# Enantioselective Organocatalytic Michael Addition of Cyclopentane-1,2-diones to Nitroolefins

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**Abstract:** Organocatalytic Michael additions of cyclopentane-1,2-dione to different nitroolefins have been investigated. Cyclopentane-1,2-dione undergoes an organocatalytic reaction with substituted nitroolefins giving 3-substituted products in good to high yields (48–97%) and good stereoselectivity (up to 76% ee).

**Key words:** Michael addition, asymmetric synthesis, asymmetric catalysis, enantioselectivity, electrophilic addition, ketones

The synthesis of substituted alicyclic rings and heterocycles in a stereocontrolled manner is an important and challenging task in building skeletons of organic compounds. The availability of convenient synthetic methods for the construction of cyclic systems depends, along with other factors, on the number of carbon atoms in the ring. There are many excellent examples describing the synthesis of substituted cyclohexanes,[1] but the synthesis of analogously substituted cyclopentanes remains a challenge and requires further development,[2] especially because the five-membered carbocyclic core is an important and common structural fragment in many natural and bioactive compounds.[3]

We have been engaged in the development of stereocontrolled methods for the synthesis of substituted cyclopentanes and lactone-acids by generating chirality via the asymmetric oxidation of cyclopentane-1,2-diones.[4] Therefore, we are developing new methods that deliver substituted cyclopentane-1,2-diones as crucial starting compounds in order to broaden the scope of this general methodology. Additionally, cyclopentane-1,2-diones have also been used as precursors for the synthesis of various bioactive compounds.[5]

Asymmetric organocatalytic methods often offer the most efficient and environmentally benign approach for enantioselective synthesis.[6] Our contribution to the field covers several new reactions for building C–C, C–O, and C–N bonds in different structures.[7]

The organocatalytic Michael addition of ketone enolates with nitroolefins to afford substituted nitroaldehydes with high enantio- and diastereoselectivities and yields has been well investigated.[8,9] The enols and enolates of 1,2-diketones are less nucleophilic than those of ketones. However, it has been demonstrated that cyclohexane-1,2-dione reacts in the presence of bifunctional thiourea and ephedrine derivatives with nitroolefins affording substituted bicyclo[3.2.1]octanes.[10] The cascade transformation using transition-metal catalysis has also been reported.[11] Unsaturated aldehydes, although less active Michael acceptors than nitroolefins, undergo a Michael–aldol cascade with cyclohexane-1,2-dione affording a bicyclo[3.2.1]octane skeleton (Scheme 1, paths A and B).[12] The organocatalytic reactions outlined in Scheme 1 have not been described for cyclopentane-1,2-diones. This is not surprising, because different reactivities of cyclohexane-1,2-diones and cyclopentane-1,2-diones have also been observed previously in oxidation reactions.[13]

Recently, we demonstrated that a bis(*tert*-butyldimethylsilyl) enol ether of cyclopentane-1,2-dione reacts smoothly in a Mukaiyama–Michael reaction with unsaturated aldehydes under aminocatalytic conditions (Scheme 1, path C);[14] chiral cyclopentane-1,2-diones were obtained in good yields (up to 66%) and stereoselectivities (up to 94% ee). Cyclopentane-1,2-dione failed to react with unsaturated aldehydes under these conditions. In the present work, we investigated the possibilities of using unprotected cyclopentane-1,2-dione (**1**) in reactions with nitroolefins **2** (Scheme 1, path D). Hydrogen-bonding organocatalysts were used as asymmetry inducers and for the activation of the electrophile.

During preliminary experiments conducted at room temperature, we observed complete consumption of the starting materials within one hour, delivering nitro diketone **3a** in 93% yield with 62% ee (Table 1, entry 1). The formation of a functionalized bicyclo[2.2.1]heptanone skeleton was not observed.

In order to find the most efficient catalyst, we screened two types of bifunctional H-bonding catalysts (Figure 1), quinine-derived thiourea catalysts **4a** and **4e**, and squaramides **4b**, **4c**, and **4d**. The obtained results are presented in Table 1 (entries 2, and 9–12). Experiments revealed the thiourea catalyst **4a** to be the most selective and active catalyst for the reaction, affording the optimal balance between enantioselectivity (up to 78% in $CH_2Cl_2$) and yield (up to 88% in $CH_2Cl_2$).

