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Divergent NHC-Catalyzed Oxidative Transformations of 3-Bromoenal: Selective Synthesis of 2*H*-Pyran-2-ones and Chiral Dihydropyranones

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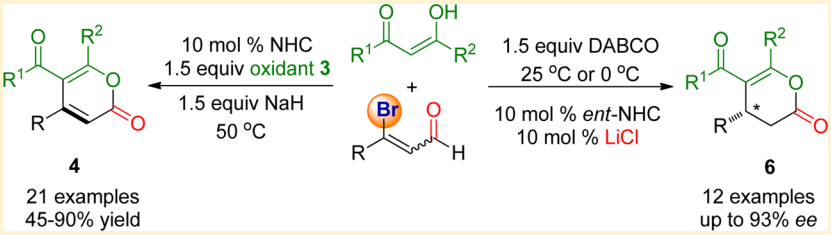
Supporting Information



ABSTRACT: A selective synthesis of either 2*H*-pyran-2-ones (**4**) or chiral dihydropyranones (**6**) from the same substrates of 3-bromoenals and 1,3-dicarbonyl compounds upon oxidative *N*-heterocyclic carbene catalysis is presented. It is shown that the oxidative transformation of 3-bromoenals under NHC catalyst can be well controlled to proceed through two pathways, i.e., elimination of reducible *β*-bromide or by an external oxidant **3**, allowing the selective generation two sorts of unsaturated acyl azoliums, respectively.

INTRODUCTION

Over the past decade, *N*-heterocyclic carbene (NHC) catalysis has developed into a powerful tool for chemical synthesis.[1] Recently, combinations of nucleophilic NHC catalysis and oxidative reactions for exploring sequential umpolung procedures[2] with more diverse substrates have received enormous interest and emerged as an active research area.[3] In this context, *α*,*β*-unsaturated acyl azoliums **I**, generated in situ from carbonyl derivatives upon treatment with NHCs, represent a distinct reactive intermediate for esterifications,[4] amidations,[5] Michael additions,[6] and Claisen rearrangements[7] (Scheme 1). Significant progress has been made by these reactions; however, to our knowledge, the generation of unsaturated acyl azoliums containing embedded functional groups, which may be exploited for further conversion, is yet to be investigated.

We have previously demonstrated that the combination of NHC catalysts with 3-haloenals **1** may generate *β*-halogen substituted Breslow intermediates **II**,[8] which can act as a masked *β*-acylvinyl anion[9] to cyclize with electrophilic carbonyl, diazene, or nitroso compounds, resulting in the formation of several sorts of furan-2-one analogies after subsequent elimination of the halogen, respectively.[10] Notably, in the case of nitrosoarenes,[10b] 3-chloroacrylic acids are competitively formed possibly through the oxidative hydrolysis of the reactive intermediate **II** (Scheme 2a). Triggered by these results, we have focused our attention on the oxidative transformation of substituted 3-haloenals in the presence of NHC catalysts; as a result, we report herein that these transformations could be controlled to proceed via two pathways by employing an external organic oxidant or not, providing access to unsaturated acyl azoliums **III** or **I**, respectively (Scheme 2b). Moreover, both of these resultant species are efficient partners in the cyclization reaction with 1,3-dicarbonyl nucleophiles, resulting in selective formation of either 2*H*-pyran-2-ones[11] or chiral dihyropyranones from same substrates with ease.[12]

RESULTS AND DISCUSSION

Our initial experiments explored the reaction of 3-bromo-3-phenyl-2-propenal (**1a**) with acetyl acetone (**2a**) in the presence of an NHC precursor **C**, oxidant **3** (3,3′,5,5′-tetra-*tert*-butyl-[1,1′-bi(cyclohexane)]-2,2′,5,5′-tetraene-4,4′-dione), and base in THF at 25 °C. As shown in Table 1, using DBU (1.5 equiv) as the base, triazolium salt **C1** gave 2*H*-pyran-2-one **4a** in 30% yield along with dieneone **5a**, arising from a competitive aldol-dehydration reaction between **1a** and **2a**; in contrast, while otherwise identical, triazolium **C2** failed to afford any annulation products (Table 1, entries 1 and 2). Moreover, other two azolium salts of **C3** and **C4** produced **4a** in diminished yield (entries 3 and 4). On the other hand, when employing **C1** as the carbene precursor, the base played a marked influence on this reaction. Switching the base to Et_3N led to **4a** in an improved yield of 43% with a small amount of byproduct **5a** (Table 1, entry 5). To our delight, when a set of inorganic bases such as K_2CO_3, *t*BuOK, and NaH were used, the side reaction to byproduct **5a** was completely suppressed (Table 1, entries 6−8). Still, the use of NaH in THF at 50 °C provided optimal reaction efficiency to afford **4a** in 72% yield,

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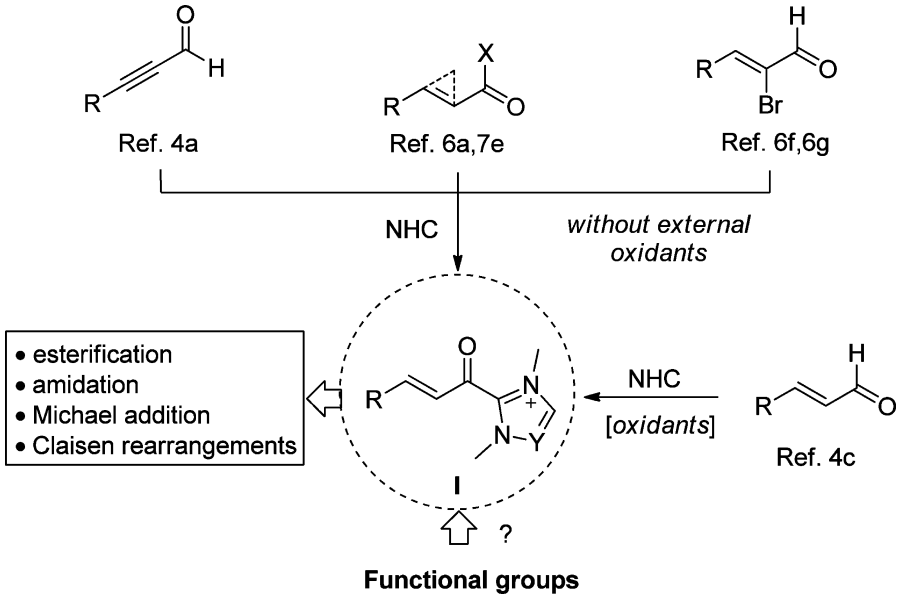
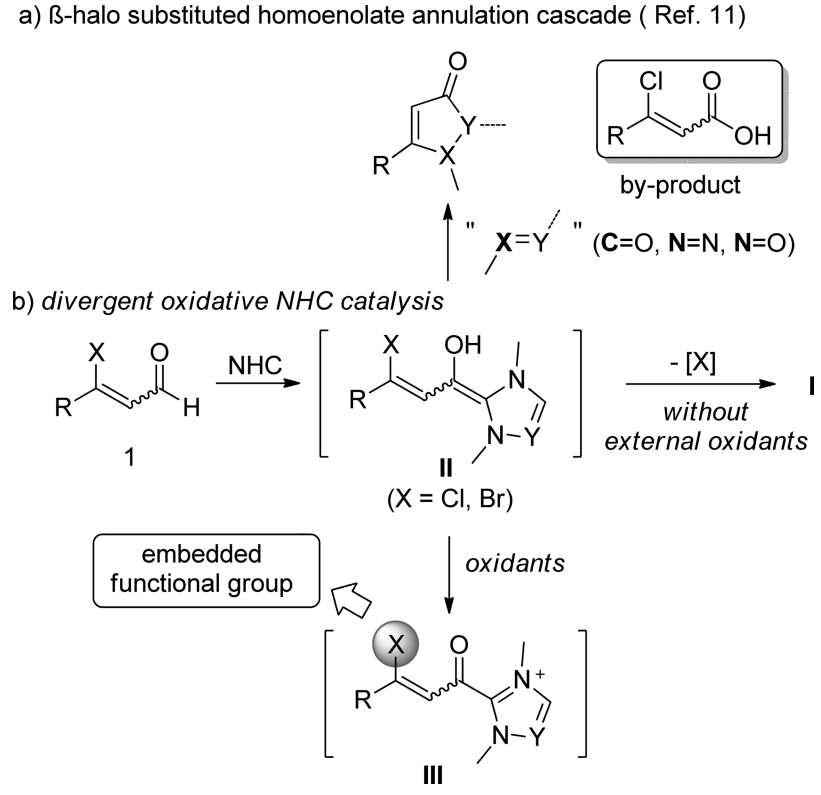
Scheme 1. Generation of α,β-Unsaturated Acyl Azolium Intermediates I



