Synthesis of functionalized γ-lactones via a three-component cascade reaction catalyzed by consecutive N-heterocyclic carbene systems

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Supporting Information

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1. General methods

NMR data was obtained for $^1$H at 400 MHz, and for $^{13}$C at 100 MHz. Chemical shifts were reported in ppm from tetramethylsilane with the solvent resonance as the internal standard in CDCl$_3$ solution. ESI HRMS was performed on a Waters SYNAPT G2. Column chromatography was performed on silica gel (200-300 mesh) using an eluent of ethyl acetate and petroleum ether. TLC was performed on glass-backed silica plates; products were visualized using UV light and I$_2$. Melting points were determined on a Mel-Temp apparatus and were not corrected. All chemicals were used from Adamas-beta without purification unless otherwise noted.

2. General procedure for the synthesis of γ-lactone 4

The reaction was carried out with precatalyst Id (0.1 mmol), DBU (0.3 mmol) and aldehyde 1 (1.6 mmol) in CH$_2$Cl$_2$ (2.0 mL) at 50 °C for a specified reaction time until the sufficient acyloin 2 was generated (monitored by TLC), after which precatalyst IIa (0.1 mmol) and 2-bromoenal 3 (0.4 mmol) were added in-situ. The reaction mixture was stirred until the reaction completed. Then the reaction mixture was concentrated and the residue was purified by flash chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) to give γ-lactone 4.

4a was obtained as a white solid in 64% yield for two steps after flash chromatography. The dr value was calculated to be 90:10 by $^1$H NMR analysis of the crude reaction mixture. m.p. 139-140 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 7.90 (d, $J = 7.6$ Hz, 2H), 7.46-7.43 (m, 1H), 7.32-7.26 (m, 2H), 7.11-7.07 (m, 8H), 6.94 (s, 2H), 4.88 (t, $J = 5.6$ Hz, 1H), 3.03 (dd, $J_1 = 18.0$ Hz, $J_2 = 8.8$ Hz, 1H), 2.88 (dd, $J_1 = 18.0$ Hz, $J_2 = 3.2$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ = 195.29, 175.24, 137.31, 135.33, 133.59, 133.42, 130.95, 128.79, 128.45, 128.27, 128.19, 128.07, 127.26, 124.68,
95.07, 47.94, 35.53 ppm; ESI HRMS: calcd. For C\textsubscript{23}H\textsubscript{18}O\textsubscript{3}+Na 365.1154, found 365.1151.

For the minor diastereomer of 4\textsubscript{a}, \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): \(\delta = 7.81\) (d, \(J = 7.6\) Hz, 2H), 7.60 (d, \(J = 7.2\) Hz, 2H), 7.47-7.40 (m, 4H), 7.30-7.24 (m, 5H), 7.18-7.17 (m, 2H), 4.17 (d, \(J = 7.6\) Hz, 1H), 2.87 (dd, \(J_1 = 17.6\) Hz, \(J_2 = 8.0\) Hz, 1H), 2.58 (d, \(J = 17.2\) Hz, 1H) ppm; \textsuperscript{13}C NMR (100 MHz, CDCl\textsubscript{3}): \(\delta = 197.48, 175.65, 140.13, 138.46, 136.14, 132.84, 129.40, 129.17, 128.97, 128.93, 128.01, 127.57, 127.49, 125.27, 95.85, 53.94, 36.43\) ppm; ESI HRMS: calcd. For C\textsubscript{23}H\textsubscript{18}O\textsubscript{3}+Na 365.1156.

