Polarizing the Nazarov cyclization: 
Efficient Catalysis under Mild Conditions

Wei He, Xiufeng Sun, and Alison J. Frontier*

Department of Chemistry, University of Rochester, Rochester, NY, 14627

Supporting information

General Methods: All reactions were carried out in vials without argon protection. Cu(OTf)$_2$ was stored in glove box before use. Dichloroethane and dichloromethane were purchased from Fisher and distilled over calcium hydride. Column chromatography was performed on EM Science silica gel 60 (230-400 mesh). Visualization was done with potassium permanganate or ceric ammonium molybdate.

Infrared spectra were recorded on a ATI Mattson Genesis FT-IR spectrometer. $^1$H NMR and $^{13}$C NMR spectra were collected on a Bruker Amx 400 or an Avance 400 MHz spectrometer at ambient temperature. Chemical shift $\delta$ was reported in unit of parts per million downfield from tetramethylsilane. Elemental Analysis was done by MHW labs at Phoenix, AZ. HRMS was done on a ThermoFinnigan MAT 95XL with electrospray with 50% MeOH.

Preparation of substrates

All Nazarov substrates bearing ester group were prepared from Knoevenagel reaction between a $\beta$-keto ester which already contains the left olefin moiety and an aldehyde. Substrate 15a, 15f, 17a and 17f were prepared from condensation between a ketone which already contains the left olefin moiety and the corresponding aldehyde under basic conditions.

Spectroscopic data of substrates:

2-(5,6-Dihydro-4H-pyran-2-carbonyl)-3-(2,4,6-trimethoxy-phenyl)-acrylic acid methyl ester
3a
$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.90 (s, 1H), 5.98 (s, 2H), 5.79 (s, 1H), 3.98 (t, $J = 4.6$ Hz, 2H), 3.74 (s, 9H).

1 While argon protection did not generally improve yield for most substrates, after submission we found that argon protection of fairly unreactive substrates 15f and 17f gave better yields.

3H), 3.71 (s, 3H), 3.66 (s, 6H), 2.06 (d, J = 4.5 Hz, 2H), 1.75(t, J = 4.4 Hz, 2H); \(^{13}\text{C}\) NMR (CDCl\(_3\), 100 MHz) \(\delta\) 188.6, 166.7, 163.4, 159.3, 151.1, 135.3, 127.5, 111.1, 104.8, 90.0, 66.1, 55.2, 54.9, 51.8, 21.6, 20.6; IR (NaCl plate, cm\(^{-1}\)): 1712, 1603, 1460, 1336, 1255, 1206, 1156, 1127, 1056; Elemental analysis calculated for C\(_{19}\)H\(_{22}\)O\(_7\): C 62.97%; H 6.12%. Found : C 62.79%; H 6.20%.

\(\text{2-(5,6-Dihydro-4H-pyran-2-carbonyl)-3-(4-methoxy-phenyl)-acrylic acid methyl ester}\)

\(3b\) \(^{1}\text{H}\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.59 (s, 1H), 7.16 (d, J = 8.8 Hz, 2H), 6.67 (d, J = 8.8 Hz, 2H), 5.87 (t, J = 4.4 Hz, 1H), 3.93 (t, J = 5.6 Hz, 2H), 3.62 (s, 6H), 1.98 (m, 2H), 1.65 (t, J = 6 Hz, 2H); \(^{13}\text{C}\) NMR (CDCl\(_3\), 100 MHz) \(\delta\) 190.7, 165.3, 161.2, 150.9, 142.5, 132.0, 127.1, 125.2, 116.2, 114.0, 66.3, 55.1, 52.0, 21.0, 20.8; IR (NaCl plate, cm\(^{-1}\)): 1714, 1601, 1512, 1259, 1204, 1175, 734; HRMS calculated for C\(_{17}\)H\(_{18}\)O\(_5\) (M+H)\(^{+}\) 303.1224, Found : 303.1227.

