SUPPORTING INFORMATION ACCOMPANYING

The effect of the N-mesityl group in NHC-catalyzed reactions

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TABLE OF CONTENTS

General methods...........................................................................................................S02
Synthesis and characterization of triazolium salt precatalysts in this study...........S03
Redox esterification of cinnamaldehyde in the absence of external base.........S10
Redox esterifications of enal and α-chloroaldehyde...........................................S11
Oxidative esterification of enal comparison......................................................... S16
Oxidative esterification of α-hydroxyenone comparison................................. S17
Redox esterification of ynal comparison..............................................................S18
Oxidative esterification of enal by hydride transfer comparison...................... S20
Additional mechanistic probes ..............................................................................S24
Extent of deprotonation of triazolium salts and enal titration experiments........ S27
Intramolecular Stetter reaction comparison.........................................................S30
Hetero Diels-Alder reaction comparison...........................................................S31
Claisen vs. esterification reaction comparison..................................................S33
General methods

All reactions were generally performed in dried glassware under an atmosphere of dry N₂. Dichloromethane (CH₂Cl₂) was distilled over CaH₂; EtOH was distilled over Na. THF and toluene were dried by passage over activated alumina under an Ar atmosphere. All other reagents were used without further purification, unless otherwise noted. Thin layer chromatography (TLC) was performed on Merck precoated plates (silica gel 60 F₂₅₄, Art 5715, 0.25 mm) and were visualized by fluorescence quenching under UV light or by staining with phosphomolybdic acid. Silica-gel preparative thin-layer chromatography (PTLC) was performed using plates prepared from Merck Kieselgel 60 PF₂₅₄ (Art 7747). Flash column chromatography was performed on E. Merck Silica Gel 60 (230–400 Mesh) using a forced flow of 0.5–1.0 bar. ¹H NMR and ¹³C NMR were measured on VARIAN Mercury 300 MHz, 75 MHz or Bruker Avance 400 MHz, 100 MHz respectively. Chemical shifts are expressed in parts per million (ppm) downfield from residual solvent peaks, and coupling constants are reported in Hertz (Hz). Splitting patterns are indicated as follows: br, broad; s, singlet; d, doublet; dd, doublet of doublet; t, triplet; q, quartet; m, multiplet. Infrared (IR) spectra were recorded using a JASCO FT:IR-4100 spectrophotometer and reported as wavenumber (cm⁻¹). Gas-chromatography/mass spectrometry was performed using an Agilent 7820A (GC, 70 eV) coupled with an Agilent 5975 MSD Series (MS) system. Liquid-chromatography/mass spectrometry was preformed using a Dionex UltiMate3000 RSLC (LC) coupled with a Surveyor MSQ Plus (MS). High-resolution mass spectrometric measurements were performed by the mass spectrometry service of the LOC at the ETHZ on Agilent 1200 (LC) and Bruker maXis for ESI-Q-TOF. High Performance Liquid Chromatography was performed using pumps and UV-VIS detector manufactured by JASCO: Daicel Chiralpak AD-H Column (4.6 × 250 mm) with 9:1 hexanes:iPrOH as eluent, flow rate of 1.0 mL/min, and detection wavelength at 220 nm.
Synthesis and characterization of triazolium salt precatalysts in this study

2-(2,4,6-trichlorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium (10 BF₄⁻)

The synthesis of N-2,4,6-trichloro triazolium salt 10 was slightly modified from a procedure reported by Rovis.¹ In a dried round bottom flask, 1.09 g (12.8 mmol; 1 equiv) of pyrrolidin-2-one was dissolved in 60 mL CH₂Cl₂ (0.2 M), followed by an addition of 1.89 g of Me₂OBF₄ (12.8 mmol; 1 equiv). The reaction was allowed to stir overnight (ca. 12 hours). GC/MS was used to monitor the reaction and identify the methyl ether product S₁.² Without further purification, 2.10 g (10.0 mmol; 0.78 equiv) of (2,4,6-trichlorophenyl)hydrazine (commercially available from TCI) was added to the solution of S₁ in CH₂Cl₂. This reaction was allowed to stir at room temperature for 3 hours (monitor by LC/MS). The mixture was concentrated in vacuo, and the desired 1-(pyrrolidin-2-ylidene)-2-(2,4,6-trichlorophenyl)hydrazin-1-ium³ (S₂) was obtained as white solid after recrystallization in CHCl₃. The obtained intermediate S₂ was dissolved in a mixture of 5 mL of (EtO)₂CH, 5 mL chlorobenzene, and 1 mL MeOH. This solution was heated under N₂ overnight (ca. 12 hours) at 110°C (monitor by LC/MS). After cooling down, three portions of toluene was added to precipitate the desired triazolium salt as yellow solid, which was recrystallized first in THF and then in EtOH to afford white crystalline solid of 10 in 45% yield: ¹H NMR (DMSO-d₆, 400 MHz): δ 10.48 (s, 1H), 8.19 (s, 2H), 4.56-4.53 (m, 2H), 3.29-3.25 (m, 2H), 2.80-2.76 (m, 2H). ¹³C NMR (DMSO-d₆, 100 MHz): δ 164.47, 143.96, 138.57, 134.09, 130.85, 129.94, 48.69, 26.98, 21.97. HRMS (ESI) [M]+ calcd. for C₁₁H₆Cl₃N₅⁺, 287.9858 found, 287.9857.