Scheme 2. NHC-Catalyzed Transformations of 3-Haloenals: Homoenolate II versus α,β-Unsaturated Acyl Azolium Ions I and III



while lowering the reaction temperature to −20 °C would lead to a sluggish conversion and reduced yield (entries 9 and 10). Under the optimal conditions, the 3-chloro counterpart of **1a** also produced **4a** but in a lower yield (34%). Interestingly, in the absence of oxidant **3**, a control entry with Et_3N as the base furnished dihydropyranone **6a** instead of **4a** in 65% yield (Table 1, entry 11), whereas that of strong base like NaH only gave trace amounts of **6a** in addition to **5a** (entry 12). These results implicate that an uncovered route to α,β-unsaturated acyl azoliums **I** from enals with a reducible group at the β-position is likely involved, as a complement to those of α-reducible aldehydes.[6f,13]

Subsequently, the substrates scope for the synthesis of 2*H*-pyran-2-ones **4** was evaluated using a range of 1,3-dicarbonyl compounds (Table 2). Symmetrical 1,3-diketones with aliphatic and aromatic substituents rendered the corresponding products **4a−d** in reasonably good yields. Gratifyingly, unsymmetrical 1,3-diketones only afforded *single* product regioisomers. Presumably for electronic effect reasons, the keto function next to the aromatic substituent preferably acted as the

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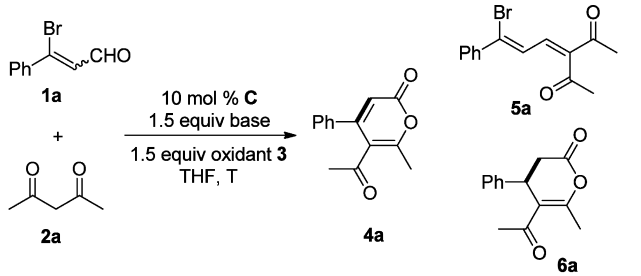
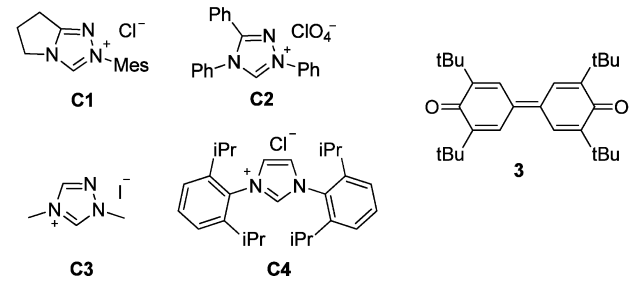
Table 1. Optimization of the Reaction Conditions for 4a[a]

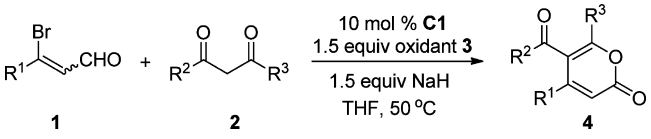


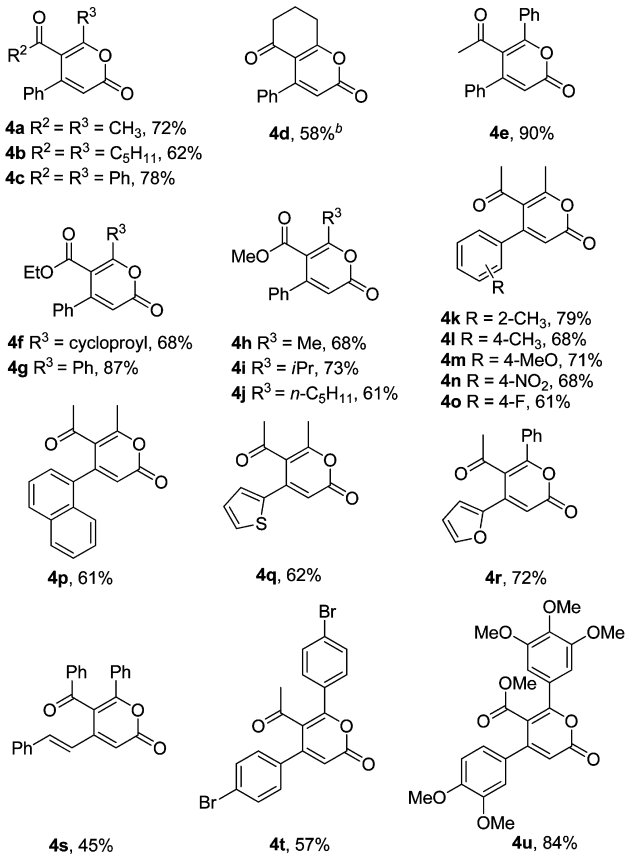


entry	C	base	T (°C)	4a (%)[b]	5a (%)[b]	6a (%)[b]
1	**C1**	DBU	25	30	20	–
2	**C2**	DBU	25	–	31	–
3	**C3**	DBU	25	17	13	–
4	**C4**	DBU	25	17	15	–
5	**C1**	Et_3N	25	43	9	–
6	**C1**	K_2CO_3	25	21	–	–
7	**C1**	*t*BuOK	25	60	–	–
8	**C1**	NaH	25	63	–	–
9	**C1**	NaH	−20	48	–	–
10	**C1**	NaH	50	72 (34)[c]	–	–
11[d]	**C1**	Et_3N	25	–	–	65
12[d]	**C1**	NaH	25	–	20	trace

[a]Reaction conditions: **1a** (0.75 mmol), **2a** (0.5 mmol), catalyst **C** (10 mol %), base (0.75 mmol), and oxidant **3** (0.75 mmol) in THF (10 mL) under N_2. [b]Isolated yield. [c]Yield of **4a** using 3-chloro-3-phenyl-2-propenal instead of **1a** in parentheses. [d]In the absence of **3**. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene.

Table 2. Scope of the NHC-Catalyzed Reaction toward 4[a]





[a]Reaction conditions: **C1** (10 mol %), NaH (1.5 equiv), and oxidant **3** (0.75 mmol) in THF (10 mL) under N_2, and then **1a** (0.75 mmol), **2a** (0.5 mmol) was added at 50 °C. Yield refers to isolated product. [b]Solutions of the corresponding substrates **1** and **2** in THF (2 mL) each were simultaneously added via syringe pumps for 1 h.

nucleophile in the cyclization reaction to give the stable isomers (**4e**, **4r**, and **4t**). Moreover, *β*-keto esters were also found to be good substrates, allowing efficient formation of pyran-2-ones **4f–j** and **4u**. Next, variation in enal partner was examined. Electron-rich and electron-poor aromatic, as well as hetero-aromatic 3-bromoenals all reacted smoothly to produce the desired products **4k–t**. The placement of *o*-substituted phenyl and 1-naphthyl in the *β*-position of enals **1** was tolerated to provide **4k** and **4p** in 79 and 61% yield, respectively, indicating that steric nature in the aromatic moiety of **1** has no negative effects on this reaction. In addition, alkenyl-substituted enal also underwent the reaction to give pyranone **4s**. However, alkyl-substituted 3-bromoenals could not achieve this cyclization reaction under the current reaction conditions.

Next, an asymmetric variation of the aforementioned cyclization of **1a** and **2a** in the absence of oxidant **3** toward dihydropyranone **6a** was explored using a set of chiral NHC precursors instead of **C1** as the catalyst (Table 3). After assessing three chiral azolium salts, we were delighted to find that triazolium catalyst **C5**, developed by Enders,[14] was the most effective to afford product **6a** in 53% *ee* albeit in very low yield (Table 3, entries 2–4). Using **C5** as the catalyst, key results of our optimization (Table 3, entries 5–11) included a sharp improvement in yield when 1,4-diazabicyclo[2.2.2]octane (DABCO) was used as the base to generate the carbene (39% *ee*, entry 8) and the observation that a mixture of Tol/*t*BuOH (v/v = 10/1) was the choice of solvent to furnish the product **6a** in 81% yield and 85% *ee* (entry 11). Moreover, the addition of LiCl (10 mol %) further improved both the yield and *ee* value of product **6a** (94% yield, 92% *ee*, entry 12), indicating that NHC/Lewis acid co-operative catalysis[15] was beneficial for this enantioselective cyclization reaction.[16]

A variety of aromatic 3-bromoenals with electron-donating and electron-withdrawing groups reacted easily with acetyl acetone, generating the corresponding products **6b–e** in moderate to good yields with consistently good enantioselectivites (Table 4). Sterically hindered enal with a methyl group at the *ortho* position was also tolerated to afford compound **6d** in moderate yield still with 90% *ee*. Heteroaromatic substrates like 3-bromo-3-(thiophen-2-yl)acrylaldehyde were also successful in yielding the expected product **6f** with high stereocontrol. Upon replacing the *β*-aryl group of enals with an alkenyl substituent, decreased yield and stereoinduction was observed for the