To improve the selectivity of the reaction, we next investigated the influence of temperature on the selectivity of the Michael addition. We observed that in toluene at a lower temperature the reaction selectivity dropped con-

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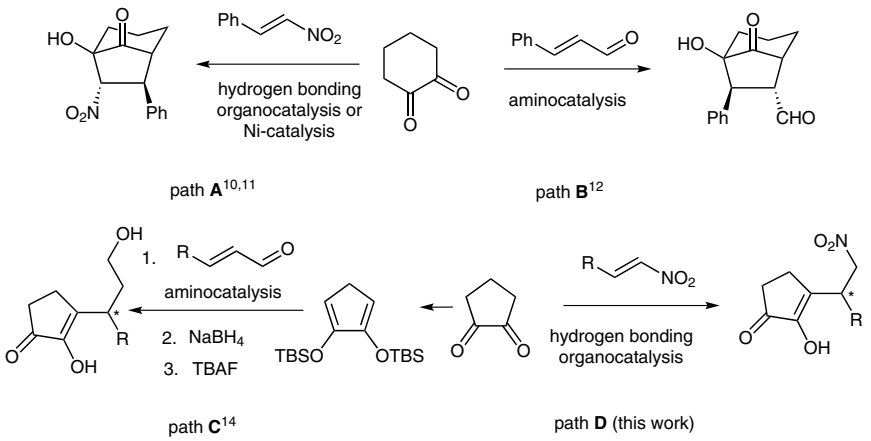
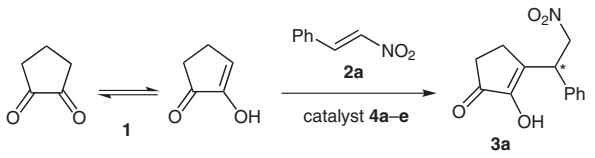



**Scheme 1** Cyclic 1,2-diones in Michael reactions

siderably (entry 1 vs. 4 and 5). Similar temperature dependence was found earlier and rationalized by Jang et al. as being a result of the self-aggregation of the catalyst.[15] By increasing the reaction temperature up to 50 °C, the selectivity was improved. Additional temperature elevation caused a slight drop in selectivity (entries 1 and 5 vs. 6 and 7). In chlorinated solvents, no temperature dependence was observed (entries 1 and 6 vs. 3 and 8).

**Table 1** Selection of the Conditions for a Michael Addition of 2-Hydroxycyclopent-2-enone **1** to Nitroolefin **2a**[a]




| Entry | Solvent | Catalyst (5 mol%) | Temp (°C) | Time (h) | Yield[b] (%) | ee[c] (%) |
|---|---|---|---|---|---|---|
| 1 | toluene | **4a** | r.t. | 1 | 93 | 62 |
| 2 | $CH_2Cl_2$ | **4a** | r.t. | 4 | 88 | 78 |
| 3 | $CHCl_3$ | **4a** | r.t. | 4 | 85 | 76 |
| 4 | toluene | **4a** | 0 | 3 | 77 | 50 |
| 5 | toluene | **4a** | –20 | 3 | 61 | 36 |
| 6 | toluene | **4a** | 50 | 0.5 | 79 | 76 |
| 7 | toluene | **4a** | 80 | 0.1 | 77 | 70 |
| 8 | $CHCl_3$ | **4a** | 50 | 1 | 77 | 73 |
| 9 | $CHCl_3$ | **4b** | r.t. | 2 | 83 | 78 |
| 10 | $CHCl_3$ | **4c** | r.t. | 24 | 2 | 46 |
| 11 | $CHCl_3$ | **4d** | r.t. | 2 | 43 | 72 |
| 12 | $CHCl_3$ | **4e** | r.t. | 3 | 97 | 68 |

[a] Reaction conditions: **1** (0.24 mmol), **2a** (0.2 mmol), **4** (5 mol%), solvent (0.7 mL).
[b] Isolated yield of **3a**.
[c] Determined by HPLC analysis on a chiral stationary phase.

In the search for the optimal solvent for the reaction, dichloromethane, chloroform, and toluene were screened at room temperature. Under the used conditions, the solvent had little or no influence on the reaction outcome. Because of experimental convenience, dichloromethane and chloroform were chosen for further optimization.