²¹H NMR (CDCl₃, 300 MHz): δ 3.80 (s, 3H), 3.66 (t, 2H), 2.47-2.44 (t, 2H), 2.05-2.00 (m, 2H). GC/MS (EI) = 99 [M-H]-, 84, 69, 56 (100%). Spectroscopic data matched those reported in the literature: C. Dinesh, M. Clive, S. Hosahalli, S. Ramesh, P. Chetan and M. Henrik, Heterocyclic Compounds as MEK Inhibitors. U.S. Patent US2009/275606 A1, April 21 2008.
³¹H NMR (acetone-d₆, 400 MHz): δ 9.52 (b, 1H), 8.03 (s, 1H), 7.69 (s, 1H), 7.59 (s, 2H), 3.98-3.95 (m, 2H), 3.14-3.10 (m, 2H), 2.46-2.41 (m, 2H). ¹³C NMR (acetone-d₆, 100 MHz): δ 171.09, 137.18, 130.09, 129.09, 128.17, 78.32, 47.89, 20.92. HRMS (ESI) [M]+ calcd. for C₁₉H₁₁Cl₃N₅⁺, 278.0013 found, 278.0015.
$^1$H and $^{13}$C NMR of 10

$^1$H NMR (400 MHz, DMSO): δ 10.48, 0.19, 4.54, 4.53, 3.14, 3.39, 2.27, 2.35, 2.84, 2.78, 2.78, 2.73, 2.52, 2.11, 0.81.

$^{13}$C NMR (100 MHz, DMSO): δ 164.47, 143.94, 133.57, 127.59, 120.85, 129.94, 46.69, 46.69, 40.31, 40.31, 40.31, 40.31, 39.80, 39.80, 28.96, 25.97, 6.39.
1-(3,4,5-trimethoxyphenyl)hydrazin-1-ium chloride S4.

The synthesis of 1-(3,4,5-trimethoxyphenyl)hydrazin-1-ium chloride S4 followed the procedure described by Bode.\textsuperscript{4} A 200 mL three-necked flask was charged with a solution of 3.0 mL concentrated HCl (aq) and 6.0 mL H\textsubscript{2}O, followed by a portion-wise addition of 2.0 g of 3,4,5-trimethoxyaniline (commercially available from Acros) over five minutes. A freshly prepared solution of NaNO\textsubscript{2} (0.8 g in 2 mL H\textsubscript{2}O) was added dropwise via syringe over 30 mins. The greenish yellow reaction mixture was vigorously stirred for another 30 mins while maintaining the temperature below 0°C. A slurry solution of 6.0 g SnCl\textsubscript{2}.H\textsubscript{2}O in 3.0 mL H\textsubscript{2}O and 3.0 mL concentrated HCl (aq) was added via an additional funnel over three hours (maintaining the temperature below 0°C). The temperature was allowed to rise to room temperature overnight. It should be noted that vigorous stirring is extremely important since a lot of foam was produced. The crude reaction mixture was neutralized with NaOH (monitor pH until neutral). This caused Sn salt to precipitate; it was then filtered off. The remaining mixture was extracted with 1:1 CH\textsubscript{2}Cl\textsubscript{2}:H\textsubscript{2}O several times. The organic layer was dried and concentrated to thick oil (GC/MS indicated the desired product in free base form was obtained: [M]\textsuperscript{+} = 198.0). This oil was dissolved in 20 mL CH\textsubscript{2}Cl\textsubscript{2} and 20 mL Et\textsubscript{2}O, followed by dropwise addition of 3.0 mL 4N HCl in dioxane to afford the crude purple solid of the hydrazine HCl salt, which was then recrystallized several times in 2-propanol:MeOH mixture to afford pale pink solid of 4 in 0.9 g (30% overall yield): \textsuperscript{1}H NMR (DMSO-\textit{d}, 400 MHz): \(\delta\) 10.20 (br, 1H), 8.03 (s, 3H), 6.45 (s, 2H), 3.75 (s, 6H), 3.60 (s, 3H). \textsuperscript{13}C NMR (DMSO-\textit{d}, 100 MHz): \(\delta\) 153.68, 142.42, 132.81, 93.70, 60.62, 56.36. HRMS (ESI) [M]\textsuperscript{+} calcd. for C\textsubscript{9}H\textsubscript{15}N\textsubscript{2}O\textsubscript{3}, 199.1074 found, 199.1077.

$^1$H and $^{13}$C NMR of S4

$^1$H NMR (400 MHz, DMSO-d$_6$): δ 10.20, 8.03, 6.45, 3.75, 2.60, 2.39, 2.53, 2.32, 2.52, 2.51, 2.51, 0.01.