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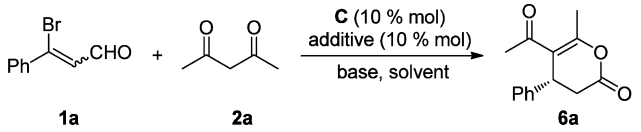
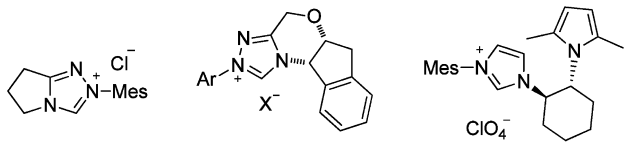
Table 3. Optimization of the Enantioselective Formation of 6a[a]





entry	C	base/additive	solvent	yield[b] (%)	*ee* (%)[c]
1	**C1**	Et_3N	THF	65	–
2	**C5**	Et_3N	THF	12	53
3	**C6**	DABCO	THF	0	–
4	**C7**	*t*BuOK	THF	24	7
5	**C5**	NaH	THF	0	
6	**C5**	DIPEA	THF	trace	
7	**C5**	K_2CO_3	THF	trace	
8	**C5**	DABCO	THF	72	39
9	**C5**	DABCO	toluene	32	80
10	**C5**	DABCO	DMF	44	−17
11	**C5**	DABCO	Tol/*t*BuOH = 10/1	81	85
12	**C5**	DABCO/LiCl	Tol/*t*BuOH = 10/1	94	92

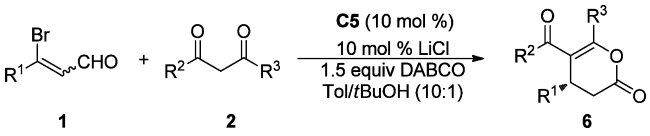
[a]Reaction conditions: **1a** (0.2 mmol), **2a** (0.3 mmol), catalyst (10 mol %), additive (10 mol %), and base (0.3 mmol) in solvent (2 mL) at 25 °C. [b]Isolated yield. [c]Determined by chiral HPLC analysis.

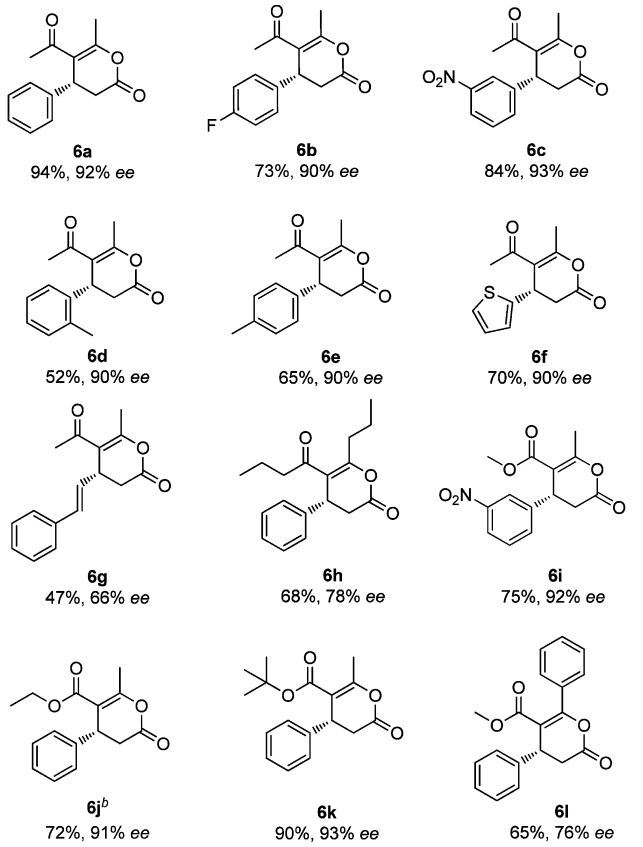
desired product **6g**. Several 1,3-dicarbonyl compounds were also tested in the reaction with **1a**. Symmetrical 1,3-diketones as well as *β*-ketoesters could serve as suitable nucleophiles for this reaction (**6h–l**); nevertheless, possibly due to steric effects, those containing large alkyl groups or aromatic ring substrates provided products (**6h** and **6l**) with slightly lower *ee* values. Finally, the absolute configuration of (*S*)-**6f** was established by X-ray analysis; others were assigned by analogy.

To gain insights into the mechanism, H_2O was used as the nucleophile instead of 1,3-carbonyl compounds **2** to interrupt the current NHC-catalyzed diverse transformations of 3-bromoenals, giving access to cinnamic acid and 3-bromo-3-phenylacrylic acid (**7**) in 71 and 75% yield, respectively (Scheme 3). Moreover, (*E*)-2-hydroxyphenyl 3-phenylacrylate (**8**) could also be isolated in 80% yield from **1a** and pyrocatechol. These results indicated that the unsaturated acylazolium ions **I** and **III** could be formed under these reaction conditions.

On the basis of these experimental results, a postulated catalytic cycle is depicted in Scheme 4. Thus, the addition of in situ generated carbene to 3-bromoenals initially gives conjugated *β*-bromo Breslow intermediates **II** and **II′**. Upon treatment with an external oxidant, *β*-bromo unsaturated acyl azoliums **III** are thereby formed. Attacked by deprotonated 1,3-dicarbonyl compounds **2′**, presumably via 1,4-adducts **IV**,[17] the intermediates **III** undergo subsequent cyclization and elimination of the bromide to furnish 2*H*-pyran-2-ones **4** with liberation of carbene catalyst. On the other hand, in the absence of external oxidants, proton transfer of homoenolate **II′** by a weak base like DABCO would yield ester enolates **V**, which afford azoliums **I** after elimination of bromide. Subsequently,

Table 4. Enantioselective Formation of 6[a]





[a]Reaction conditions: **1a** (0.2 mmol), **2a** (0.3 mmol), **C5** (10 mol %), LiCl (10 mol %), DABCO (1.5 equiv) in toluene/*t*BuOH (v/v = 10:1, 2 mL) at 25 °C. Yield refers to isolated product. The *ee* values were determined by chiral HPLC analysis. [b]At 0 °C.

the Michael addition of 1,3-carbonyl compounds onto **I** followed by ring-closure to provide the annulation product **6** and regenerate the catalyst.

■ CONCLUSION

In summary, we have presented a flexible protocol for the selective synthesis of either chiral dihydropyranones or 2*H*-pyran-2-ones from the same starting materials of 3-bromoenals and 1,3-dicarbonyl compounds upon controlled and divergent NHC-catalyzed oxidative transformations. Mechanistically, taking advantage of the embedded *β*-reducible halogen, the oxidative transformation of 3-bromoenals under NHC catalysis can be well controlled to proceed through either internal or external pathways, allowing the selective generation two sorts of unsaturated acyl azoliums **I** or **III**, respectively. The current research on the reactivity of *β*-bromoenal constitutes a complement to those of *α*-reducible aldehydes in NHC catalysis.

■ EXPERIMENTAL SECTION

General Methods. All reactions were performed under a nitrogen atmosphere, with dry, freshly distilled solvents in anhydrous

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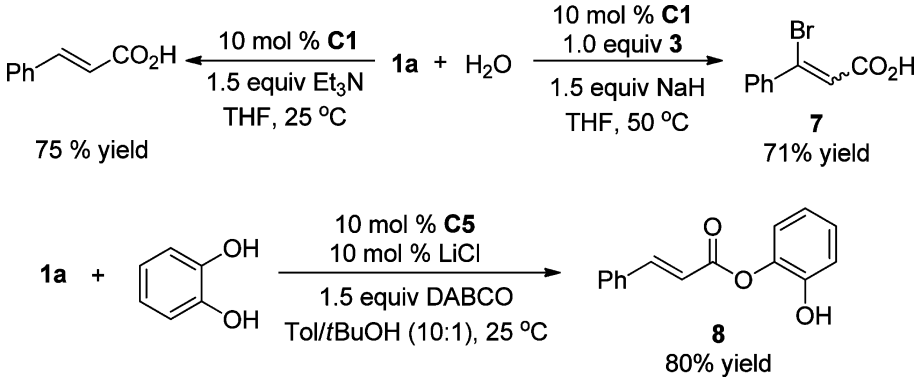
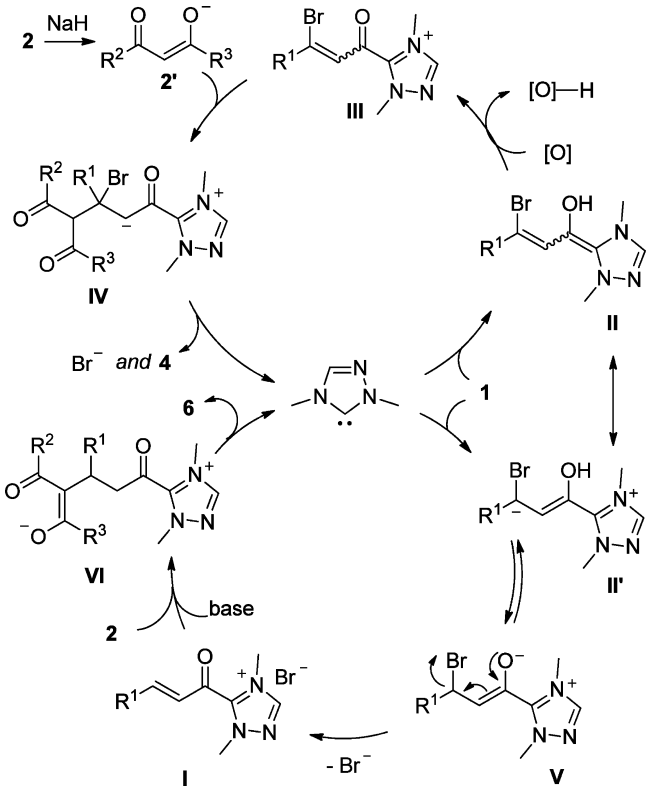
Scheme 3. Interruption of the NHC-Catalyzed Oxidative Conversions of 1a