\(\text{2-(5,6-Dihydro-4H-pyran-2-carbonyl)-3-(3-methoxy-phenyl)-acrylic acid methyl ester}\)

\(3c\) \(^{1}\text{H}\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.58 (s, 1H), 7.03 (t, J = 3.6 Hz, 1H), 6.75 (d, J = 9.6 Hz, 1H), 6.69 (s, 2H), 5.81 (t, J = 4.4 Hz, 1H), 3.86 (t, J = 4.6 Hz, 2H), 3.58 (s, 3H), 3.53 (s, 3H), 1.94 (d, J = 6 Hz, 2H), 1.57 (t, J = 6.0 Hz, 2H); \(^{13}\text{C}\) NMR (CDCl\(_3\), 100 MHz) \(\delta\) 189.9, 164.8, 159.3, 150.9, 142.6, 133.9, 130.3, 129.5, 122.4, 116.4, 115.8, 114.3, 66.2, 54.7, 52.1, 21.0, 20.7; IR (NaCl plate, cm\(^{-1}\)): 1715, 1671, 1624, 1236, 1051; HRMS calculated for C\(_{19}\)H\(_{18}\)O\(_5\) (M+H)\(^{+}\) 303.1233 Found : 303.1227.

\(\text{2-(5,6-Dihydro-4H-pyran-2-carbonyl)-3-phenyl-acrylic acid methyl ester}\)

\(3d\) \(^{1}\text{H}\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.58 (s, 1H), 7.13 (m, 2H), 7.04 (m, 3H), 5.77 (t, J = 4.1 Hz, 1H), 3.79 (t, J = 4.4 Hz, 2H), 3.53 (s, 3H), 1.86 (m, 2H), 1.52 (m, 2H); \(^{13}\text{C}\) NMR (CDCl\(_3\), 100 MHz) \(\delta\) 189.9, 164.8, 150.8, 142.6, 132.6, 131.1, 129.8, 128.4, 115.9, 66.1, 52.1, 52.1, 20.9, 20.6; IR (NaCl plate, cm\(^{-1}\)): 1714, 1257, 1201, 1051; Elemental analysis calculated for C\(_{16}\)H\(_{16}\)O\(_4\): C 70.57%; H 5.92%. Found : C 70.80%; H 6.02%.

\(\text{2-(5,6-Dihydro-4H-pyran-2-carbonyl)-3-furan-2-yl-acrylic acid methyl ester}\)

\(3e\) \(^{1}\text{H}\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.34 (s, 1H), 7.28 (d, J = 1.2 Hz, 1H), 6.51 (d, J = 3.6 Hz, 1H), 6.26 (q, J = 1.6 Hz, 1H), 5.77 (t, J = 3.6 Hz, 1H), 3.91 (t, J = 4.8 Hz, 2H), 3.56 (s, 3H), 1.98 (m, 2H), 1.63 (t, J = 5.2 Hz, 2H); \(^{13}\text{C}\) NMR (CDCl\(_3\), 100 MHz) \(\delta\) 189.0, 164.9, 151.1, 148.9, 146.0, 128.2, 125.8, 117.8, 115.5,
112.4, 66.2, 52.1, 22.1, 20.7; IR (NaCl plate, cm⁻¹): 1710, 1671, 1626, 1253, 1212; Elemental analysis calculated for C₁₄H₁₄O₃: C 64.12%; H 5.38%. Found: C 63.83%; H 5.42%.

3-Cyclohexyl-2-(5,6-dihydro-4H-pyran-2-carbonyl)-acrylic acid methyl ester
3f ¹H NMR (400 MHz, CDCl₃) δ 6.69 (d, J = 10.8 Hz, 1H), 5.85 (t, J = 4.4 Hz, 1H), 3.99 (t, J = 5.2 Hz, 2H), 3.60 (s, 3H), 2.08 (m, 2H), 2.03 (m, 1H), 1.76 (m, 2H), 1.54 (m, 5H), 1.02 (m, 5H); ¹³C NMR (CDCl₃, 100 MHz) δ 189.1, 164.9, 152.7, 151.5, 130.4, 115.4, 66.2, 51.8, 38.4, 31.3, 25.3, 24.8, 21.1, 20.8; IR (NaCl plate, cm⁻¹): 2925, 2853, 1738, 1713, 1645, 1444, 1300, 1266, 1216, 1162, 1123, 1071, 1034; Elemental analysis calculated for C₁₆H₂₂O₄: C 69.04%; H 7.97%. Found: C 69.17%; H 7.79%.

