7**, 2583–2596; (e) S. Mondal, S. R. Yetra, S. Mukherjee and A. T. Biju, *Acc. Chem. Res.*, 2019, **52**, 425–436.
- (a) D. T. Cohen, B. Cardinal-David, J. M. Roberts, A. A. Sarjeant and K. A. Scheidt, *Org. Lett.*, 2011, **13**, 1068–1071; (b) V. R. Yatham, W. Harnying, D. Kootz, J. M. Neudörfl, N. E. Schlörer and A. Berkessel, *J. Am. Chem. Soc.*, 2016, **138**, 2670–2677; (c) E. R. Miller, M. T. Hovey and K. A. Scheidt, *J. Am. Chem. Soc.*, 2020, **142**, 2187–2192.
- For NHC catalytic reactions between aldehydes and enals, see: (a) S. R. Yetra, T. Kaicharla, S. S. Kunte, R. G. Gonnade and A. T. Biju, *Org. Lett.*, 2013, **15**, 5202–5205; (b) C. Burstein and F. Glorius, *Angew. Chem., Int. Ed.*, 2004, **43**, 6205–6208; (c) S. S. Sohn, E. L. Rosen and J. W. Bode, *J. Am. Chem. Soc.*, 2004, **126**, 14370–14371; (d) S. S. Sohn and J. W. Bode, *Org. Lett.*, 2005, **7**, 3873–3876; (e) R. Ide,



- R. Kyan, T. P. Le, Y. Kitagawa, K. Sato, N. Mase and T. Narumi, *Org. Lett.*, 2019, **21**, 9119–9123.
- 10 (a) T. Yao, X. Zhang and R. C. Larock, *J. Am. Chem. Soc.*, 2004, **126**, 11164–11169; (b) Y. Xiao and J. Zhang, *Angew. Chem., Int. Ed.*, 2008, **47**, 1903–1906; (c) X. Yu, B. Du, K. Wang and J. Zhang, *Org. Lett.*, 2010, **12**, 1876–1879.
- 11 (a) S. S. Sohn and J. W. Bode, *Org. Lett.*, 2005, **7**, 3873–3876; (b) A. Chan and K. A. Scheidt, *Org. Lett.*, 2005, **7**, 905–908; (c) A. G. Kravina, J. Mahatthananchai and J. W. Bode, *Angew. Chem., Int. Ed.*, 2012, **51**, 9433–9436.
- 12 P. H. Poulsen, Y. Li, V. H. Lauridsen, D. K. B. Jorgensen, T. A. Palazzo, M. Meazza and K. A. Jørgensen, *Angew. Chem., Int. Ed.*, 2018, **57**, 10661–10665.
- 13 For a pioneering study using NHCs as chiral non-covalent organic catalysts, see: (a) J. Chen and Y. Huang, *Nat. Commun.*, 2014, **5**, 3437. For selected examples, see: (b) E. M. Phillips, M. Riedrich and K. A. Scheidt, *J. Am. Chem. Soc.*, 2010, **132**, 13179–13181; (c) J. Chen, S. Meng, L. Wang, H. Tang and Y. Huang, *Chem. Sci.*, 2015, **6**, 4184–4189; (d) L. Wang, J. Chen and Y. Huang, *Angew. Chem., Int. Ed.*, 2015, **54**, 15414–15418; (e) S. Santra, A. Porey, B. Jana and J. Guin, *Chem. Sci.*, 2018, **9**, 6446–6450; (f) S. Lu, J.-Y. Ong, H. Yang, S. B. Poh, X. Liew, C. S. D. Seow, M. W. Wong and Y. Zhao, *J. Am. Chem. Soc.*, 2019, **141**, 17062–17067; (g) S. Santra, U. Maji and J. Guin, *Org. Lett.*, 2020, **22**, 468–473.
- 14 (a) G. J. Hollingworth and J. B. Sweeney, *Synlett*, 1993, **7**, 463–465; (b) I. J. S. Fairlamb, L. R. Marrison, J. M. Dickinson, F.-J. Lu and J. P. Schmidt, *Bioorg. Med. Chem.*, 2004, **12**, 4285–4429; (c) K. Hyoungsu, L. Hyunjoo, L. Dongjoo, K. Sanghee and K. Deukjoon, *J. Am. Chem. Soc.*, 2007, **129**, 2269–2274; (d) Y. Zhou, Y. Zhang and J. Wang, *Org. Biomol. Chem.*, 2016, **14**, 6638–6650; (e) T. T. Talele, *J. Med. Chem.*, 2020, **63**, 5625–5633.
- 15 M. He, G. J. Uc and J. W. Bode, *J. Am. Chem. Soc.*, 2006, **128**, 15088–15089.
- 16 M. S. Kerr, J. R. Alaniz and T. Rovis, *J. Am. Chem. Soc.*, 2002, **124**, 10298–10299.
- 17 M. S. Kerr and T. Rovis, *J. Am. Chem. Soc.*, 2004, **126**, 8876–8877.
- 18 C. Zhao, F. Li and J. Wang, *Angew. Chem., Int. Ed.*, 2016, **55**, 1820–1824.
- 19 T. Satyanarayana, S. Abraham and H. B. Kaga, *Angew. Chem., Int. Ed.*, 2009, **48**, 456–494.
- 20 (a) C. Hansch, A. Leo and R. W. Taft, *Chem. Rev.*, 1991, **91**, 165–195; (b) E. Casper, J. Thomas, R.-R. Sergio and F. Peter, *ACS Catal.*, 2013, **3**, 294–302; (c) Y. Ayana, A. Yoshinori and C. Naoto, *J. Org. Chem.*, 2014, **79**, 11922–11932; (d) M. R. Brennan, D. Kim and A. R. Fout, *Chem. Sci.*, 2014, **5**, 4831–4839.
- 21 Y.-L. Wang, W.-M. Zhang, J.-J. Dai, Y.-S. Feng and H.-J. Xu, *RSC Adv.*, 2014, **4**, 61706–61710.
- 22 (a) J. Xiang, R. Yuan, R. Wang, N. Yi, L. Lu, H. Zou and W. He, *J. Org. Chem.*, 2014, **79**, 11378–11382; (b) Y.-T. He, Q. Zhao, X. Wang, J.-Y. Liu, P.-F. Xu and Y.-M. Liang, *Chem. Commun.*, 2015, **51**, 13209–13212; (c) X. Li, X. Shi, M. Fang and X. Xu, *J. Org. Chem.*, 2013, **78**, 9499–9504; (d) Q. Gu, H. H. A. Mamari, K. Graczyk, E. Diers and L. Ackermann, *Angew. Chem., Int. Ed.*, 2014, **53**, 3868–3871; (e) L. W. C. Lawrence and A. K. Yudin, *Org. Lett.*, 2009, **11**, 1281–1284; (f) Y. Kim and C.-J. Li, *Green Synthesis & Catalysis*, 2020, **1**, 1–11.
- 23 W.-B. Liu, D. P. Schuman, Y.-F. Yang, A. A. Toutov, Y. Liang, H. F. T. Klare, N. Nesnas, M. Oestreich, D. G. Blackmond, S. C. Virgil, S. Banerjee, R. N. Zare, R. H. Grubbs, K. N. Houk and B. M. Stoltz, *J. Am. Chem. Soc.*, 2017, **139**, 6867–6879.