$^{13}$C NMR (100 MHz, DMSO-d$_6$): δ 153.8, 147.4, 132.5, 120.3, 57.0, 56.8, 56.0, 56.0, 40.4, 40.4, 39.7, 39.7, 39.7, 39.7, 39.7, 39.7.
The synthesis of \(\text{N-3,4,5-trimethoxy triazolium salt 9}\) was slightly modified from a procedure reported by Bode.\(^4\) In a dried round bottom flask, 0.52 g (4.40 mmol; 1 equiv) of pyrrolidin-2-one was dissolved in 60 mL CH\(_2\)Cl\(_2\) (0.2 M), followed by an addition of 0.65 g of Me\(_3\)OBF\(_4\) (4.84 mmol; 1.1 equiv). The reaction was allowed to stir overnight (ca. 12 hours), worked up with sat. NaHCO\(_3\) solution and extracted thrice in CH\(_2\)Cl\(_2\) to afford the desired methyl ether \(\text{S1}\) in quantitative yield. This product was then dissolved in 15.0 mL MeOH (0.15 M) and mixed with 0.98 g (1.00 equiv) of 3,4,5-trimethoxy hydrazine HCl \(\text{S4}\); the solution was allowed to stir at 60°C for 2 hours. The mixture was concentrated in vacuo to afford orange solid, which was recrystallized once in a mixture of 2-propanol and CH\(_2\)Cl\(_2\) to afford \(\text{1-(pyrrolidin-2-ylidene)}-2-(3,4,5\text{-trimethoxyphenyl})\text{hydrazin-1-ium chloride (S5)}\) in 0.98 g (85% yield).

The obtained intermediate \(\text{S5}\) was dissolved in a mixture of 5.4 mL of (EtO)\(_3\)CH (10.0 equiv), 3.0 mL chlorobenzene (10.0 equiv), and 0.75 mL 4N solution of HCl in dioxane (1.0 equiv). This solution was heated under N\(_2\) overnight (ca. 12 hours) at 110°C (monitor by LC/MS). After cooling, three portions of toluene was added to precipitate the desired triazolium salt as black solid, which was recrystallized five times in a mixture of 2-propanol and acetone to afford white powder of the triazolium salt \(\text{9}\) in 0.5 g (50% yield): \(^1\)H NMR (CDCl\(_3\), 300 MHz): 12.85 (s, 1H), 7.36 (s, 2H), 4.72-4.67 (m, 2H), 3.97 (s, 6H), 3.87 (s, 3H), 3.28-3.23 (m, 2H), 2.94-2.90 (m, 2H). \(^{13}\)C NMR (CDCl\(_3\), 100 MHz): \(\delta\) 161.58, 154.15, 139.47, 139.28, 131.15, 98.00, 61.03, 57.06, 47.41, 26.96, 21.85. HRMS (ESI) [M]\(^+\) calcd. for C\(_{14}\)H\(_{18}\)N\(_3\)O\(_3\)\(^+\), 276.1341 found, 276.1343.

\(^{1}\)H NMR (DMSO-d\(_6\), 400 MHz): \(\delta\) 11.42 (br, 1H), 10.02 (br, 1H), 8.48 (br, 1H), 6.16 (s, 2H), 3.61 (s, 6H), 3.58-3.56 (overlapping m & s, 5H), 3.02-2.98 (m, 2H), 2.19 (m, 2H). \(^{13}\)C NMR (DMSO-d\(_6\), 100 MHz): \(\delta\) 170.81, 153.95, 143.16, 132.43, 91.99, 91.44, 60.68, 56.44, 47.43, 29.04, 21.11. HRMS (ESI) [M]\(^+\) calcd. for C\(_{15}\)H\(_{20}\)N\(_3\)O\(_3\)\(^+\), 266.1499 found, 266.1492.
$^1$H and $^{13}$C NMR of 9

$^1$H NMR (500 MHz, CDCl$_3$): δ 12.85, 7.06, 6.16, 4.72, 4.70, 4.67, 3.95, 3.87, 3.26, 3.25, 3.20, 3.19, 3.02, 2.87, 2.17.

$^{13}$C NMR (125 MHz, CDCl$_3$): δ 161.58, 154.15, 130.47, 130.20, 131.15, 90.00, 77.35, 77.24, 77.03, 76.72, 61.01, 57.88, 47.41, 39.90, 21.83.
Counter-ion exchange from BF$_4^-$ to Cl$^-$ salt of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium 2.

In a dried flask, 50.0 mg of the BF$_4^-$ salt of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium (2) and 0.5 g of Fluka Amberlite ion-exchange resin IRA 402 (Cl$^-$) were dissolved in 2.0 mL MeOH and allowed to stir at room temperature overnight (ca. 12 hours). Filtration and washing with CH$_2$Cl$_2$ afforded the desired Cl$^-$ salt of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium (2) in 12.0 mg (28% yield). With the exception of the chemical shift of the C-2 H in $^1$H NMR (acetone-d$_6$) from 10.26 ppm (BF$_4^-$ salt) to 12.41 ppm (Cl$^-$ salt), other spectroscopic data were identical to those reported by Rovis. $^{19}$F NMR spectra was measured on the Cl$^-$ salt and compared against BF$_4^-$ salt (spectra below clearly showed almost complete disappearance of BF$_4^-$).