2-(Cyclohex-1-eneacarbonyl)-3-(2,4,6-trimethoxy-phenyl)-acrylic acid methyl ester
5a ¹H NMR (400 MHz, CDCl₃) δ 7.98 (s, 1H), 6.62 (s, 1H), 6.06 (s, 2H), 3.78 (s, 3H), 3.76 (s, 3H), 3.71 (s, 6H), 2.25 (m, 2H), 2.04 (m, 2H), 1.52 (m, 4H); ¹³C NMR (CDCl₃, 100 MHz) δ 194.8, 167.3, 163.1, 159.3, 141.5, 138.2, 134.9, 128.4, 105.3, 89.9, 55.2, 54.9, 51.9, 25.8, 22.8, 21.8, 21.6; IR (NaCl plate, cm⁻¹): 1710, 1603, 1251, 1206, 1157, 1128; Elemental analysis calculated for C₂₀H₂₄O₆: C 66.65%; H, 6.71%. Found: C 66.48%; H 6.56%.

2-(Cyclohex-1-eneacarbonyl)-3-cyclohexyl-acrylic acid methyl ester
5f A separable mixture of E and Z stereoisomers were obtained in a ratio of 10:1 (ratio of mass after column on silica). The geometry was assigned by comparing the chemical shift of the vinyl proton at β position. E isomer: ¹H NMR (400 MHz, CDCl₃) δ 6.63 (m, 2H), 3.56 (s, 3H), 2.10 (m, 4H), 1.88 (m, 1H), 1.51 (m, 9H), 1.02 (m, 5H); ¹³C NMR (CDCl₃, 100 MHz) δ 195.3, 165.1, 150.8, 144.6, 139.9, 131.2, 51.7, 38.5, 31.3, 25.9, 25.3, 24.8, 22.2, 21.5, 21.3; IR (NaCl plate, cm⁻¹): 2927, 2852, 1722, 1658, 1254, 1228; Elemental analysis calculated for C₁₇H₂₁O₅: C 73.88%; H 8.75%. Found: C 74.12%; H 8.54%.

4-Methyl-3-oxo-2-(2,4,6-trimethoxy-benzylidene)-pent-4-enoic acid methyl ester
7a ¹H NMR (400 MHz, CDCl₃) δ 7.95 (s, 1H), 5.96 (s, 2H), 5.71 (s, 1H), 5.61 (s, 1H), 3.76 (s, 3H), 3.71 (s, 3H), 3.65 (s, 6H), 1.85 (s, 3H); ¹³C NMR (CDCl₃, 100 MHz) δ 195.2, 167.2, 163.4, 159.5, 143.6, 135.0, 127.8, 125.8, 105.8, 90.1, 55.2, 54.9, 51.9, 16.8; IR (NaCl plate, cm⁻¹): 1710, 1664, 1603, 1462, 1436, 1252,
1208, 1158, 1129, 735; Elemental analysis calculated for C₁₇H₂₀O₆: C 63.74%; H 6.29%. Found: C 63.86%; H 6.35%.

2-(Benzo[1,3]dioxole-5-carbonyl)-3-(2,4,6-trimethoxy-phenyl)-acrylic acid methyl ester

9a. ¹H NMR (400 MHz, CDCl₃) δ 8.15 (s, 1H), 7.48 (q, J = 9.8 Hz, 1H), 7.44 (d, J = 1.6 Hz, 1H), 6.79 (d, J = 8.1 Hz, 1H), 6.03 (s, 2H), 5.96 (s, 2H), 3.79 (s, 3H), 3.72 (s, 3H), 3.53 (s, 6H); ¹³C NMR (CDCl₃, 100 MHz) δ 191.8, 167.2, 163.4, 159.6, 151.0, 147.6, 135.5, 132.5, 128.0, 125.1, 108.2, 107.5, 105.0, 101.5, 90.7, 55.2, 54.6, 52.0; IR (NaCl plate, cm⁻¹): 1707, 1664, 1603, 1439, 1254, 1209, 1158, 1129, 1035; Elemental analysis calculated for C₂₁H₂₆O₆: C 63.00%; H 5.03%. Found: C 63.24%; H 4.99%.