4\textsubscript{b} was obtained as a white solid in 65% yield for two steps after flash chromatography. The dr value was calculated to be 95:5 by \textsuperscript{1}H NMR analysis of the crude reaction mixture. m.p. 144-145 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): \(\delta = 7.57\) (d, \(J = 7.2\) Hz, 1H), 7.39 (d, \(J = 7.6\) Hz, 1H), 7.26-7.21 (m, 1H), 7.12-6.93 (m, 10H), 5.05 (d, \(J = 8.8\) Hz, 1H), 3.62 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 9.2\) Hz, 1H), 2.71 (d, \(J = 18.0\) Hz, 1H) ppm; \textsuperscript{13}C NMR (100 MHz, CDCl\textsubscript{3}): \(\delta = 193.46, 175.25, 139.28, 134.30, 134.02, 133.48, 131.81, 131.11, 130.70, 129.80, 129.70, 129.32, 128.21, 127.93, 127.38, 126.77, 125.48, 94.29, 45.32, 37.97\) ppm; ESI HRMS: calcd. For C\textsubscript{23}H\textsubscript{16}Cl\textsubscript{2}O\textsubscript{3}+Na 433.0374, found 433.0370.

4\textsubscript{c} was obtained as a white solid in 68% yield for two steps after flash chromatography. The dr value was calculated to be 88:15 by \textsuperscript{1}H NMR analysis of the crude reaction mixture. m.p. 114-115 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): \(\delta = 7.84\) (d, \(J = 8.4\) Hz, 2H), 7.31-7.29 (m, 2H), 7.11-7.09 (m, 5H), 6.98-6.93 (m, 4H), 4.85 (dd, \(J_1 = 8.0\) Hz, \(J_2 = 5.6\) Hz, 1H), 3.03 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 8.4\) Hz, 1H), 2.87 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 5.6\) Hz, 1H) ppm; \textsuperscript{13}C NMR (100 MHz, CDCl\textsubscript{3}): \(\delta = 193.84, 174.65, 140.29, 136.89, 134.49, 133.76, 132.27, 131.61, 128.79, 128.76, 128.63, 128.35, 127.62, 126.07, 94.48, 47.75, 35.38\) ppm; ESI HRMS: calcd. For C\textsubscript{23}H\textsubscript{16}Cl\textsubscript{2}O\textsubscript{3}+Na 433.0374, found 433.0371.

4\textsubscript{d} was obtained as a white solid in 65% yield for two steps after flash chromatography. The dr value was calculated to be 92:8 by \textsuperscript{1}H NMR analysis of the crude reaction mixture. m.p. 126-127 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): \(\delta = 8.08\) (s, 1H), 7.79 (d, \(J = 8.0\) Hz, 1H), 7.60-7.56 (m, 1H), 7.25-7.23 (m, 1H),
7.20-7.16 (m, 2H), 7.11 (m, 3H), 7.00-6.91 (m, 4H), 4.84 (t, $J = 6.8$ Hz, 1H), 3.03 (dd, $J_1 = 18.0$ Hz, $J_2 = 8.4$ Hz, 1H), 2.88 (dd, $J_1 = 18.0$ Hz, $J_2 = 5.2$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 193.60, 174.52, 137.25, 136.73, 136.55, 135.04, 133.47, 131.57, 130.07, 129.94, 129.60, 128.59, 128.32, 127.78, 127.70, 123.26, 122.92, 122.68, 94.20, 47.94, 35.24 ppm; ESI HRMS: calcd. For C$_{23}$H$_{16}$Br$_2$O$_3$+Na 520.9364, found 520.9367.

4e was obtained as a white solid in 70% yield for two steps after flash chromatography. The dr value was calculated to be 85:15 by $^1$H NMR analysis of the crude reaction mixture. m.p. 143-144 $^\circ$C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 7.76 (d, $J = 8.4$ Hz, 2H), 7.47 (d, $J = 8.0$ Hz, 2H), 7.26-7.24 (m, 3H), 7.11 (s, 3H), 6.91-6.89 (m, 3H), 4.84 (t, $J = 6.4$ Hz, 1H), 3.03 (dd, $J_1 = 18.0$ Hz, $J_2 = 8.4$ Hz, 1H), 2.87 (dd, $J_1 = 18.0$ Hz, $J_2 = 5.2$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 193.85, 174.58, 136.83, 134.26, 132.31, 132.01, 131.78, 131.74, 129.19, 128.62, 128.36, 126.44, 125.82, 124.94, 94.70, 47.70, 35.37 ppm; ESI HRMS: calcd. For C$_{23}$H$_{16}$Br$_2$O$_3$+Na 520.9364, found 520.9366.