$^{19}$F NMR spectra of authentic 2 BF$_4^-$ salt

$^{19}$F NMR spectra of anion-exchanged 2 Cl$^-$ salt
Redox esterification of cinnamaldehyde in the absence of external base

A solution of cinnamaldehyde (13.2 mg, 0.1 mmol, 1.0 equiv) and 1-(tert-butyl)-4-methoxybenzene (16.4 mg, 0.1 mmol, 1.0 equiv as internal standard), and 5.0 µL MeOH (0.1 mmol, 1.0 equiv) was prepared using 1.0 mL Tol-d₈ (with 10% CD₂Cl₂ to ensure solubility). This solution was transferred equally (0.5 mL) to two NMR tubes: one charged with 10 mol% of 2-mesityl-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride 1 and another with 10 mol% 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride 2 (prepared as described above). ¹H NMR spectra of the two reactions were recorded (A) before and (B and C) after heating at 40°C in an oil bath (see spectra comparison below). The percentage conversions were measured by the disappearance of the enal, from the integration of the peak at 9.45 ppm (d, 1H) against the internal standard peak at 1.22 ppm (9H). At 5 hours, the reaction with N-mesityl triazolium salt proceeded to 73% conversion while the N-C₆F₅ triazolium salt showed no conversion (even after 17 hours). The identity of the isolated ester product 4 was confirmed by ¹H NMR and GC/MS.¹H NMR (CDCl₃, 300 MHz): 7.30-7.19 (m, 5H), 3.68 (s, 3H), 2.98-2.93 (m, 2H), 2.67-2.61 (m, 2H). GC/MS (EI): 164 (M⁺), 104 (100%), 90.9, 77.0.


Redox esterifications of enal and α-chloroaldehyde

A) Enal comparison

The reaction was prepared according to the procedure describe previously with two exception: 1) 10 mol% of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium tetrafluoroborate \(^1\) \(2\) was used in one case while 10 mol% of 2-mesityl-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride \(1\) was used in another, and 2) 10 mol% of \(\text{iPr}_2\text{NET}\) was added to both reaction. The rate was measured by the disappearance of MeOH and the formation of the product \(4\) \(^7\) via integrations of the peak at 3.20 ppm (MeOH) and 3.38 (Me ester) against the internal standard peak at 1.29 ppm (9H). The rate plots are shown below.
$^1$H NMR recorded over 170 minutes for the reaction with catalyst 1.

$^1$H NMR recorded over 170 minutes for the reaction with catalyst 2.
Plots of rate comparison:

**Enal redox esterification (product formation)**

B) α-chloraldehyde comparison

![Diagram showing reaction conditions and products](image)
A solution of 2-chloro-3-phenylpropanal (17.0 mg, 0.1 mmol, 1.0 equiv) and 1-(tert-butyl)-4-methoxybenzene (16.4 mg, 0.1 mmol, 1.0 equiv as internal standard), 5.0 µL MeOH (0.1 mmol, 1.0 equiv), and 20.0 µL Et3N was prepared using 1.0 mL CDCl3. Then this solution was transferred equally (0.5 mL) to two NMR tubes: one charged with 10 mol% of 2-mesityl-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride 1 and another with 10 mol% of 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium BF4⁻ 2. ¹H NMR spectra of the two reactions were recorded over 15 minutes while the reaction was allowed to run at room temperature (see spectra comparison below). The rate was measured by the formation of the ester product 4 via integrations of the peak at 3.69 (Me ester) against the internal standard peak at 1.29 ppm (9H). The rate plots are shown below.

¹H NMR recorded over 15 minutes for the reaction with catalyst 2.

$^1$H NMR recorded over 15 minutes for the reaction with catalyst 1.

A plot of rate comparison:

![Plot of rate comparison](image-url)
Oxidative esterification of enal comparison

A solution of cinnamaldehyde (26.4 mg, 0.2 mmol, 1.0 equiv), 30.0 µL MeOH (0.6 mmol, 3.0 equiv), diquinone oxidant 7 (80.0 mg, 0.2 mmol, 1.0 equiv), and 10 mol% 1,8-diazabicycloundec-7-ene (DBU) was prepared using 2.0 mL CD₂Cl₂. Then this solution was transferred equally (0.5 mL) to four NMR tubes charged with triazolium salt precatalyst 9, 2, 10, and 1 respectively. ¹H NMR spectra of all four reactions were recorded after the reaction was allowed to run at room temperature for 60 seconds (upon shimming). Percentage conversions were measured by the integration of enal peak at 6.77-6.69 ppm (dd, 1H) against the product peak at 6.50-6.45 (d, ¹J = 15 Hz, 1H) ppm (see ¹H NMR spectra of unpurified mixture below for comparison). Percent conversions are calculated to be 100%, 100%, 75%, and 50% for 9, 2, 10, and 1 respectively. The identity of the ester product 8 was confirmed by GC/MS¹⁰ (EI): 162 (50%, M⁺), 131 (100%, M⁺-OMe), 103 (M⁺-CO₂Me), 77 (Ph).