Under optimal conditions [catalyst **4a** (5 mol%), $CH_2Cl_2$ or $CHCl_3$, r.t.], we next examined the substrate scope of the reaction. The results are presented in Scheme 2.

On the basis of these results, we may conclude that the reaction tolerates a variety of aromatic nitroolefins, with little dependence on the electronic nature of the substituent. The substituents in the aromatic ring also had little or no influence on the enantioselectivity. Nitroolefins with heteroaromatic substituents or an aliphatic cyclohexane group can also be used in the reaction to give products **3i–k**. Aliphatic substitution reduces the reactivity of the nitroolefin, and therefore a prolonged reaction time is necessary, for example the formation of **3k**.

The absolute configuration of compound **3b** was determined by X-ray crystal structure analysis (Figure 2). The absolute configurations of other compounds in the series were assigned in analogy.

In summary, we have developed a chiral thiourea **4a** catalyzed Michael addition reaction of cyclopentane-1,2-dione with nitroolefins under mild conditions. The reaction has a wide substrate scope, as even an aliphatic nitroolefin yielded the expected product in good yield and selectivity. The developed methodology offers straightforward access to useful building blocks containing versatile functional groups, broadening the possibilities of using these synthons in chemical transformations.



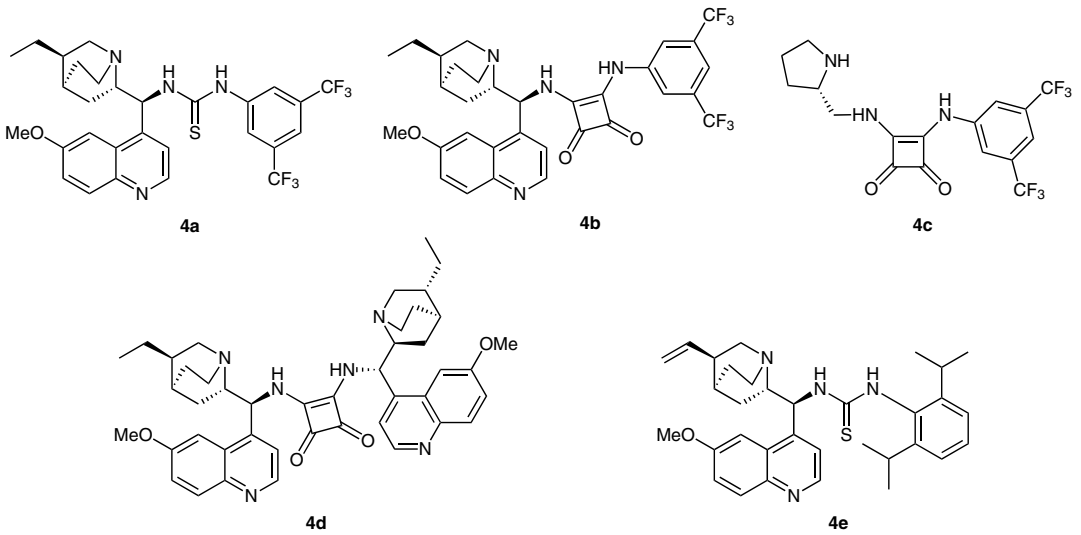
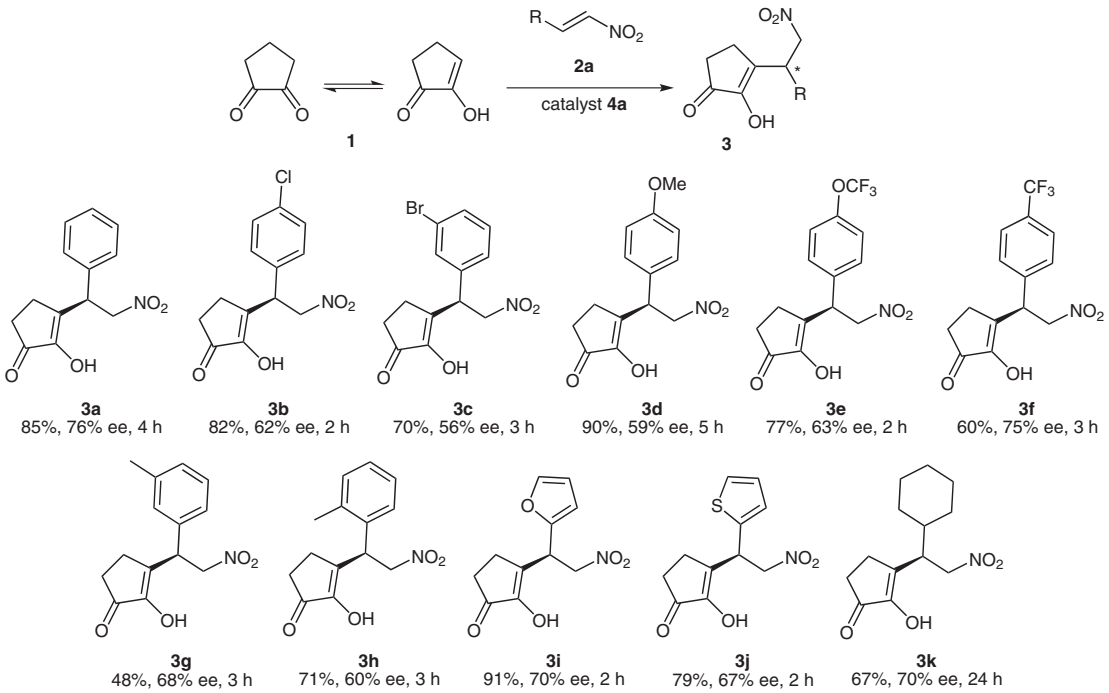