4f was obtained as a white solid in 65% yield for two steps after flash chromatography. The dr value was calculated to be 87:13 by $^1$H NMR analysis of the crude reaction mixture. m.p. 127-128 $^\circ$C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 7.95 (s, 2H), 7.10 (br s, 3H), 7.01-7.00 (m, 4H), 6.92 (m, 2H), 6.83-6.79 (m, 2H), 4.86 (t, $J = 6.0$ Hz, 1H), 3.03 (dd, $J_1 = 18.0$ Hz, $J_2 = 8.4$ Hz, 1H), 2.88 (dd, $J_1 = 18.0$ Hz, $J_2 = 4.8$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 193.59, 174.82, 165.77 (d, $J_{CF} =$ 255 Hz), 162.41 (d, $J_{CF} =$ 247 Hz), 137.10, 133.78 (d, $J_{CF} =$ 9 Hz), 131.14 (d, $J_{CF} =$ 4 Hz), 129.72 (d, $J_{CF} =$ 3 Hz), 128.65, 128.27, 127.50, 126.54 (d, $J_{CF} =$ 9 Hz), 115.72 (d, $J_{CF} =$ 3 Hz), 115.50 (d, $J_{CF} =$ 2 Hz), 94.57, 47.81, 35.38 ppm; ESI HRMS: calcd. For C$_{23}$H$_{16}$F$_2$O$_3$+Na 401.0965, found 401.0968.

4g was obtained as a white solid in 70% yield for two steps after flash chromatography. The dr value was calculated to be 92:8 by $^1$H NMR analysis of the crude reaction mixture. m.p. 148-149 $^\circ$C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 7.49 (d, $J = 8.4$ Hz, 1H), 7.43 (s, 1H), 7.19-7.17 (m, 1H), 7.07-6.97 (m, 8H), 4.98 (d, $J = 8.8$ Hz, 1H), 3.61 (dd, $J_1 = 18.0$ Hz, $J_2 = 9.2$ Hz, 1H), 2.82 (d, $J = 18.4$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 192.09, 174.73, 138.86, 137.85, 135.08, 134.85,
4h was obtained as a white solid in 54% yield for two steps after flash chromatography. The dr value was calculated to be 86:14 by $^1$H NMR analysis of the crude reaction mixture. m.p. 131-132 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 7.86 (d, $J = 8.4$ Hz, 2H), 7.17-7.15 (m, 2H), 7.04-7.03 (m, 3H), 6.96-6.88 (m, 6H), 4.82 (dd, $J_1 = 8.4$ Hz, $J_2 = 6.4$ Hz, 1H), 2.99 (dd, $J_1 = 18.0$ Hz, $J_2 = 8.8$ Hz, 1H), 2.90-2.83 (m, 2H), 2.77-2.71 (m, 1H), 1.20 (d, $J = 2.0$ Hz, 3H), 1.18 (d, $J = 1.6$ Hz, 3H), 1.11 (d, $J = 3.2$ Hz, 3H), 1.10 (d, $J = 3.2$ Hz, 3H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ = 195.06, 175.47, 154.91, 148.99, 137.40, 132.71, 131.44, 131.32, 128.85, 127.86, 127.06, 126.39, 124.57, 95.20, 48.04, 35.40, 34.24, 33.60, 23.78, 23.77, 23.53, 23.47 ppm; ESI HRMS: calcd. For C$_{23}$H$_{14}$Cl$_4$O$_3$+Na 500.9595, found 500.9597.