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(9) Prepared according to M. S. Kharasch and B. S. Joshi, J. Org. Chem., 1957, 22, 1439–1443. Emphatically, the oxidant must be pure and free of trace amount of hydroxide base (used in the preparation) in order to obtain consistent result.

Oxidative esterification of α-hydroxyenone comparison

A solution of (E)-4-hydroxy-1-(4-methoxyphenyl)-4-methylpent-1-en-3-one\textsuperscript{11} (13, 44.0 mg, 0.2 mmol, 1.0 equiv), 30.0 μL MeOH (0.6 mmol, 3.0 equiv), diquinone oxidant 7 (80.0 mg, 0.2 mmol, 1.0 equiv), and 10 mol% 1,8-diazabicycloundec-7-ene (DBU) was prepared using 2.0 mL \( \text{CD}_2\text{Cl}_2 \). This solution was transferred equally (0.5 mL) to four NMR tubes charged with triazolium salt precatalyst 9, 2, 10, and 1 respectively. \(^1\)H NMR spectra of all four reactions were recorded after the reaction was allowed to run at room temperature for 20 minutes. Percentage conversions were measured by the integration of the enone peak at 6.95 ppm against the product peak at 6.33 ppm (see \(^1\)H NMR spectra of unpurified mixture

Percent conversions are calculated to be 100%, 50%, ~5%, and ~5% for 1, 10, 2, and 9 respectively (the reactions with 2 and 9 did proceed to full conversion over 12 hours). The identity of the ester product 12 was confirmed by $^1$H NMR and GC/MS$^{12}$: $^1$H NMR (CD$_2$Cl$_2$, 300 MHz): 7.67-7.62 (d, $^J$ = 15 Hz, 1H), 7.53-7.51 (m, 2H), 6.94-6.92 (m, 2H), 6.36-6.31 (d, $^J$ = 15 Hz, 1H), 3.84 (s, 3H), 3.77 (s, 3H). GC/MS (EI): 192 (M$^+$, 75%), 162, 161 (100%), 134, 133, 118, 90, 89, 63.

Redox esterification of ynal comparison

A solution of 3-(4-methoxyphenyl)propiolaldehyde 11 (32.0 mg, 0.2 mmol, 1.0 equiv), 10.0 µL MeOH (0.2 mmol, 1.0 equiv), 1,3-di-tert-butylbenzene (0.1 mmol, 0.5 equiv as internal standard), and 10 mol% iPr₂NEt was prepared using 2.0 mL tol-d₈ (with 10% CD₂Cl₂ to ensure solubility). This solution was transferred equally (0.5 mL) to four NMR tubes charged with triazolium salts 9, 2, 10, and 1. ¹H NMR spectra of all four reactions were recorded after the reactions were allowed to run at 40°C for 90 minutes. Percentage conversions were measured by the integration of the ynal peak at 9.18 ppm against an internal standard at 1.45 ppm (see ¹H NMR spectra comparison of unpurified mixtures). Percent conversions¹³ are calculated to be 100%, ~90%, 50%, and ~5% for 9, 2, 10, and 1 respectively.

¹³ Both E and Z esters were formed and detected in GC/MS: Rᵢ = 13.4 and 12.8 mins (M⁺ = 192.1).
Oxidative esterification of enal by hydride transfer comparison

A solution of (E)-cinnamaldehyde (56.0 mg, 0.4 mmol, 1.0 equiv), 1,4-naphthoquinone 14 (63.2 mg, 0.4 mmol, 1.0 equiv), and N-methylmorpholine (NMM, 40.0 µL, 1.0 equiv) was prepared using 4.0 mL CH₂Cl₂. This solution was transferred equally (0.5 mL) to four dried vials containing triazolium salts 9, 1, 10, and 2 respectively. ¹H NMR spectra of all four reactions were recorded for the concentrated, unpurified mixture after stirring at 40°C for 6 hours. Both mono and diacylated products were obtained (in 1:1 ratio) in quantitative conversion for catalyst 2, in ~50% for 10, and 0% for 1 and 9 (see ¹H NMR spectra below for comparison). The products 15 and 16 were isolated by preparative TLC in 3:2 hexanes: EtOAc.
Characterization data of both the monoacylated and diacylated products 15 and 16

4-hydroxynaphthalen-1-yl cinnamate (15). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 1H NMR (300 MHz, CDCl$_3$) $\delta$ 8.18-8.15 (m, 1H), 8.02-7.96 (d, $^J = 16$ Hz, 1H), 7.86-7.83 (m, 1H), 7.66-7.63 (m, 2H), 7.54-7.44 (m, 5H), 7.13-7.11 (d, $^J = 6$ Hz, 1H), 6.82-6.76 (d, $^J = 16$ Hz, 1H), 6.77-6.73 (d, $^J = 12$ Hz, 1H), 5.42 (s, 1H). $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 166.05, 149.50, 146.94, 140.25, 134.21, 130.81, 129.06, 128.40, 127.71, 127.00, 125.76, 125.10, 122.16, 121.24, 117.88, 117.08, 107.80. IR (thin film) v 3401, 1703, 1631, 1548, 1386, 1352, 1331, 1260, 1239, 1201, 1146, 1063 cm$^{-1}$; HRMS (ESI) [M+H]$^+$ calcd. for C$_{19}$H$_{15}$O$_3$, 291.1013 found, 291.1016.