**Figure 1** Catalysts investigated




**Scheme 2** Screening of the substrate scope of the Michael addition. *Reagents and conditions*: **1** (0.24 mmol), **2** (0.2 mmol), **4a** (5 mol%), $CH_2Cl_2$ (0.7 mL). Isolated yields are given; ee values were determined by HPLC analysis on a chiral stationary phase.

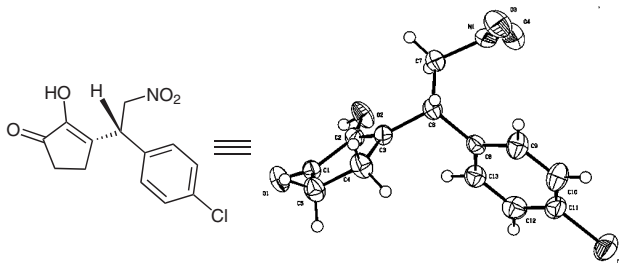


**Figure 2** X-ray crystal structure of **3b**

Full assignment of $^1H$ and $^{13}C$ chemical shifts is based on the 1D and 2D FT NMR spectra on a 400 MHz instrument. Solvent peaks ($CHCl_3/CDCl_3$ δ = 7.3/77.2) were used as chemical shift references. Chiral HPLC was performed using Chiralcel OD-H and Chiralpak AD-H columns. Mass spectra were recorded by using Agilent Technologies 6540 UHD Accurate-Mass Q-TOF LC/MS spectrometer by using AJ-ESI ionization. Optical rotations were obtained by using an Anton Paar GWB Polarimeter MCP500. IR spectra were recorded on a Bruker Tensor 27 FT-IR spectrophotometer. Absolute structure of the single crystal was obtained with Bruker SMART X2S benchtop diffractometer. Precoated silica gel 60 $F_{254}$ plates

were used for TLC, whereas for column chromatography Merck silica gel was used. Commercial reagents were generally used as received. $CH_2Cl_2$ and EtOAc were distilled from $P_2O_5$.

**Synthesis of Catalysts**

Thioureas **4a**[16] and **4e**[7b,17] and squaramides **4b**,[18] **4c**,[19] and **4d**[20] were prepared according to literature procedures.

**Synthesis of Starting Materials**

Cyclopentane-1,2-dione was prepared according to the literature procedure[21] from commercially available cyclopentanone. Nitroolefins **2a**–**k** were synthesized according to a literature procedure[22] from commercially available aldehydes and nitromethane.