4i was obtained as a white solid in 72% yield for two steps after flash chromatography. The dr value was calculated to be 80:20 by $^1$H NMR analysis of the crude reaction mixture. m.p. 126-127 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 7.65 (s, 1H), 7.32 (br s, 1H), 7.18 (br s, 4H), 7.09 (br s, 2H), 6.49 (s, 1H), 6.15 (d, $J = 8.8$ Hz, 2H), 4.70 (t, $J = 8.4$ Hz, 1H), 3.11-2.97 (m, 2H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ = 181.03, 174.27, 149.14, 148.16, 147.95, 143.20, 136.25, 128.29, 128.24, 127.66, 123.13, 112.56, 110.58, 109.38, 89.67, 46.69, 34.42 ppm; ESI HRMS: calcd. For C$_{19}$H$_{14}$O$_5$+Na 345.0739, found 345.0743.

4j was obtained as a white solid in 71% yield for two steps after flash chromatography. The dr value was calculated to be 75:25 by $^1$H NMR analysis of the crude reaction mixture. m.p. 90-91 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 7.98 (d, $J = 3.6$ Hz, 1H), 7.66 (d, $J = 4.8$ Hz, 1H), 7.16-7.05 (m, 7H), 6.75-6.72 (m, 1H), 6.60-6.59 (m, 1H), 4.75 (t, $J = 7.2$ Hz, 1H), 3.06-2.93 (m, 2H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ = 187.83, 174.24, 139.34, 138.10, 136.77, 136.63, 135.76, 128.70, 128.61, 128.18, 127.67, 127.10, 126.17, 126.09, 93.47, 48.18, 34.96 ppm; ESI HRMS: calcd. For C$_{19}$H$_{14}$O$_3$S$_2$+Na 377.0282, found 377.0280.
**4k** was obtained as a white solid in 60% yield for two steps after flash chromatography. The dr value was calculated to be 92:8 by ¹H NMR analysis of the crude reaction mixture. m.p. 101-103 °C; ¹H NMR (400 MHz, CDCl₃): δ = 7.93 (d, J = 7.6 Hz, 2H), 7.48-7.44 (m, 1H), 7.34-7.26 (m, 5H), 7.12-7.03 (m, 5H), 7.00-6.97 (m, 1H), 5.72 (d, J = 8.8 Hz, 1H), 3.15 (dd, J₁ = 18.0 Hz, J₂ = 9.2 Hz, 1H), 2.75 (d, J = 18.4 Hz, 1H) ppm; ¹³C NMR (100 MHz, CDCl₃): δ = 194.80, 175.42, 136.79, 134.83, 134.20, 133.48, 133.29, 131.04, 129.50, 128.57, 128.54, 128.31, 128.24, 128.20, 126.92, 124.67, 95.86, 43.24, 36.73 ppm; ESI HRMS: calcd. For C₂₃H₁₇ClO₃+Na 399.0764, found 399.0760.

**4l** was obtained as a white solid in 61% yield for two steps after flash chromatography. The dr value was calculated to be 86:14 by ¹H NMR analysis of the crude reaction mixture. m.p. 123-124 °C; ¹H NMR (400 MHz, CDCl₃): δ = 7.89 (d, J = 8.0 Hz, 2H), 7.47-7.43 (m, 1H), 7.32-7.29 (m, 2H), 7.15 (br s, 3H), 7.06-7.04 (m, 4H), 6.86 (d, J = 7.6 Hz, 2H), 4.85 (t, J = 7.6 Hz, 1H), 3.01 (dd, J₁ = 18.0 Hz, J₂ = 8.4 Hz, 1H), 2.82 (dd, J₁ = 18.0 Hz, J₂ = 6.4 Hz, 1H) ppm; ¹³C NMR (100 MHz, CDCl₃): δ = 194.03, 173.71, 134.67, 134.01, 132.50, 132.41, 132.18, 129.91, 129.10, 127.65, 127.46, 127.26, 127.17, 123.58, 93.64, 46.37, 34.28 ppm; ESI HRMS: calcd. For C₂₃H₁₇ClO₃+Na 399.0764, found 399.0767.