$^1$H and $^{13}$C NMR of 4-hydroxynaphthalen-1-yl cinnamate 15
(2E,2′E)-naphthalene-1,4-diyl bis(3-phenylacrylate) (16). ¹H NMR (400 MHz, CDCl₃) δ 8.03-7.95 (m, 4H), 7.67-7.65 (m, 4H), 7.57-7.55 (m, 2H), 7.47-7.37 (m, 8H), 6.84-6.80 (d, ¹J = 16 Hz, 2H). ¹³C NMR (100 MHz, CDCl₃) δ 165.38, 147.20, 144.47, 134.15, 130.89, 129.08, 128.44, 127.84, 126.99, 121.79, 117.77, 116.90, 77.34, 77.22, 77.02, 76.70. IR (thin film) ν 1733, 1634, 1600, 1577, 1329, 1308, 1262, 1244, 1215, 1201, 1131, 1060 cm⁻¹; HRMS (ESI) [M+H]⁺ calcd. for C₂₈H₂₁O₄, 421.1429 found, 421.1434.
$^1$H and $^{13}$C NMR of (2E,2'E)-naphthalene-1,4-diy1 bis(3-phenylacrylate) 16
Additional mechanistic probes

A) Evidence for the irreversibility of the Breslow intermediate

AA) No aldehyde formation observed when α-hydroxyenone was used:

\[
\text{MeCO} \quad \text{MeOH} \quad \text{MeOH} \quad \text{MeOH}
\]

\[
\text{H} \quad \text{H} \quad \text{H} \quad \text{H}
\]

13 observed

56 not observed

AB) No aldehyde H-D exchange during redox esterification:

\[
\text{O} \quad \text{CH}_{3} \text{OH} \quad \text{CH}_{3} \text{Cl} \quad \text{CH}_{3} \text{Cl}
\]

\[
\text{O} \quad \text{D} \quad \text{D} \quad \text{D}
\]

3 1 equiv 1 equiv

4 observed

5 not observed

\[
\text{O} \quad \text{CH}_{3} \text{OH} \quad \text{CH}_{3} \text{Cl} \quad \text{CH}_{3} \text{Cl}
\]

\[
\text{O} \quad \text{D} \quad \text{D} \quad \text{D}
\]

5 1 equiv 1 equiv

4 observed

3 not observed

\[ ^1 \text{H NMR of a representative reaction (2) with N-C}_6\text{F}_5 \text{catalyst 2} \]
**B) An additional evidence for hydride transfer mechanism.**

As an addition confirmation of the proposed hydride transfer mechanism by Csáky,\(^1\(^4\)\) (\(E\))-4-hydroxy-1-(4-methoxyphenyl)-4-methylpent-1-en-3-one 13 was used in place of enal with 1,4-naphthoquinone 14 as the stoichiometric oxidant with all 4 triazolium salts used in this study. We obtained no reaction (starting material recovery) for all four reactions. This showed that the mechanism of oxidation by 1,4-naphthoquinone 14 (hydride transfer) must be different than that with diquinone oxidant 7 (electron-transfer oxidation).\(^1\(^5\)\) With \(\alpha\)-hydroxyenone, the Breslow intermediate \(\text{II}\) is generated directly, does not revert back to the initial adduct \(\text{I}\) (vide supra), and therefore no hydride donor was generated (below).

\[\text{I} \rightarrow \text{III} \]

The proposed mechanism:

\[\text{enal} \xrightarrow{\text{hydride transfer}} \text{III (unsaturated acyl azolium)} \]

\[\text{II (Breslow intermediate)} \]

**C) The Breslow intermediate from \(\alpha\)-methyl cinnamaldehyde is reversible**

\[\text{S7} \xrightarrow{\text{MeOD}} \text{S8} \]


A solution of α-methyl cinnamaldehyde S7 (14.6 mg, 0.1 mmol, 1.0 equiv) and 1-(tert-butyl)-4-methoxybenzene (16.4 mg, 0.1 mmol, 1.0 equiv as internal standard), and 5.0 µL MeOD (0.1 mmol, 1.0 equiv) was prepared using 0.5 mL told8 (with 10% CD2Cl2 to ensure solubility). This solution was transferred (0.5 mL) to an NMR tubes charged with 10 mol% of 2-mesityl-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium chloride 1 or with 10 mol% 2-(perfluorophenyl)-6,7-dihydro-5H-pyrrolo[2,1-c][1,2,4]triazol-2-ium BF4 - 2. The NMR tubes were heated at 40°C in an oil bath, and 1H NMR was used to minor both reactions periodically over 3 hours. The rate of H/D exchange was measured by the disappearance of the aldehyde singlet at 9.50 ppm (1H) against an internal standard peak (9H) at 1.29 ppm (see plots below). The N-C6F5 catalyst is more reversible by 1.5 time than the N-mesityl counterpart.
Extent of deprotonation of triazolium salts and enal titration experiments