Scheme 4. Proposed Catalytic Cycle



conditions. Column chromatography was conducted on silica gel (300–400 mesh) using compound-appropriate mixtures of *n*-hexane and EtOAc as eluent. Infrared spectra were recorded as thin films on NaCl plates unless otherwise indicated and are reported in cm^{-1}. HRMS data was collected using a TOF mass spectrometer. ^1H NMR (400 or 500 MHz) and ^{13}C NMR (100 or 125 MHz) spectra were recorded in deuterated solvents and are reported in ppm relative to tetramethylsilane (TMS).

A variety of substituted 3-bromoenals (**1**) were synthesized from the corresponding ketones with Vilsmeier–Haack according to the literature.[10,18] All other chemicals were obtained from commercial sources and used without further purification.

Preparation of 3-Bromoenals. A solution of DMF (15 mmol, 3.0 equiv) in $CHCl_3$ (10 mL) was cooled to 0 °C, followed by the addition of PBr_3 (13.5 mmol, 2.7 equiv) over 15 min. The reaction mixture was stirred for another 1 h at room temperature; during this time, yellow solid precipitated in the solution. Ketone (5 mmol, 1.0 equiv) was added, and the mixture was then stirred overnight. The resulting mixture was poured into ice water, neutralized with K_2CO_3 to pH = 8, and extracted with Et_2O (30 mL × 3). After washing with brine, the organic phase was dried over Na_2SO_4 and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (300–400 mesh) to afford the corresponding compounds **1**.

3-Bromo-3-phenylacrylaldehyde (1a).[18] The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow oil (0.85 g, 81%): ^1H NMR (400 MHz, $CDCl_3$) δ 10.07 (d, J = 6.8 Hz, 1H), 7.72–7.69 (m, 2H), 7.49–7.41 (m, 3H), 6.79 (d, J = 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.6, 189.6, 145.0, 137.4, 131.7, 128.8, 128.1, 127.5.

3-Bromo-3-(*o*-tolyl)acrylaldehyde (1b). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow oil (0.86 g, 76%): ^1H NMR (400 MHz, $CDCl_3$) δ 10.05, 9.13 (d, J = 7.2 Hz, 1H), 7.34–7.24 (m, 4H), 6.79, 6.39 (d, J = 7.2 Hz, 1H), 2.39 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.4, 189.4, 149.4, 144.1, 139.1, 136.2, 135.7, 135.4, 134.9, 131.0, 130.8, 130.8, 130.3, 130.1, 128.9, 128.2, 126.0, 19.9, 19.5; IR (thin film) ν 3062, 2846, 1682, 1609, 1250, 1116, 854, 757 cm^{-1}; HRMS (EI) calculated for $C_{10}H_9BrO$, $[M]^+$, 223.9837, found 223.9845.

3-Bromo-3-(4-nitrophenyl)acrylaldehyde (1c). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow solid (0.91 g, 71%): mp 57–59 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 10.08 (d, J = 6.0 Hz, 1H), 8.31 (d, J = 8.8 Hz, 2H), 7.88 (d, J = 8.8 Hz, 2H), 6.87 (d, J = 6.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.7, 149.3, 143.3, 141.0, 129.9, 129.0, 124.0; IR (KBr) ν 3017, 2853, 1679, 1590, 1518, 1348, 1124, 841 cm^{-1}; HRMS (EI) calculated for $C_9H_6BrNO_3$, $[M]^+$, 254.9531, found 254.9536.

3-Bromo-3-(thiophen-2-yl)acrylaldehyde (1d). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow solid (0.74 g, 68%): mp 50–52 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 10.00 (d, J = 6.4 Hz, 1H), 7.68 (d, J = 3.2 Hz, 1H), 7.57 (d, J = 6.4 Hz, 1H), 7.15 (t, J = 4.0 Hz, 1H), 6.78 (d, J = 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.1, 141.1, 135.3, 131.9, 131.2, 128.4, 124.2; IR (KBr) ν 3130, 2876, 1663, 1383, 1218, 1069, 876, 652 cm^{-1}; HRMS (EI) calculated for C_7H_5BrOS, $[M]^+$, 215.9244, found 215.9238.

3-Bromo-3-(furan-2-yl)acrylaldehyde (1e). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow solid (0.69 g, 69%): mp 68–70 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 10.00–9.96 (m, 1H), 7.61–7.60 (m, 1H), 7.12–7.11 (m, 1H), 6.91–6.87 (m, 1H), 6.57–6.56 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ = 192.8, 192.8, 150.2, 146.7, 129.1, 122.6, 122.6, 118.0, 113.1; IR (KBr) ν 3118, 2869, 1655, 1588, 1468, 1125, 949, 767 cm^{-1}; HRMS (EI) calculated for $C_7H_5BrO_2$, $[M]^+$, 199.9473, found 199.9470.

(4*E*)-3-Bromo-5-phenylpenta-2,4-dienal (1f). The title compound was obtained according to the general procedure described

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above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow solid (0.83 g, 70%): mp 75−78 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.12−9.96 (m, 1H), 7.74−7.39 (m, 6H), 6.87 (d, J = 5.6 Hz, 1H), 6.61−6.48 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.5, 187.0, 144.2, 142.1, 141.9, 134.9, 131.3, 130.3, 130.2, 129.1, 128.9, 128.2, 128.1, 126.4, 121.4; IR (KBr) ν 3024, 2848, 1665, 1610, 1567, 1155, 953, 751 cm^{-1}; HRMS (EI) calculated for $C_{11}H_9BrO$, $[M]^+$, 235.9837, found 235.9841.

3-Bromo-3-(4-bromophenyl)acrylaldehyde (1g). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 30/1) as a yellow solid (1.18 g, 82%): mp 89−92 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.05 (d, J = 6.8 Hz, 1H), 7.58 (s, 4H), 6.78 (d, J = 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.3, 143.3, 136.3, 132.1, 129.4, 127.7, 126.3; IR (KBr) ν 3030, 2861, 1685, 1526, 1127, 849, 753, 694 cm^{-1}; HRMS (EI) calculated for $C_9H_6Br_2O$, $[M]^+$, 287.8785, found 287.8789.

General Procedure for the Synthesis of 2*H*-Pyran-2-one (4). NaH (60%, 30 mg, 0.75 mmol) was added to a suspension of triazolium salt **C1** (13 mg, 0.05 mmol) in anhydrous THF (4 mL) under N_2. The mixture was stirred for 5 min, followed by the addition of 1,3-dicarbonyl compounds **2** (0.5 mmol, 1.0 equiv) and 3,3′,5,5′-tetra-*tert*-butyldiphenoquinone (**3**, 306.5 mg, 0.75 mmol). After stirring for 5 min, a solution of 3-haloenals **1** (0.75 mmol, 1.5 equiv) in THF (1 mL) was added. The mixture was stirred at 50 °C until complete consumption of **2**; the reaction was neutralized by aqueous solution of HCl (1.2 M) and extracted with CH_2Cl_2 (5 mL × 3). After washing with brine (10 mL), the combined organic phase was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was purified by column chromatography to afford compounds **4**.

5-Acetyl-6-methyl-4-phenyl-2*H*-pyran-2-one (4a). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (82.2 mg, 72%): mp 120−122 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50−7.44 (m, 3H), 7.34−7.29 (m, 2H), 6.19 (s, 1H), 2.36 (s, 3H), 1.83 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.7, 162.3, 160.8, 155.1, 136.4, 130.3, 129.4, 127.1, 120.9, 111.8, 31.8, 18.6; IR (KBr) ν 3067, 1740, 1697, 1538, 1389, 1288, 772, 700 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{12}O_3$, $[M]^+$, 228.0786, found 228.0783.