**4m** was obtained as a white solid in 66% yield for two steps after flash chromatography. The dr value was calculated to be 85:15 by ¹H NMR analysis of the crude reaction mixture. m.p. 149-150 °C; ¹H NMR (400 MHz, CDCl₃): δ = 7.89 (d, J = 8.0 Hz, 2H), 7.46-7.43 (m, 1H), 7.32-7.28 (m, 2H), 7.21-7.15 (m, 5H), 7.04 (br s, 2H), 6.80 (d, J = 8.0 Hz, 2H), 4.83 (t, J = 7.6 Hz, 1H), 3.01 (dd, J₁ = 18.0 Hz, J₂ = 8.8 Hz, 1H), 2.81 (dd, J₁ = 18.0 Hz, J₂ = 6.4 Hz, 1H) ppm; ¹³C NMR (100 MHz, CDCl₃): δ = 195.04, 174.70, 136.23, 135.02, 133.53, 133.44, 131.16, 130.94, 130.49, 128.70, 128.52, 128.30, 124.62, 121.37, 94.59, 47.48, 35.26 ppm; ESI HRMS: calcd. For C₁₂₃H₁₇BrO₃+Na 443.0259, found 443.0262.

**4n** was obtained as a white solid in 57% yield for two steps after flash chromatography. The dr value was calculated to be 90:10 by ¹H NMR analysis of the crude reaction mixture. m.p. 112-114 °C; ¹H NMR (400 MHz, CDCl₃): δ = 7.93 (d, J = 7.6 Hz, 2H), 7.47-7.44 (m, 1H), 7.33-7.30 (m, 2H), 7.23-7.21 (m, 2H), 7.13-7.00 (m,
5H), 6.93-6.90 (m, 1H), 6.75-6.70 (m, 1H), 5.28 (dd, \(J_1 = 9.2\) Hz, \(J_2 = 1.6\) Hz, 1H), 3.09 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 8.8\) Hz, 1H), 2.85 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 2.0\) Hz, 1H) ppm; \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \(\delta = 194.87, 175.19, 160.44\) (d, \(J_{CF} = 245\) Hz), 135.29, 133.47, 133.34, 131.04, 129.88 (d, \(J_{CF} = 4\) Hz), 129.24 (d, \(J_{CF} = 9\) Hz), 128.38, 128.29, 128.21, 125.80 (d, \(J_{CF} = 13\) Hz), 124.38, 123.97 (d, \(J_{CF} = 4\) Hz), 115.38 (d, \(J_{CF} = 23\) Hz), 95.34, 42.16, 35.45 ppm; ESI HRMS: calcd. For C\(_{23}\)H\(_{17}\)FO\(_3\)+Na 383.1059, found 383.1063.

4o was obtained as a white solid in 61% yield for two steps after flash chromatography. The dr value was calculated to be 85:15 by \(^1\)H NMR analysis of the crude reaction mixture. m.p. 129-130 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta = 7.90\) (d, \(J = 8.0\) Hz, 2H), 7.47-7.43 (m, 1H), 7.33-7.29 (m, 2H), 7.15-7.14 (m, 3H), 7.07-7.02 (m, 3H), 6.79-6.73 (m, 2H), 6.65 (d, \(J = 10.0\) Hz, 1H), 4.88 (t, \(J = 7.2\) Hz, 1H), 3.03 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 8.8\) Hz, 1H), 2.86 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 6.0\) Hz, 1H) ppm; \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \(\delta = 194.96, 174.70, 162.36\) (d, \(J_{CF} = 244\) Hz), 139.85 (d, \(J_{CF} = 7\) Hz), 135.05, 133.53, 133.42, 130.97, 129.52, 128.62, 128.45, 128.30, 125.17, 124.57, 115.93 (d, \(J_{CF} = 21\) Hz), 114.25 (d, \(J_{CF} = 21\) Hz), 94.76, 47.59, 35.27 ppm; ESI HRMS: calcd. For C\(_{23}\)H\(_{17}\)FO\(_3\)+Na 383.1059, found 383.1056.