**A general procedure:** In an NMR tube charged with triazolium salt (either 9, 2, 10, or 1; 0.05 mmol, 1 equiv) and 0.5 mL (0.1 M) CD$_2$Cl$_2$, 7.5 µL (0.05 mmol, 1.0 equiv) of DBU was added. The mixture was shaken, and $^1$H NMR was recorded (frame C). For triazolium salt 2
and 9, apparent shift of DBU signals indicated complete (if not near) protonation of DBU and hence implies deprotonation of azolium salts. On the contrary, 10 and 1 seemed to be partially deprotonated (not significant shift for DBU peaks). To this mixture, 3.3 µL (0.05 mmol, 1.0 equiv) of cinnamaldehyde was added in, and ¹H NMR was recorded (frame D). After about 5 minutes, an additional 3.3 µL (0.05 mmol, 1.0 equiv) of cinnamaldehyde was added in; ¹H NMR was recorded again (frame E). For N-C₆F₅ catalyst 2, no change was observed in the ¹H NMR spectra as cinnamaldehyde was titrated in. While DBU was protonated, the N-3,4,5-trimethoxy catalyst 9 formed some adduct¹⁶ (based on rapid consumption of enal), which is irreversible¹⁷ and unidentifiable. As for catalysts 10 and 1, DBU became more protonated while cinnamaldehyde was titrated in, which also formed similar catalyst-dead-end adduct. These ¹H NMR spectra were compared against one with only DBU in CD₂Cl₂ (frame A) and another with just triazolium salt in CD₂Cl₂ (frame B).

¹H NMR spectra of the extent of deprotonation of 2 and titration with enal 3

(16) In the absence of other suitable reaction partner, enal seemed to form a complex adduct with NHC catalysts, possibly such as that demonstrated in A. Berkessel, S. Elfert, K. Etzenbach-Effers and J. H. Teles, Angew. Chem., Int. Ed., 2010, 49, 7120–7124.
(17) For example, adding MeOH to any of these complex mixture did not afford redox esterification product. Adding diquinone oxidant 7 and MeOH – a reaction demonstrated to be very rapid – also did not afford any oxidative esterification product.
$^1$H NMR spectra of the extent of deprotonation of 9 and titration with enal 3

A)

B)

C) 1:1 9 + DBU → complete deprotonation

D) 1.0 equiv enal added

E) 2.0 equiv enal added

$^1$H NMR spectra of the extent of deprotonation of 10 and titration with enal 3

A)

B)

C) 1:1 10 + DBU → mostly still DBU

D) 1.0 equiv enal added

E) 2.0 equiv enal added

Partial deprotonation

DBU more protonated
$^1$H NMR spectra of the extent of deprotonation of 1 and titration with enal 3

Intramolecular Stetter reaction comparison

A solution of (E)-methyl 4-(2-formylphenoxy)but-2-enoate 17 (52.8 mg, 0.4 mmol, 1.0 equiv), triethylamine (7.0 µL, 20.0 mol%), and 1,3-di-tert-butylbenzene (0.1 mmol, 0.5 equiv as internal standard) was prepared using 1.2 mL THF-$d_8$. This solution was transferred equally (0.6 mL) to two NMR tubes containing triazolium salts 1 and 2 respectively. The reactions were carried out at room temperature, and $^1$H NMR spectra of both reactions were recorded for the unpurified reaction mixture at 1 and 6 hours. The reaction with $N$-$C_6F_5$ catalyst is more rapid and completed within 1 hour while that with the $N$-mesityl catalyst proceeded more slowly (20% at 6 hours). $^1$H NMR spectra below compared the result. The
identity of methyl 2-(4-oxochroman-3-yl)acetate\textsuperscript{18} \textbf{18} was confirmed by \textsuperscript{1}H NMR and GC/MS: \textsuperscript{1}H NMR (300 MHz, THF-\textit{d}_8): \(\delta\) 7.83-7.80 (m, 1H), 7.46-7.43 (1H), 7.17 (s, 1H), 7.01-6.94 (m, 1H), 4.62-4.57 (m, 1H), 4.32-4.24 (t, 1H), 3.65 (s, 3H), 3.32-3.28 (m, 1H), 2.92-2.85 (m, 1H), 2.51-2.43 (m, 1H). GC/MS (EI): 220 (M\textsuperscript{+}), 207, 189, 147 (100%), 120, 92, 97.