5-Hexanoyl-6-pentyl-4-phenyl-2*H*-pyran-2-one (4b). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 6/1) as a yellow solid (105.6 mg, 62%): mp 32−33 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47−7.42 (m, 3H), 7.31−7.30 (m, 2H), 6.17 (s, 1H), 2.51 (t, J = 6.8 Hz, 2H), 2.00 (t, J = 7.2 Hz, 2H), 1.76−1.72 (m, 2H), 1.36−1.29 (m, 6H), 1.10−1.05 (m, 2H), 0.99−0.89 (m, 5H), 0.76 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ = 203.8, 165.1, 161.2, 155.1, 136.5, 130.1, 129.3, 127.3, 120.4, 111.8, 44.7, 32.0, 31.5, 30.9, 27.7, 23.5, 22.3, 22.1,13.9, 13.8; IR (KBr) ν 3061, 2954, 2930, 2861, 1732, 1693, 1539, 1383 cm^{-1}; HRMS (EI) calculated for $C_{22}H_{28}O_3$, $[M]^+$, 340.2038, found 340.2046.

5-Benzoyl-4,6-diphenyl-2*H*-pyran-2-one (4c). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (137.4 mg, 78%): mp 180−182 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (d, J = 8.0 Hz, 2H), 7.54 (d, J = 7.2 Hz, 2H), 7.39 (t, J = 7.6 Hz, 1H), 7.31−7.28 (m,1H), 7.26−7.19 (m, 9H), 6.36 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 193.8, 160.9, 160.3, 157.2, 137.1, 135.9, 133.7, 131.5, 131.0, 129.5, 129.3, 129.2, 128.7, 128.6, 128.5, 127.5, 117.9, 113.3; IR (KBr) ν 3060, 1724, 1664, 1448, 1372, 1259, 1007, 911 cm^{-1}; HRMS (EI) calculated for $C_{24}H_{16}O_3$, $[M]^+$, 352.1099, found 352.1095.

4-Phenyl-7,8-dihydro-2*H*-chromene-2,5(6*H*)-dione (4d). NaH (60%, 30 mg, 0.75 mmol) was added to a suspension of triazolium salt **C1** (13 mg, 0.05 mmol) in anhyd. THF (4 mL) under N_2. The mixture was heated to 50 °C, followed by the addition of 3,3′,5,5′-tetra-*tert*-butyl-diphenoquinone (**3**, 306.5 mg, 0.75 mmol). After stirring for 5 min, cyclohexane-1,3-dione (56 mg, 0.5 mmol, in 2 mL THF) and 3-bromo-3-phenylacrylaldehyde (158.3 mg, 0.75 mmol, in 2 mL THF) were simultaneously added using syringe pumps for 1 h. The mixture was stirred for additional 30 min and then was neutralized by aqueous solution of HCl (1.2 M), extracted with CH_2Cl_2 (5 mL × 3). After washing with brine (10 mL), the organic phase was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (300−400 mesh) with *n*-hexane/EtOAc 4:1 as an eluent to afford **4d** (69.6 mg, 58%) as a pale yellow solid: mp 166−168 °C (EtOAc/*n*-hexane); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.41−7.37 (m, 3H), 7.20−7.18 (m, 2H), 6.08 (s, 1H), 2.94 (t, J = 6.5 Hz, 2H), 2.54 (t, J = 6.5 Hz, 2H), 2.19−2.14 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 193.1, 174.8, 159.4, 156.6, 137.3, 128.9, 127.9, 127.0, 114.4, 114.2, 38.2, 29.2, 19.8; IR (KBr) ν 3052, 2946, 1759, 1682, 1533, 1393, 1293, 1016 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{12}O_3$, $[M]^+$, 240.0786, found 240.0782.

5-Benzoyl-6-methyl-4-phenyl-2*H*-pyran-2-one (4e). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a white solid (130.9 mg, 90%): mp 137−139 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68−7.65 (m, 2H), 7.48−7.44 (m, 1H), 7.32 (t, J = 6.8 Hz, 2H), 7.22−7.18 (m, 5H), 6.24 (s, 1H), 2.27 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.0, 162.1, 161.1, 156.3, 137.0, 136.0, 133.7, 129.6, 129.1, 128.6, 127.3, 117.9, 111.6, 18.8; IR (KBr) ν 3062, 1736, 1664, 1622, 1543, 1287, 1166, 917 cm^{-1}; HRMS (EI) calculated for $C_{19}H_{14}O_3$, $[M]^+$, 290.0943, found 290.0951.

Ethyl 6-cyclopropyl-2-oxo-4-phenyl-2*H*-pyran-5-carboxylate (4f). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (96.6 mg, 68%): mp 126−128 °C (EtOAc/*n*-hexane); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43−7.40 (m, 3H), 7.31−7.27 (m, 2H), 6.06 (s, 1H), 3.97 (q, J = 7.5 Hz, 2H), 2.39−2.36 (m, 1H), 1.35−1.32 (m, 2H), 1.11−1.08 (m, 2H), 0.84 (t, J = 7.5 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 168.3, 166.2, 160.3, 158.4, 137.5, 129.4, 128.7, 126.6, 111.9, 110.3, 61.5, 13.4, 12.6, 10.1; IR (KBr) ν 3069, 2984, 1721, 1607, 1390, 1254, 1165, 1068 cm^{-1}; HRMS (EI) calculated for $C_{17}H_{16}O_4$, $[M]^+$, 284.1049, found 284.1047.

Ethyl 2-oxo-4,6-diphenyl-2*H*-pyran-5-carboxylate (4g). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a white solid (139.3 mg, 87%): mp 112−114 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66−7.64 (m, 2H), 7.50−7.41 (m, 6H), 7.38−7.36 (m, 2H), 6.28 (s, 1H), 3.93 (q, J = 7.2 Hz, 2H), 2.46 (s, 3H), 0.86 (t, J = 7.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.9, 161.0, 160.5, 156.1, 136.3, 131.7, 131.1, 129.7, 128.7, 128.6, 128.2, 127.0, 113.6, 112.8, 61.9, 13.3; IR (KBr) ν 3060, 2984, 1735, 1618, 1534, 1382, 1263, 1001 cm^{-1}; HRMS (EI) calculated for $C_{20}H_{16}O_4$, $[M]^+$, 320.1049, found 320.1053.

Methyl 6-methyl-2-oxo-4-phenyl-2*H*-pyran-5-carboxylate (4h). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (83.0 mg, 68%): mp 81−83 °C (EtOAc/*n*-hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.41 (m, 3H), 7.29−7.27 (m, 2H), 6.17 (s, 1H), 3.51 (s, 3H), 2.45 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.4, 164.5, 160.7, 155.9, 137.0, 129.6, 128.7, 126.5, 112.6, 111.8, 52.3, 19.1 ppm; IR (KBr) ν 3065, 2951, 1713, 1630, 1546, 1443, 1293, 1086 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{12}O_4$, $[M]^+$, 244.0736, found 244.0733.

Methyl 6-isopropyl-2-oxo-4-phenyl-2*H*-pyran-5-carboxylate (4i). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a pale yellow oil (99.3 mg, 73%): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.40 (m, 3H), 7.31−7.29 (m, 2H), 6.16 (s, 1H), 3.52 (s, 3H), 3.19−3.09 (m, 1H), 1.32 ppm (d, J = 6.8 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.5, 166.4, 160.9, 155.8, 136.8, 129.7, 128.8, 126.6, 111.8, 111.4, 52.4, 31.5, 20.2 ppm; IR (thin

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film) ν 3062, 2926, 1719, 1629, 1544, 1439, 1270, 1081 cm^{-1}; HRMS (EI) calculated for $C_{16}H_{16}O_4$, $[M]^+$, 272.1049, found 272.1043.

Methyl 2-oxo-6-pentyl-4-phenyl-2*H*-pyran-5-carboxylate (4j). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 6/1) as a colorless oil (91.6 mg, 61%): ^1H NMR (400 MHz, $CDCl_3$) δ 7.43−7.41 (m, 3H), 7.30−7.28 (m, 2H), 6.17 (s, 1H), 3.51 (s, 3H), 2.68 (t, J = 8.0 Hz, 2H), 1.79−1.73 (m, 2H), 1.37−1.34 (m, 4H), 0.91 ppm (t, J = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.7, 166.4, 160.8, 155.8, 136.9, 129.6, 128.7, 126.6, 112.5, 111.7, 52.3, 32.4, 31.3, 27.4, 22.3, 13.9 ppm; IR (thin film) ν 3059, 2965, 2926, 2857, 1730, 1623, 1534, 1369 cm^{-1}; HRMS (EI) calculated for $C_{18}H_{20}O_4$, $[M]^+$, 300.1362, found 300.1364.