2-(2-Methyl-cyclohex-1-enecarboxy)-3-(2,4,6-trimethoxy-phenyl)-acrylic acid methyl ester

11a. ¹H NMR (400 MHz, CDCl₃) δ 7.72 (s, 1H), 6.00 (s, 2H), 3.74 (s, 3H), 3.71 (s, 3H), 3.63 (s, 6H), 2.11 (m, 2H), 2.00 (m, 2H), 1.88 (s, 3H), 1.43 (m, 4H); ¹³C NMR (CDCl₃, 100 MHz) δ 195.5, 166.9, 162.9, 159.1, 145.7, 134.6, 132.5, 131.8, 105.1, 90.2, 55.3, 55.2, 51.8, 34.2, 26.5, 22.5, 22.3, 22.0; IR (NaCl plate, cm⁻¹): 2935, 1726, 1602, 1459, 1336, 1232, 1208, 1157, 1129; Elemental analysis calculated for C₂₁H₂₆O₆: C 67.36%; H 7.00%. Found: C 67.50%; H 6.98%.

3-Oxo-2-(2,4,6-trimethoxy-benzylidene)-hex-4-enoic acid ethyl ester

13a. As an unseparable mixture of Z and E stereoisomers (0.6: 1.0 according to the integration on ¹H NMR). ¹H NMR (400 MHz, CDCl₃) δ 7.95 (s, 1H), 7.78 (s, 0.6H), 7.00 (m, 0.6H), 6.68 (m, 1H), 6.19 (d, J = 1.6 Hz, 0.6H), 6.15 (d, J = 1.6 Hz, 1H), 6.08 (m, 1.2H), 6.04 (s, 2H), 4.24 (m, 2H), 4.13 (m, 1.2H), 3.88 (s, 2.4H), 3.83 (s, 3.6H), 3.79 (s, 6H), 3.73 (s, 6H), 1.92 (d, J = 1.6 Hz, 1.2H), 1.82 (d, J = 1.8 Hz, 2H), 1.28 (m, 1.8H), 1.24 (m, 3H); ¹³C NMR (CDCl₃, 100 MHz) δ 193.0, 188.3, 167.8, 166.5, 163.5, 163.3, 159.8, 159.5, 143.7, 142.4, 136.1, 135.1, 133.0, 132.0, 129.6, 128.6, 105.8, 105.2, 90.2, 60.9, 60.4, 55.4, 55.3, 54.9, 18.4, 18.1, 14.2, 13.9; IR (NaCl plate, cm⁻¹): 1653, 1605, 1207, 1155, 1128, 500; Elemental analysis calculated for C₁₆H₁₂O₆: C 64.66%; H 6.63%. Found: C 64.75%; H 6.52%.

1-(5,6-Dihydro-4H-pyran-2-yl)-3-(2,4,6-trimethoxy-phenyl)-propenone

15a. ¹H NMR (400 MHz, CDCl₃) δ 8.14 (d, J = 16 Hz, 1H), 7.58 (d, J = 16 Hz, 1H), 6.08 (s, 2H), 6.02 (t,
\[ J = 3.6 \text{ Hz}, 1\text{H}), 4.11 (m, 2\text{H}), 3.85 (s, 6\text{H}), 3.82 (s, 3\text{H}), 2.23 (m, 2\text{H}), 1.86 (m, 2\text{H}); ^{13}\text{C NMR (CDCl}_3, 100 \text{ MHz}) \delta 186.7, 162.8, 161.5, 152.3, 134.8, 120.0, 109.6, 106.3, 90.2, 66.1, 55.6, 55.2, 21.5, 20.8; \text{IR (NaCl plate, cm}^{-1}) \]: 1567, 1463, 1324, 1206, 1177, 1157, 1120, 1062; Elemental analysis calculated for \( \text{C}_{17}\text{H}_{26}\text{O}_5 \): C 67.09%; H 6.62%. Found: C 67.18%; H 6.69%.