4p was obtained as a white solid in 68% yield for two steps after flash chromatography. The dr value was calculated to be 82:18 by \(^1\)H NMR analysis of the crude reaction mixture. m.p. 120-122 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta = 7.89\) (d, \(J = 8.0\) Hz, 2H), 7.47-7.43 (m, 1H), 7.33-7.29 (m, 2H), 7.15-7.14 (m, 3H), 7.04-7.03 (m, 2H), 6.91-6.88 (m, 2H), 6.79-6.75 (m, 2H), 4.88-4.85 (m, 1H), 3.02 (dd, \(J_1 = 17.6\) Hz, \(J_2=8.4\) Hz, 1H), 2.83 (dd, \(J_1 = 18.0\) Hz, \(J_2 = 6.4\) Hz, 1H) ppm; \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \(\delta = 195.16, 174.92, 161.85\) (d, \(J_{CF} = 245\) Hz), 135.17, 133.52, 133.46, 132.93 (d, \(J_{CF} = 3\) Hz), 130.95, 130.37 (d, \(J_{CF} = 8\) Hz), 128.63, 128.40, 128.30, 124.60, 114.96 (d, \(J_{CF} = 21\) Hz), 94.77, 47.25, 35.43; ESI HRMS: calcd. For C\(_{23}\)H\(_{17}\)FO\(_3\)+Na 383.1059, found 383.1060.

4q was obtained as a white solid in 63% yield for two steps after flash chromatography. The dr value was calculated to be 84:16 by \(^1\)H NMR analysis of the crude reaction mixture. m.p. 158-160 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta = 7.94\) (d, \(J = 8.8\) Hz, 2H), 7.90 (d, \(J = 7.6\) Hz, 2H), 7.49-7.46 (m, 1H), 7.35-7.31 (m, 2H),
7.16-7.11 (m, 5H), 7.04-7.03 (m, 2H), 5.02-4.99 (m, 1H), 3.09 (dd, $J_1 = 18.0$ Hz, $J_2 = 8.4$ Hz, 1H), 2.89 (dd, $J_1 = 18.0$ Hz, $J_2 = 6.4$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta = 194.64, 174.08, 146.97, 144.81, 134.69, 133.78, 133.11, 131.00, 129.81, 128.93, 128.87, 128.39, 124.46, 123.16, 94.42, 47.70, 35.10$ ppm; ESI HRMS: calcd. For C$_{23}$H$_{17}$NO$_5$+Na 410.1004, found 410.1009.

4r was obtained as a white solid in 54% yield for two steps after flash chromatography. The dr value was calculated to be 80:20 by $^1$H NMR analysis of the crude reaction mixture. m.p. 99-100 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 7.90 (d, $J = 7.6$ Hz, 2H), 7.45-7.41 (m, 1H), 7.31-7.27 (m, 2H), 7.12-7.11 (m, 3H), 7.07-7.06 (m, 2H), 6.87 (d, $J = 8.0$ Hz, 2H), 6.81 (d, $J = 8.0$ Hz, 2H), 4.83 (t, $J = 7.2$ Hz, 1H), 2.99 (dd, $J_1 = 17.6$ Hz, $J_2 = 8.4$ Hz, 1H), 2.84 (dd, $J_1 = 18.0$ Hz, $J_2 = 6.0$ Hz, 1H), 2.19 (s, 3H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 195.40, 175.32, 136.91, 135.38, 134.15, 133.78, 133.36, 130.92, 128.74, 128.66, 128.44, 128.25, 128.17, 124.76, 95.06, 47.68, 35.64, 20.96 ppm; ESI HRMS: calcd. For C$_{24}$H$_{20}$O$_3$+Na 379.1310, found 379.1315.