**(*R*)-2-Hydroxy-3-(2-nitro-1-phenylethyl)cyclopent-2-enone (3a); Typical Procedure**

2-Hydroxycyclopent-2-enone (**1**, 23.5 mg, 0.2 mmol), nitrostyrene **2a** (29.5 mg, 0.24 mmol), and organocatalyst **4a** (6 mg, 0.01 mmol) were dissolved in $CH_2Cl_2$ (0.7 mL). The mixture was stirred at r.t. for 4 h. The mixture was purified by column chromatography (silica gel, $CH_2Cl_2$–EtOAc, 25:1) to give **3a** as a white solid; yield: 42 mg (85%); mp 154 °C; 76% ee [HPLC (Chiralcel OD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 254 nm): $t_R$ = 24.97 (major), 17.45 min (minor)].

$[\alpha]_D^{25}$ –42.3 (*c* 0.05, MeOH).

IR (KBr): 3302, 2922, 1690, 1641, 1551, 1382, 696 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.40–7.28 (m, 5 H), 6.20 (s, 1 H), 5.31 (dd, *J* = 13.8, 8.6 Hz, 1 H), 4.91 (dd, *J* = 13.8, 7.3 Hz, 1 H), 4.52–4.45 (m, 1 H), 2.50–2.34 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.1, 148.8, 141.4, 136.8, 129.3, 128.4, 128.0, 76.6, 45.4, 31.7, 24.7.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{13}H_{14}NO_4$: 248.0917; found: 248.0925.

**(*R*)-3-[1-(4-Chlorophenyl)-2-nitroethyl]-2-hydroxycyclopent-2-enone (3b)**

White solid; yield: 46 mg (82%); mp 144–146 °C; 62% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 31.28 (major), 33.47 min (minor)].

$[\alpha]_D^{25}$ –49.1 (*c* 0.05, MeOH).

IR (KBr): 3258, 2914, 1700, 1655, 1556, 1405, 1120, 840 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.37–7.31 (m, 2 H), 7.28–7.22 (m, 2 H), 6.03 (s, 1 H), 5.25 (dd, *J* = 13.8, 8.2 Hz, 1 H), 4.91 (dd, *J* = 13.8, 7.7 Hz, 1 H), 4.45 (t, *J* = 8.0 Hz, 1 H), 2.52–2.31 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 202.7, 148.8, 140.2, 135.2, 134.4, 129.6, 129.3, 76.4, 44.8, 31.7, 24.7.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{13}H_{13}ClNO_4$: 282.0528; found: 282.0531.

**(*R*)-3-[1-(3-Bromophenyl)-2-nitroethyl]-2-hydroxycyclopent-2-enone (3c)**

White solid; yield: 45 mg (70%); mp 163 °C; 56% ee [HPLC (Chiralcel OD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 20.6 (major), 31.1 min (minor)].

$[\alpha]_D^{25}$ –35.8 (*c* 0.04, MeOH).

IR (KBr): 3335, 2923, 1696, 1655, 1551, 1407, 1125, 780, 668 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.50–7.42 (m, 2 H), 7.26–7.20 (m, 2 H), 5.91 (s, 1 H), 5.27 (dd, *J* = 13.9, 8.4 Hz, 1 H), 4.90 (dd, *J* = 13.9, 7.5 Hz, 1 H), 4.44 (t, *J* = 7.9 Hz, 1 H), 2.52–2.34 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 202.6, 148.9, 139.7, 139.0, 131.6, 131.0, 130.9, 126.6, 123.3, 76.23, 45.0, 31.6, 24.7.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{13}H_{13}BrNO_4$: 326.0022; found: 326.0029.

**(*R*)-2-Hydroxy-3-[1-(4-methoxyphenyl)-2-nitroethyl]cyclopent-2-enone (3d)**

White solid; yield: 50 mg (90%); mp 98–100 °C; 59% ee [HPLC (Chiralcel OD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 20.8 (major), 26.7 min (minor)].

$[\alpha]_D^{25}$ +41.9 (*c* 0.04, MeOH).