3-Cyclohexyl-1-(5,6-dihydro-4H-pyran-2-yl)-propenone

\[ ^{1}\text{H NMR (400 MHz, CDCl}_3) \delta 6.96 (dd, J_1 = 15.6 \text{ Hz}, J_2 = 6.8 \text{ Hz}, 1\text{H}), 6.62 (d, J = 15.6 \text{ Hz}, 1\text{H}), 6.02 (t, J = 8 \text{ Hz}, 1\text{H}), 4.11 (m, 2\text{H}), 2.24 (m, 2\text{H}), 2.21 (m, 1\text{H}), 1.86 (m, 2\text{H}), 1.17-1.75 (m, 10\text{H}); ^{13}\text{C NMR (CDCl}_3, 100 \text{ MHz}) \delta 185.9, 153.8, 151.7, 121.4, 110.7, 66.25, 43.3, 31.7, 26.4, 26.2, 21.5, 20.8; \text{IR (NaCl plate, cm}^{-1}) \]: 2926, 2853, 1725, 1632, 1448, 1309, 1280, 1243, 1176, 1062, 916; Elemental analysis calculated for \( \text{C}_{14}\text{H}_{20}\text{O}_2 \): C 76.33%; H 9.15%. Found: C 76.18%; H 9.19%.

1-Cyclohexyl-1-enyl-3-(2,4,6-trimethoxy-phenyl)-propenone

\[ ^{1}\text{H NMR (400 MHz, CDCl}_3) \delta 8.02 (d, J = 16 \text{ Hz}, 1\text{H}), 7.60 (d, J = 16 \text{ Hz}, 1\text{H}), 6.91 (t, J = 4 \text{ Hz}, 1\text{H}), 6.09 (s, 2\text{H}), 3.85 (s, 6\text{H}), 3.81 (s, 3\text{H}), 2.34 (m, 2\text{H}), 2.26 (m, 2\text{H}), 1.64(m, 4\text{H}); ^{13}\text{C NMR (CDCl}_3, 100 \text{ MHz}) \delta 192.7, 162.4, 161.2, 140.3, 138.1, 133.5, 121.4, 106.5, 90.3, 55.6, 55.2, 26.0, 23.6, 22.0, 21.6; \text{IR (NaCl plate, cm}^{-1}) \]: 2933, 1642, 1571, 1458, 1322, 1205, 1156, 1120; Elemental analysis calculated for \( \text{C}_{18}\text{H}_{25}\text{O}_4 \): C 71.50%; H 7.33%. Found: C 71.68%; H 7.25%.

1-Cyclohexyl-1-enyl-3-cyclohexyl-propenone

\[ ^{1}\text{H NMR (400 MHz, CDCl}_3) \delta 6.84 (br, m, 1\text{H}), 6.74 (dd, J_1 = 15.2 \text{ Hz}, J_2 = 7.8 \text{ Hz}, 1\text{H}), 6.52 (d, J = 15.2 \text{ Hz}, 1\text{H}), 2.20 (m, 4\text{H}), 2.08 (m, 1\text{H}), 1.70 (m, 4\text{H}), 1.56(m, 5\text{H}), 1.25 (m, 2\text{H}), 1.15 (m, 3\text{H}); ^{13}\text{C NMR (CDCl}_3, 100 \text{ MHz}) \delta 191.4, 151.6, 139.7, 139.4, 122.0, 40.6, 31.8, 25.9, 25.8, 25.6, 25.6, 23.2, 21.8, 21.4; \text{IR (NaCl plate, cm}^{-1}) \]: 2924, 2852, 1659, 1613; Elemental analysis calculated for \( \text{C}_{13}\text{H}_{22}\text{O} \): C 82.52%; H 10.16%. Found: C 82.19%; H 9.90%.

Representative procedure of Cu(OOTf)₂ catalyzed Nazarov cyclization

To a stirred suspension of Cu(OOTf)₂ (2.2 mg, 0.006 mmol, 0.02 eq.) in dichloroethane (0.5 mL) was added a solution of 5a (110 mg, 0.304 mmol, 1.00 eq.) in dichloroethane (1 mL). The resulting mixture was heated to 40 °C under vigorous stirring. After 15 minutes, TLC found complete consumption of the starting material. The reaction was then cooled down to room temperature and purified by flash chromatography on
silica eluting with 20% EtOAc/Hexanes to give 6a-1 (43 mg 40%) and 6a-2 (49 mg, 45%).