4s was obtained as a white solid in 50% yield for two steps after flash chromatography. The dr value was calculated to be 87:13 by $^1$H NMR analysis of the crude reaction mixture. m.p. 89-90 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 7.94 (d, $J = 7.6$ Hz, 2H), 7.46-7.42 (m, 1H), 7.32-7.29 (m, 2H), 7.23-7.21 (m, 2H), 7.07-7.00 (m, 5H), 6.74-6.70 (m, 1H), 6.50-6.48 (m, 1H), 5.22 (d, $J = 9.6$ Hz, 1H), 3.64 (s, 3H), 2.98 (dd, $J_1 = 18.0$ Hz, $J_2 = 10.0$ Hz, 1H), 2.83 (dd, $J_1 = 17.6$ Hz, $J_2 = 1.2$ Hz, 1H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 195.59, 176.22, 156.91, 135.81, 133.70, 133.22, 131.03, 130.88, 128.72, 128.19, 127.73, 127.69, 127.09, 124.57, 120.14, 110.11, 95.68, 54.29, 44.66, 35.39 ppm; ESI HRMS: calcd. For C$_{24}$H$_{20}$O$_4$+Na 395.1259, found 395.1263.

4t was obtained as a white solid in 35% yield for two steps after flash chromatography. The dr value was calculated to be 80:20 by $^1$H NMR analysis of the crude reaction mixture. m.p. 102-104 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta =$ 7.91 (d, $J = 6.4$ Hz, 2H), 7.46 (br s, 1H), 7.32-7.26 (m, 3H), 7.19 (br s, 5H), 7.07 (br s, 1H), 6.08 (s, 1H), 6.01 (s, 1H), 4.94 (br s, 1H), 2.94 (br s, 2H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta =$ 194.64, 174.49, 150.44, 142.14, 135.45, 133.57, 133.24, 131.01, 128.56, 128.34, 128.31, 124.03, 110.17, 108.94,
94.14, 42.59, 33.26 ppm; ESI HRMS: calcd. For C_{21}H_{16}O_{4}Na 355.0946, found 355.0943.

5a was obtained as a white solid in 87% yield for two steps after flash chromatography. m.p. 104-106 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): δ = 7.98 (d, \(J = 7.2\) Hz, 2H), 7.78 (d, \(J = 16.0\) Hz, 1H), 7.52 (br s, 5H), 7.43-7.38 (m, 7H), 7.25 (s, 1H), 7.01 (s, 1H), 6.60 (d, \(J = 16.0\) Hz, 1H) ppm; \(^13\)C NMR (100 MHz, CDCl\(_3\)): δ = 193.83, 166.32, 146.21, 134.71, 134.27, 133.78, 133.52, 130.53, 129.37, 129.19, 128.91, 128.88, 128.78, 128.68, 128.28, 117.14, 77.65 ppm; ESI HRMS: calcd. For C_{23}H_{18}O_{3}Na 365.1154, found 365.1151.
3. Crystal data of 4a

![Crystal Structure Image]

**Empirical formula**: C₂₃H₁₈O₃

**Formula weight**: 342.37

**Temperature/K**: 293(2)

**Crystal system**: monoclinic

**Space group**: P2₁

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**2Θ range for data collection**: 9.46 to 134.48°

**Index ranges**: -5 ≤ h ≤ 8, -16 ≤ k ≤ 14, -11 ≤ l ≤ 11

**Reflections collected**: 5229

**Independent reflections**: 2737 [R(int) = 0.0221]

**Data/restraints/parameters**: 2737/1/236

**Goodness-of-fit on F²**: 1.096

**Final R indexes [I>=2σ (I)]**: R₁ = 0.0317, wR₂ = 0.0877

**Final R indexes [all data]**: R₁ = 0.0333, wR₂ = 0.0894

**Largest diff. peak/hole / e Å⁻³**: 0.15/-0.13
4. NMR spectra