5-Acetyl-6-methyl-4-*o*-tolyl-2*H*-pyran-2-one (4k). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (95.7 mg, 79%): mp 127−129 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (t, J = 7.6 Hz, 1H), 7.28−7.24 (m, 2H), 7.10 (d, J = 7.6 Hz, 1H), 6.08 (s, 1H), 2.36 (s, 3H), 2.25 (s, 3H), 1.75 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.9, 162.7, 160.6, 155.4, 136.1, 134.7, 131.1, 129.7, 127.9, 126.4, 121.7, 112.8, 31.3, 19.8, 19.0; IR (KBr) ν 3070, 1755, 1686, 1538, 1382, 1287, 873, 769 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{14}O_3$, $[M]^+$, 242.0943, found 242.0948.

5-Acetyl-6-methyl-4-*p*-tolyl-2*H*-pyran-2-one (4l). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (82.4 mg, 68%): mp 134−136 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.28−7.21 (m, 4H), 6.17 (s, 1H), 2.41 (s, 3H), 2.34 (s, 3H), 1.85 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.9, 162.0, 160.8, 155.0, 140.6, 133.4, 130.0, 127.0, 120.8, 111.3, 31.8, 21.3, 18.5 ppm; IR (KBr) ν 3061, 1732, 1615, 1537, 1382, 1285, 897, 816 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{14}O_3$, $[M]^+$, 242.0943, found 242.0940.

5-Acetyl-4-(4-methoxyphenyl)-6-methyl-2*H*-pyran-2-one (4m). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (91.7 mg, 71%): mp 115−117 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.27 (d, J = 8.4 Hz, 2H), 6.97 (d, J = 8.4 Hz, 2H), 6.15 (s, 1H), 3.86 (s, 3H), 2.34 (s, 3H), 1.87 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.1, 162.0, 161.4, 161.0. 154.7, 128.7, 128.5, 120.9, 114.8, 110.9, 55.4, 31.9, 18.6; IR (KBr) ν 3067, 1732, 1682, 1610, 1514, 1252, 899, 849 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{14}O_4$, $[M]^+$, 258.0892, found 258.0893.

5-Acetyl-6-methyl-4-(4-nitrophenyl)-2*H*-pyran-2-one (4n). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (81.3 mg, 68%): mp 150−152 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, J = 8.0 Hz, 2H), 7.47 (d, J = 8.0 Hz, 2H), 6.15 (s, 1H), 2.31 (s, 3H), 1.85 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 198.5, 162.1, 158.8, 151.6, 147.7, 141.5, 127.3, 123.5, 119.1, 112.0, 31.1, 17.9; IR (KBr) ν 3059, 1740, 1669, 1615, 1542, 1291, 1154, 923 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{11}NO_5$, $[M]^+$, 273.0637, found 273.0631.

5-Acetyl-4-(4-fluorophenyl)-6-methyl-2*H*-pyran-2-one (4o). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (75.0 mg, 61%): mp 127−128 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.36−7.29 (m, 2H), 7.19−7.15 (m, 2H), 6.16 (s, 1H), 2.35 (s, 3H), 1.87 (s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.6, 163.9 (J_{C-F} = 249.8 Hz), 162.4, 160.6, 154.0, 132.4 (J_{C-F} = 3.9 Hz), 129.2 (J_{C-F} = 8.3 Hz), 120.7, 116.6 (J_{C-F} = 21.1 Hz), 111.9, 31.9, 18.6 ppm; IR (KBr) ν 3059, 1736, 1699, 1508, 1287, 1225, 850, 841 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{11}FO_3$, $[M]^+$, 246.0692, found 246.0687.

5-Acetyl-6-methyl-4-(naphthalen-1-yl)-2*H*-pyran-2-one (4p). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (84.8 mg, 61%): mp 167−169 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.96−7.90 (m, 2H), 7.80 (d, J = 8.0 Hz, 1H), 7.55−7.50 (m, 3H), 7.35 (d, J = 7.2 Hz, 1H), 6.29 (s, 1H), 2.42 (s, 3H), 1.55 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.7, 163.0, 160.5, 154.3, 134.0, 133.6, 130.3, 129.9, 128.7, 127.5, 127.0, 126.0, 125.3, 124.7, 122.1, 113.8, 31.2, 19.1; IR (KBr) ν 3062, 1736, 1686, 1524, 1283, 1247, 1055, 890 cm^{-1}; HRMS (EI) calculated for $C_{18}H_{14}O_3$, $[M]^+$, 278.0943, found 278.0948.

5-Acetyl-6-methyl-4-(thiophen-2-yl)-2*H*-pyran-2-one (4q). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (72.6 mg, 62%): mp 94−96 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.52−7.50 (m, 1H), 7.16−7.11 (m, 2H), 6.27 (s, 1H), 2.31 (s, 3H), 2.08 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.1, 161.3, 160.6, 147.1, 137.0, 129.4, 129.0, 128.7, 120.2, 110.8, 32.0, 18.5; IR (KBr) ν 3097, 1728, 1689, 1544, 1382, 1247, 889, 743 cm^{-1}; HRMS (EI) calculated for $C_{12}H_{10}O_3S$, $[M]^+$, 234.0351, found 234.0359.

5-Acetyl-4-(furan-2-yl)-6-phenyl-2*H*-pyran-2-one (4r). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (100.8 mg, 72%): mp 170−172 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 6.8 Hz, 2H), 7.62 (t, J = 6.8 Hz, 2H) 7.48 (t, J = 6.8 Hz, 1H), 7.37 (s, 1H), 6.59 (d, J = 6.8 Hz, 1H), 6.56 (s, 1H), 6.34−6.33 (m, 1H), 2.15 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.1, 161.6, 160.8, 147.3, 145.4, 142.2, 136.7, 134.4, 129.3, 129.1, 114.8, 114.4, 112.7, 106.0, 18.8; IR (KBr) ν 3133, 3117, 1713, 1664, 1624, 1579, 1298, 1023 cm^{-1}; HRMS (EI) calculated for $C_{17}H_{12}O_4$, $[M]^+$, 280.0736, found 280.0734.

(*E*)-5-Benzoyl-6-phenyl-4-styryl-2*H*-pyran-2-one (4s). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 4/1) as a yellow solid (85.1 mg, 45%): mp 171−174 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.80−7.78 (m, 2H), 7.54−7.52 (m, 2H), 7.46−7.44 (m, 1H), 7.35−7.29 (m, 9H), 7.27−7.22 (m, 2H); 6.71 (d, J = 16.0 Hz, 1H), 6.62 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.5, 161.4, 159.9, 152.0, 137.9, 137.0, 135.3, 134.2, 131.6, 131.0, 129.7, 129.5, 128.8, 128.8, 128.7, 128.5, 127.6, 121.6, 117.0, 107.5; IR (KBr) ν 3069, 1713, 1659, 1597, 1492, 1447, 1382, 959 cm^{-1}; HRMS (EI) calculated for $C_{26}H_{18}O_3$, $[M]^+$, 378.1256, found 378.1262.

5-Acetyl-4,6-bis(4-bromophenyl)-2*H*-pyran-2-one (4t). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (104.8 mg, 47%): mp 181−183 °C (EtOAc/*n*-hexane); ^1H NMR (500 MHz, $CDCl_3$) δ 7.56−7.50 (m, 4H), 7.38−7.36 (m, 2H), 7.06−7.04 (m, 2H), 6.21 (s, 1H), 2.25 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.8, 162.6, 160.6, 154.8, 135.7, 134.7, 132.3, 132.1, 130.6, 129.6, 128.8, 124.5, 117.1, 112.0, 19.0; IR (KBr) ν 3060, 1741, 1666, 1625, 1549, 1294, 1171, 924 cm^{-1}; HRMS (EI) calculated for $C_{19}H_{12}Br_2O_3$, $[M]^+$, 445.9153, found 445.9151.

Methyl 4-(3,4-dimethoxyphenyl)-2-oxo-6-(3,4,5-trimethoxyphenyl)-2*H*-pyran-5-carboxylate (4u). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (191.7 mg, 84%): mp 100−102 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 6.96−6.91 (m, 5H), 6.27 (s, 1H), 3.93 (s, 3H), 3.91 (s, 3H), 3.90 (s, 3H), 3.88 (s, 6H), 3.54 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.0, 160.5, 160.1, 155.5, 153.1, 150.4, 149.0, 140.5, 128.4, 126.6, 119.8, 113.1, 111.7, 111.1, 110.0, 105.4, 60.9, 56.1, 55.8, 52.8 ; IR (KBr) ν 2943, 2840, 1729, 1583, 1513, 1422, 1352, 1130 cm^{-1}; HRMS (EI) calculated for $C_{24}H_{24}O_9$, $[M]^+$, 456.1420, found 456.1424.