IR (KBr): 3278, 2918, 1701, 1655, 1554, 1407, 1250, 843 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.25–7.19 (m, 2 H), 6.91–6.85 (m, 2 H), 6.18 (s, 1 H), 5.26 (dd, *J* = 13.7, 8.5 Hz, 1 H), 4.88 (dd, *J* = 13.7, 7.5 Hz, 1 H), 4.42 (t, *J* = 8.0 Hz, 1 H), 3.79 (s, 3 H), 2.50–2.33 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.1, 159.5, 148.6, 141.9, 129.1, 128.6, 114.7, 76.8, 55.3, 44.7, 31.7, 24.7.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{16}NO_5$: 278.1023; found: 278.1004.

**(*R*)-2-Hydroxy-3-{2-nitro-1-[4-(trifluoromethoxy)phenyl]ethyl}cyclopent-2-enone (3e)**

Yellow liquid; yield: 51 mg (77%); 63% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 19.9 (major), 18.9 min (minor)].

$[\alpha]_D^{25}$ –3.2 (*c* 0.02, MeOH).

IR (KBr): 3323, 2925, 1706, 1661, 1557, 1510, 1264, 1117, 857 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.40–7.33 (m, 2 H), 7.24–7.16 (m, 2 H), 6.62 (s, 1 H), 5.26 (dd, *J* = 14.1, 7.1 Hz, 1 H), 4.93 (dd, *J* = 13.9, 7.7 Hz, 1 H), 4.50 (t, *J* = 8.0 Hz, 1 H), 2.54–2.35 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.3, 149.1, 141.0, 135.5, 129.5, 121.8, 120.4 (q, *J* = 257.7 Hz), 76.4, 44.8, 31.8, 24.8.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{13}F_3NO_5$: 332.074; found: 332.0743.

**(*R*)-2-Hydroxy-3-{2-nitro-1-[4-(trifluoromethyl)phenyl]ethyl}cyclopent-2-enone (3f)**

Yellow liquid; yield: 82 mg (60%); 75% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 22.1 (major), 25.2 min (minor)].

$[\alpha]_D^{25}$ –66.4 (*c* 0.04, MeOH).

IR (KBr): 3323, 2924, 1715, 1673, 1558, 1326, 1134, 850 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.63 (d, *J* = 8.1 Hz, 2 H), 7.46 (d, *J* = 8.1 Hz, 2 H), 6.66 (s, 1 H), 5.31 (ddd, *J* = 13.9, 8.1, 1.7 Hz, 1 H), 4.97 (dd, *J* = 13.9, 7.8 Hz, 1 H), 4.57 (t, *J* = 7.9 Hz, 1 H), 2.54–2.33 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.3, 149.3, 140.8, 140.6, 130.7 (dd, *J* = 65.5, 32.7 Hz), 128.5, 126.3 (dd, *J* = 7.4, 3.7 Hz), 123.8 (dd, *J* = 544.5, 272.3 Hz), 76.1, 45.1, 31.8, 24.8.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{13}F_3NO_4$: 316.0791; found: 316.0800.

**(*R*)-2-Hydroxy-3-[2-nitro-1-(*m*-tolyl)ethyl]cyclopent-2-enone (3g)**

White solid; yield: 52 mg (48%); mp 107–108 °C; 68% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 28.0 (major), 18.0 min (minor)].

$[\alpha]_D^{25}$ –58.3 (*c* 0.04, MeOH).

IR (KBr): 3314, 2928, 1693, 1658, 1561, 1404, 833, 794 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.25–7.21 (m, 1 H), 7.15–7.06 (m, 3 H), 6.34 (s, 1 H), 5.29 (dd, *J* = 13.8, 8.6 Hz, 1 H), 4.90 (dd, *J* = 13.8, 7.3 Hz, 1 H), 4.48–4.41 (m, 1 H), 2.51–2.36 (m, 4 H), 2.34 (s, 3 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.3, 148.8, 141.9, 139.2, 136.7, 129.2, 129.1, 128.7, 125.0, 76.6, 45.4, 31.8, 24.7, 21.5.



HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{16}NO_4$: 262.1074; found: 262.1081.

**(*R*)-2-Hydroxy-3-[2-nitro-1-(*o*-tolyl)ethyl]cyclopent-2-enone (3h)**

Yellow liquid; yield: 37 mg (71%); 60% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 18.0 (major), 28.4 min (minor)].

$[\alpha]_D^{25}$ +43.4 (*c* 0.04, MeOH).