Hetero Diels-Alder reaction comparison

A solution of 2-chloro-3-phenylpropanal \textbf{6} (26.0 mg, 0.4 mmol, 1.0 equiv), triethylamine (20.0 µL, 3.0 equiv), and \((E)\)-methyl 4-oxo-4-phenylbut-2-enoate \textbf{19} (20.0 mg,

0.4 mmol, 1.0 equiv) was prepared using 0.5 mL PhCH₃. This solution was transferred equally to two vials containing chiral triazolium salts 7¹ and 9² respectively. The reactions were carried out at room temperature, and ¹H NMR spectra of both reactions were recorded for the unpurified reaction mixtures at 1 and 18 hours. The reaction with N-mesityl catalyst is more rapid and completed within 1 hour while that with the N-C₆F₅ catalyst proceeded more slowly (47% at 14 hours). The products were isolated by preparative TLC using 10:1 hexanes: EtOAc. ¹H NMR spectra below compared the result. HPLC analysis showed that both the N-mesityl and the N-C₆F₅ catalyst have the same sense of asymmetric induction, despite a different degree of enantioselectivity. The identity of the product 2¹ was confirmed by ¹H NMR and GC/MS: ¹H (300 MHz, CDCl₃): δ 7.63-7.60 (m, 2H), 7.38-7.16 (m, 8H), 5.82-5.79 (d, ¹J = 9 Hz), 3.76 (s, 3H), 3.58-3.52 (dd, ¹J = 16.5 Hz, ²J = 6 Hz), 3.32-3.27 (m, 1H), 3.01-2.80 (m, 1H), 2.75-2.72 (m, 1H). GC/MS (EI): 322.1 (M⁺), 262.0, 231.0, 199.0, 131.0, 105.0, 91.0 (100%), 77.

¹H NMR spectra comparison

Prepared with catalyst:

HPLC trace:

Claisen vs. esterification reaction comparison

Electronic Supplementary Material (ESI) for Chemical Science
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Into an oven dried 4.0 mL vial, 2-((tert-butyldimethylsilyloxy)methyl)-5-hydroxy-4H-pyran-4-one 23 (25.6 mg, 0.10 mmol, 1.0 equiv), (R,S) triazolium precatalyst (1' or 2'; 0.10 equiv), and N-methylmorpholine (NMM; 0.15 equiv), were added, followed by 1.0 mL toluene (0.1 M) and 3-(4-chlorophenyl)propionaldehyde 22 (16.4 mg, 0.10 mmol, 1.0 equiv). The flask was sealed with a polyethylene cap. The resulting solution was heated to 40°C and stirred for 24 hours before it was concentrated. The reaction with chiral N-mesityl catalyst 9' afforded the desired Coates-Claisen annulation product 24 as described previously. The reaction with the chiral N-C₆F₅ catalyst 2' afforded the desired ester product 25 as the sole product, which was isolated as white solid preparative TLC (3:1 hexanes:EtOAc) as the sole product in 60% yield.

**Characterization data**

![Structure](image)

(E)-6-((tert-butyldimethylsilyloxy)methyl)-4-oxo-4H-pyran-3-yl-3-(4-chlorophenyl)acrylate 25. $^1$H NMR (400 MHz, CDCl₃) δ 7.97 (s, 1H), 7.87–7.83 (d, 1H, $^1J = 16$ Hz), 7.53–7.85 (m, 2H), 7.42–7.40 (m, 2H), 6.64–6.60 (d, 1H, $^1J = 16$ Hz), 6.63 (s, 1H), 4.53 (s, 2H), 0.96 (s, 9H); 0.15 (s, 6H); $^{13}$C NMR (100 MHz, CDCl₃) δ 172.83, 167.91, 163.57, 147.47, 146.41, 141.02, 136.93, 132.47, 129.58, 129.33, 61.08, 25.74, 18.27, -5.47. IR (thin film) ν 3106, 2928, 2859, 2359, 1732, 1659, 1635, 1460, 1204, 1146, 1109, 838, 779 cm⁻¹; HRMS (ESI) [M+H]$^+$ calcd. for C₂₁H₂₆ClO₅Si, 421.1233 found, 421.1241.

$^1$H and $^{13}$C NMR of ester 25

$^1$H NMR (400 MHz, CDCl$_3$): 7.97, 7.87, 7.83, 7.53, 7.52, 7.51, 7.42, 7.40, 7.40, 7.38, 6.64, 6.63, 6.63, 6.65, 6.51, 6.53, 6.97, 6.96, 6.95, 6.36, 0.58, 0.55, 0.34.

$^{13}$C NMR (100 MHz, CDCl$_3$): 139, 137, 130, 123, 119, 119, 118, 117, 116, 115, 114, 113, 112, 111, 110, 109, 108, 107, 106, 105, 104, 103, 102, 101, 100, 99, 98, 97, 96, 95, 94, 93, 92, 91, 90, 89, 88, 87, 86, 85, 84, 83, 82, 81, 80, 79, 78, 77, 76, 75, 74, 73, 72, 71, 70, 69, 68, 67, 66, 65, 64, 63, 62, 61, 60, 59, 58, 57, 56, 55, 54, 53, 52, 51, 50, 49, 48, 47, 46, 45, 44, 43, 42, 41, 40, 39, 38, 37, 36, 35, 34, 33, 32, 31, 30, 29, 28, 27, 26, 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0, -1.

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Page S35 of S35