(*Z*)-3-(3-Bromo-3-phenylallylidene)pentane-2,4-dione (5a). The title compound was obtained as a byproduct of **4a** when DBU was used as base after flash column chromatography (eluting with *n*-hexane/EtOAc 3/1) as a yellow solid (29.3 mg, 20%): mp 104−106 °C (EtOAc/*n*-hexane); ^1H NMR (400 MHz, $CDCl_3$) δ 7.66−7.64 (m, 2H), 7.58 (d, J = 10.8 Hz, 1H), 7.40−7.37 (m, 3H), 7.21 (d, J = 10.8

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Hz, 1H), 2.47 (s, 3H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.9, 197.5, 143.6, 139.5, 139.0, 138.5, 130.6, 128.7, 128.2, 123.9, 31.7, 26.5; IR (KBr) ν 3059, 2924, 1663, 1599, 1247, 1183, 1154, 761 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{13}BrO_2$, $[M]^+$ 292.0099, found 292.0097.

General Procedure for the Synthesis of 3,4-Dihydro-2*H*-pyran-2-one (6). DABCO (34.8 mg, 0.3 mmol) was added to a mixture of 3-bromoenals **1** (0.2 mmol), 1,3-dicarbonyl compounds **2** (0.3 mmol, 1.5 equiv), chiral triazolium salt **C5** (7.7 mg, 0.02 mmol), and LiCl (0.85 mg, 0.02 mmol) in toluene/*t*BuOH (2 mL, v/v = 10:1) in a Schlenk tube under N_2 at 25 °C. The reaction mixture was stirred for 1 h until complete consumption of **1** (detected by TLC). The reaction was then quenched with H_2O (5 mL) and extracted with CH_2Cl_2 (5 mL × 3). After washing with brine (10 mL), the combined organic phase was dried over anhydrous Na_2SO_4 and concentrate under reduced pressure. The residue was purified by column chromatography on silica gel (300−400 mesh) to afford compounds **6**.

(*R*)-5-Acetyl-6-methyl-4-phenyl-3,4-dihydro-2*H*-pyran-2-one (6a). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a white solid (43.2 mg, 94%, 92% *ee*): $[\alpha]_D^{20}$ = −116.1 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36−7.32 (m, 2H), 7.29−7.27 (m, 1H), 7.16−7.14 (m, 2H), 4.15 (d, J = 6.0 Hz, 1H), 2.97 (dd, J_1 = 16.0 Hz, J_2 = 7.6 Hz, 1H), 2.83 (dd, J_1 = 16.0 Hz, J_2 = 2.8 Hz, 1H), 2.43 (s, 3H), 2.12 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.9, 165.6, 160.3, 139.7, 129.4, 128.0, 126.7, 117.3, 38.8, 37.2, 29.8, 19.1; IR (thin film) ν 3029, 1783, 1690, 1493, 1360, 1173, 1115, 1026 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{14}O_3$, $[M]^+$, 230.0943, found 230.0939. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 15.34 min (minor), t_R = 19.56 min (major).

(*R*)-5-Acetyl-4-(4-fluorophenyl)-6-methyl-3,4-dihydro-2*H*-pyran-2-one (6b). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a pale yellow solid (36.2 mg, 74%, 90% *ee*): $[\alpha]_D^{20}$ = −120.6 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.14−7.11 (m, 2H), 7.05−7.00 (m, 2H), 4.16 (d, J = 6.4 Hz, 1H), 2.96 (dd, J_1 = 15.6 Hz, J_2 = 7.2 Hz, 1H), 2.81 (dd, J_1 = 15.6 Hz, J_2 = 2.4 Hz, 1H) 2.43 (s, 3H), 2.14 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.6, 165.4, 162.3 (J_{C-F} = 246.3 Hz), 160.5, 135.5 (J_{C-F} = 3.2 Hz), 128.4 (J_{C-F} = 7.9 Hz), 117.4, 116.4 (J_{C-F} = 22 Hz), 38.1, 37.2, 29.8, 19.2; IR (thin film) ν 2923, 1784, 1690, 1606, 1509, 1360, 1225, 1115 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{13}FO_3$, $[M]^+$, 248.0849, found 248.0846. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 14.33 min (minor), t_R = 18.91 min (major).

(*R*)-5-Acetyl-6-methyl-4-(3-nitrophenyl)-3,4-dihydro-2*H*-pyran-2-one (6c). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 2/1) as a yellow solid (46.2 mg, 84%, 93% *ee*): $[\alpha]_D^{20}$ = −176.2 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 8.15 (d, J = 8.0 Hz, 1H), 8.04 (s, 1H), 7.55 (t, J = 8.0 Hz, 1H), 7.50 (d, J = 7.6 Hz, 1H), 4.37 (d, J = 6.8 Hz, 1H), 3.04 (dd, J_1 = 15.6 Hz, J_2 = 7.2 Hz, 1H), 2.88 (J_1 = 15.6 Hz, J_2 = 2.4 Hz, 1H), 2.49 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.7, 164.9, 161.5, 148.9, 142.1, 132.7, 130.6, 123.1, 122.0, 117.0, 38.2, 36.6, 30.3, 19.6; IR (thin film) ν 2924, 1785, 1654, 1529, 1348, 1113, 1050, 944 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{13}NO_5$, $[M]^+$, 275.0794, found 275.0790. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 70:30, flow rate = 0.8 mL/min), t_R = 17.91 min (minor), t_R = 26.91 min (major).

(*R*)-5-Acetyl-6-methyl-4-*o*-tolyl-3,4-dihydro-2*H*-pyran-2-one (6d). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a white solid (25.4 mg, 52%, 90% *ee*): $[\alpha]_D^{20}$ = −165.4 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20−7.13 (m, 3H), 6.98−6.96 (m, 1H), 4.35 (d, J = 7.2 Hz, 1H), 2.93 (dd, J_1 = 15.6 Hz, J_2 = 7.2 Hz, 1H), 2.72 (J_1 = 15.6 Hz, J_2 = 2.6 Hz, 1H), 2.45 (s, 3H), 2.40 (s, 3H), 2.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.9, 164.6, 159.5, 136.2, 133.7, 130.4, 126.9, 124.5, 116.3, 34.5, 34.0, 28.3, 18.2, 18.0; IR (thin film) ν 2926, 1686, 1676, 1615, 1597, 1443, 1332, 1171 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{16}O_3$, $[M]^+$, 244.1099, found 244.1101. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 17.23 min (minor), t_R = 18.46 min (major).

(*R*)-5-Acetyl-6-methyl-4-*p*-tolyl-3,4-dihydro-2*H*-pyran-2-one (6e). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a white solid (31.7 mg, 65%, 90% *ee*): $[\alpha]_D^{20}$ = −43.2 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13 (d, J = 8.4 Hz, 2H), 7.03 (d, J = 8.0 Hz, 2H), 4.10 (d, J = 6.8 Hz, 1H), 2.94 (dd, J_1 = 15.6 Hz, J_2 = 7.2 Hz, 1H), 2.81 (J_1 = 15.6 Hz, J_2 = 2.8 Hz, 1H), 2.42 (s, 3H), 2.31 (s, 3H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.1, 165.8, 160.1, 137.7, 136.7, 130.1, 126.6, 117.4, 38.5, 37.3, 29.7, 21.0, 19.1; IR (thin film) ν 2923, 1784, 1692, 1514, 1420, 1359, 1171, 1114 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{16}O_3$, $[M]^+$, 244.1099, found 244.1100. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 15.84 min (minor), t_R = 19.44 min (major).

(*S*)-5-Acetyl-6-methyl-4-(thiophen-2-yl)-3,4-dihydro-2*H*-pyran-2-one (6f). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a white solid (33 mg, 70%, 90% *ee*): $[\alpha]_D^{20}$ = −19.8 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.17 (d, J = 5.2 Hz, 1H), 6.92−6.89 (m, 1H), 6.82 (d, J = 3.6 Hz,1H), 4.53 (d, J = 6.4 Hz, 1H), 3.76 (s, 3H), 3.01 (dd, J_1 = 16.0 Hz, J_2 = 2.0 Hz, 1H), 2.93 (dd, J_1 = 16.0 Hz, J_2 = 6.8 Hz, 1H) 2.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.1, 165.8, 162.1, 143.5, 127.1, 124.7, 124.1, 110.3, 52.0, 36.5, 32.9, 19.0; IR (thin film) ν 2922, 1784, 1689, 1609, 1379, 1277, 1145, 1115 cm^{-1}; HRMS (EI) calculated for $C_{12}H_{12}O_3S$, $[M]^+$, 236.0507, found 236.0502. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 17.13 min (minor), t_R = 20.79 min (major).