IR (KBr): 3369, 2922, 1712, 1655, 1555, 1378, 1117, 794, 706 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.27–7.17 (m, 4 H), 6.66 (s, 1 H), 5.28 (dd, *J* = 16.0, 10.8 Hz, 1 H), 4.91–4.82 (m, 2 H), 2.49–2.32 (m, 7 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.5, 149.3, 142.1, 136.4, 135.1, 131.3, 128.1, 127.2, 127.0, 76.0, 40.8, 31.8, 24.5, 19.7.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{16}NO_4$: 262.1074; found: 262.1091.

**(*R*)-3-[1-(Furan-2-yl)-2-nitroethyl]-2-hydroxycyclopent-2-enone (3i)**

Yellow liquid; yield: 43 mg (91%); 70% ee [HPLC (Chiralcel OD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 254 nm): $t_R$ = 13.1 (major), 16.2 min (minor)].

$[\alpha]_D^{25}$ +28.3 (*c* 0.04, MeOH).

IR (KBr): 3492, 2925, 1716, 1673, 1558, 1407, 1106, 910 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.39 (dd, *J* = 1.8, 0.7 Hz, 1 H), 6.35 (dd, *J* = 3.2, 1.9 Hz, 1 H), 6.25 (d, *J* = 3.3 Hz, 1 H), 5.87 (s, 1 H), 5.10 (dd, *J* = 13.4, 8.3 Hz, 1 H), 4.93 (dd, *J* = 13.4, 7.3 Hz, 1 H), 4.81 (t, *J* = 7.8 Hz, 1 H), 2.52–2.42 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 202.5, 149.3, 148.9, 142.9, 138.1, 110.7, 108.1, 74.4, 37.9, 31.7, 24.1.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{12}NO_5$: 238.071; found: 238.071.

**(*R*)-2-Hydroxy-3-[2-nitro-1-(thiophen-2-yl)ethyl]cyclopent-2-enone (3j)**

White solid; yield: 40 mg (79%); mp 120–121 °C; 67% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 254 nm): $t_R$ = 36.8 (major), 43.2 min (minor)].

$[\alpha]_D^{25}$ –49.9 (*c* 0.04, MeOH).

IR (KBr): 3315, 2918, 1699, 1658, 1552, 1407, 1124, 662 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 7.26 (dd, *J* = 5.1, 1.3 Hz, 1 H), 7.00 (ddd, *J* = 8.6, 4.3, 2.3 Hz, 2 H), 6.57 (s, 1 H), 5.28–5.18 (m, 1 H), 4.91 (dq, *J* = 14.4, 7.1 Hz, 2 H), 2.54–2.42 (m, 4 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 203.3, 148.9, 140.8, 138.3, 127.4, 126.3, 125.6, 76.7, 39.6, 31.9, 24.3.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{12}NO_5S$: 254.0482; found: 254.0486.

**(*R*)-3-(1-Cyclohexyl-2-nitroethyl)-2-hydroxycyclopent-2-enone (3k)**

White solid; yield: 34 mg (67%); mp 117–118 °C; 70% ee [HPLC (Chiralcel AD-H, hexane–*i*-PrOH, 90:10, 1 mL/min, 230 nm): $t_R$ = 17.9 (major), 20.4 min (minor)].

$[\alpha]_D^{25}$ –3.7 (*c* 0.04, MeOH).

IR (KBr): 3344, 2926, 2856, 1694, 1655, 1558, 1408, 1107 $cm^{-1}$.

$^1H$ NMR (400 MHz, $CDCl_3$): δ = 5.81 (s, 1 H), 4.84 (dd, *J* = 12.8, 10.7 Hz, 1 H), 4.67 (dd, *J* = 12.9, 4.7 Hz, 1 H), 3.19 (ddd, *J* = 10.9, 7.9, 4.7 Hz, 1 H), 2.52–2.39 (m, 4 H), 1.84–1.59 (m, 6 H), 1.33–0.99 (m, 5 H).

$^{13}C$ NMR (101 MHz, $CDCl_3$): δ = 202.6, 150.0, 142.7, 75.3, 44.4, 39.0, 31.8, 31.1, 30.9, 26.1, 26.1, 26.0, 25.4.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{13}H_{20}NO_4$: 254.1387; found: 254.1389.

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