(*R*,*E*)-5-Acetyl-6-methyl-4-styryl-3,4-dihydro-2*H*-pyran-2-one (6g). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a white solid (25.4 mg, 47%, 66% *ee*): $[\alpha]_D^{20}$ = −12.8 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34−7.29 (m, 4H), 7.26−7.25 (m, 1H), 6.44 (d, J = 12.8 Hz, 1H), 6.10 (dd, J_1 = 12.8 Hz, J_2 = 6.8 Hz, 1H), 3.76−3.75 (m, 1H), 2.83−2.81 (m, 2H), 2.38 (s, 3H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.3, 160.8, 155.1, 130.7, 126.8, 123.4, 122.8, 121.6, 121.3, 111.9, 30.4, 29.4, 24.7, 14.1; IR (thin film) ν 2929, 1795, 1687, 1523, 1419, 1365, 1177, 1113 cm^{-1}; HRMS (EI) calculated for $C_{16}H_{16}O_3$, $[M]^+$, 256.1099, found 256.1097. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 24.24 min (minor), t_R = 33.61 min (major).

(*R*)-5-Butyryl-4-phenyl-6-propyl-3,4-dihydro-2*H*-pyran-2-one (6h). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a colorless oil (39.0 mg, 68%, 78% *ee*): $[\alpha]_D^{20}$ = −99.7 (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35−7.32 (m, 2H), 7.29−7.26 (m, 1H), 7.16−7.14 (m, 2H), 4.12−4.11 (m, 1H), 2.94 (dd, J_1 = 16.0 Hz, J_2 = 7.5 Hz, 1H), 2.81 (dd, J_1 = 16.0 Hz, J_2 = 3.5 Hz, 1H), 2.72−2.63 (m, 2H), 2.45−2.40 (m, 1H), 2.23−2.16 (m, 1H), 1.76−1.72 (m, 2H), 1.52−1.44 (m, 2H), 1.02 (t, J = 7.5 Hz, 3H), 0.76 (t, J = 7.5 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 200.8, 166.0, 162.2, 139.7, 129.4, 127.9, 126.7, 117.5, 43.3, 38.8, 37.4, 33.5, 20.8, 17.3, 13.8, 13.6; IR (thin film) ν 2963, 2874, 1783, 1688, 1608, 1454, 1170, 1115 cm^{-1}; HRMS (EI) calculated for $C_{18}H_{22}O_3$, $[M]^+$, 286.1569, found 286.1572. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 10.61 min (minor), t_R = 13.28 min (major).

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(*R*)-Methyl 6-methyl-4-(3-nitrophenyl)-2-oxo-3,4-dihydro-2*H*-pyran-5-carboxylate (6i). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 5/1) as a colorless oil (43.7 mg, 75%, 92% *ee*): $[\alpha]_D^{20}$ = −237.7 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (m, 1H), 8.03 (m, 1H), 7.54−7.46 (m, 2H), 4.39 (d, J = 6.8 Hz, 1H), 3.71 (s, 3H), 3.03 (dd, J_1 = 16.4 Hz, J_2 = 8.0 Hz, 1H), 2.86 (dd, J_1 = 16.4 Hz, J_2 = 2.0 Hz, 1H), 2.53 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 164.1, 162.0, 147.7, 141.6, 131.6, 129.2, 121.8, 121.0, 107.6, 51.2, 36.6, 35.1, 18.1 ppm; IR (thin film) ν 2953, 1787, 1719, 1648, 1530, 1351, 1118, 1077 cm^{-1}; HRMS (EI) calculated for $C_{14}H_{13}NO_6$, $[M]^+$, 291.0743, found 291.0750. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 70:30, flow rate = 0.8 mL/min), t_R = 14.86 min (minor), t_R = 39.78 min (major).

(*R*)-Ethyl 6-methyl-2-oxo-4-phenyl-3,4-dihydro-2*H*-pyran-5-carboxylate (6j). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 8/1) as a colorless oil (37.5 mg, 72%, 91% *ee*): $[\alpha]_D^{20}$ = −151.3 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.23 (m, 3H), 7.14 (d, J = 7.2 Hz, 2H), 4.26 (d, J = 7.2 Hz, 1H), 4.13 (q, J = 7.2 Hz, 2H), 2.95 (dd, J_1 = 16.0 Hz, J_2 = 7.2 Hz, 1H), 2.82 (dd, J_1 = 16.0 Hz, J_2 = 2.0 Hz, 1H), 2.47 (s, 3H), 1.19 (t, 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.2, 166.0, 161.3, 140.7, 129.0, 127.5, 126.6, 110.0, 60.9, 37.8, 36.4, 18.9, 14.1; IR (thin film) ν 2983, 1787, 1713, 1454, 1369, 1244, 1148, 1029 cm^{-1}; HRMS (EI) calculated for $C_{15}H_{16}O_4$, $[M]^+$, 260.1049, found 260.1053. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 90:10, flow rate = 0.8 mL/min), t_R = 11.05 min (minor), t_R = 18.95 min (major).

(*R*)-*tert*-Butyl 6-methyl-2-oxo-4-phenyl-3,4-dihydro-2*H*-pyran-5-carboxylate (6k). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 8/1) as a colorless oil (51.9 mg, 90%, 93% *ee*): $[\alpha]_D^{20}$ = −146.9 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.22 (m, 3H), 7.14−7.12 (m, 2H), 4.18−4.16 (m, 1H), 2.94 (dd, J_1 = 15.6 Hz, J_2 = 7.6 Hz, 1H), 2.79 (dd, J_1 = 15.6 Hz, J_2 = 3.2 Hz, 1H), 2.43 (s, 3H), 1.35 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.3, 165.1, 160.1, 140.9, 128.8, 127.3, 126.5, 111.3, 81.3, 38.2, 36.3, 27.9, 18.6; IR (thin film) ν 2977, 1787, 1709, 1652, 1368, 1249, 1172, 1116 cm^{-1}; HRMS (EI) calculated for $C_{17}H_{20}O_4$, $[M]^+$, 288.1362, found 288.1366. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 9.44 min (minor), t_R = 15.05 min (major).

(*R*)-Methyl 2-oxo-4,6-diphenyl-3,4-dihydro-2*H*-pyran-5-carboxylate (6l). The title compound was obtained according to the general procedure described above after flash column chromatography (eluting with *n*-hexane/EtOAc 6/1) as a pale yellow oil (40.1 mg, 65%, 76% *ee*): $[\alpha]_D^{20}$ = −54.7 (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.52−7.50 (m, 2H), 7.44−7.39 (m, 3H), 7.34−7.31 (m, 2H), 7.27−7.23 (m, 3H), 4.41−4.39 (m, 1H), 3.45 (s, 3H), 3.08 (dd, J_1 = 16.0 Hz, J_2 = 7.5 Hz, 1H), 2.92 (dd, J_1 = 16.0 Hz, J_2 = 3.5 Hz, 1H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 166.8, 165.9, 158.7, 139.7, 132.9, 130.2, 129.2, 128.5, 128.0, 127.8, 126.7, 112.3, 51.9, 38.8, 36.3; IR (thin film) ν 2951, 1783, 1710, 1653, 1494, 1350, 1116, 1068 cm^{-1}; HRMS (EI) calculated for $C_{19}H_{16}O_4$, $[M]^+$, 308.1049, found 308.1045. The *ee* value was determined by HPLC with Chiralpack OD−H column at 254 nm (hexane/*i*PrOH = 85:15, flow rate = 0.8 mL/min), t_R = 19.42 min (minor), t_R = 22.89 min (major).

3-Bromo-3-phenylacrylic acid (7).[19] White solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.79 (b, 1H), 7.67−7.65 (m, 2H), 7.44−7.38 (m, 3H), 6.79 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.7, 140.8, 139.2, 130.9, 128.6, 128.3, 119.5; HRMS (EI) calculated for C_9H_7BrO, $[M]^+$, 209.9680, found 209.9687.

2-Hydroxyphenyl cinnamate (8).[20] White solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 15.6 Hz, 1H), 7.58−7.57 (m, 2H), 7.43−7.42 (m, 3H), 7.16−7.11 (m, 2H), 7.01 (d, J = 8.0 Hz, 1H), 6.94 (t, J = 8.0 Hz, 1H), 6.66 (d, J = 15.6 Hz, 1H), 5.75 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.4, 147.8, 147.2, 138.7, 133.9, 131.0, 129.0, 128.5, 127.1, 122.4, 121.0, 118.0, 116.3; HRMS (EI) calculated for $C_{15}H_{12}O_2$, $[M]^+$, 224.0837, found 224.0832.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Copies of ^{1}H and ^{13}C spectra for all new compounds, HPLC spectra of chiral products **6**; X-ray crystallographic data (in CIF format) for compound (*S*)-**6f**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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