**Spectroscopic data of Nazarov products**

1-Oxo-3-(2,4,6-trimethoxy-phenyl)-2,3,3a,4,5,6-hexahydro-1H-indene-2-carboxylic acid methyl ester

6a-1  $^1$H NMR (400 MHz, CDCl$_3$) δ 6.80 (dd, $J_1 = 6.4$ Hz, $J_2 = 3.2$ Hz, 1H), 6.14 (s, 2H), 4.30 (d, $J = 12.1$ Hz, 1H), 3.80 (t, $J = 12.1$ Hz, 1H), 3.77 (s, 3H), 3.74 (s, 6H), 3.65 (s, 3H), 2.93 (m, 1H), 2.04 (m, 2H), 1.80 (m, 2H), 1.25 (m, 1H), 1.13 (m, 1H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 199.4, 170.3, 159.9, 159.7, 140.6, 134.4, 107.5, 91.1, 91.0, 57.6, 55.2, 55.0, 52.0, 40.4, 39.6, 27.1, 25.6, 21.5; IR (NaCl plate, cm$^{-1}$): 1742, 1711, 1606, 1459, 1202, 1151, 1115; Elemental analysis calculated for C$_{26}$H$_{24}$O$_6$: C 66.65%; H, 6.71%. Found : C 66.80%; H 6.75%.

1-Oxo-3-(2,4,6-trimethoxy-phenyl)-2,3,4,5,6,7-hexahydro-1H-indene-2-carboxylic acid methyl ester

6a-2  $^1$H NMR (400 MHz, CDCl$_3$) δ 6.16 (d, $J = 2.4$ Hz, 1H), 6.06 (d, $J = 2.4$ Hz, 1H), 4.84 (m, 1H), 3.81 (s, 6H), 3.74 (s, 3H), 3.67 (s, 3H), 3.59 (d, $J = 5.8$ Hz, 1H), 2.00 (m, 2H), 1.73 (m, 1H), 1.71 (m, 1H), 1.63 (m, 4H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 201.6, 177.1, 170.7, 160.4, 159.4, 159.2, 134.9, 107.2, 90.7, 58.2, 56.0, 55.2, 55.1, 41.6, 26.2, 22.1, 21.5, 20.2; IR (NaCl plate, cm$^{-1}$): 2937, 1737, 1697, 1643, 1604, 1459, 1436, 1332, 1258, 1228, 1205, 1150, 1116, 733; Elemental analysis calculated for C$_{26}$H$_{24}$O$_6$: C 66.65%; H, 6.71%. Found : C 66.81%; H 6.62%.

7-Oxo-5-(2,4,6-trimethoxy-phenyl)-2,3,4,5,6,7-hexahydro-cyclopenta[b]pyran-6-carboxylic acid methyl ester

4a  $^1$H NMR (400 MHz, CDCl$_3$) δ 6.11 (s, 1H), 6.04 (s, 1H), 4.78 (d, $J = 1.6$ Hz, 1H), 4.05 (t, $J = 4.6$ Hz, 2H), 3.74 (s, 6H), 3.69 (s, 3H), 3.64 (s, 3H), 3.54 (d, $J = 1.6$ Hz, 1H), 1.92 (m, 1H), 1.90 (m, 1H), 1.87 (m, 1H), 1.82 (m, 1H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 193.9, 170.0, 160.5, 149.5, 148.2, 106.2, 90.7, 66.6, 56.1, 55.9, 52.2, 37.1, 22.0, 21.3; IR (NaCl plate, cm$^{-1}$): 1738, 1708, 1605, 1205, 1150, 1120; X-ray crystallography please see attached cif file.
5-(4-Methoxy-phenyl)-7-oxo-2,3,4,5,6,7-hexahydro-cyclopenta[b]pyran-6-carboxylic acid methyl ester

4b $^1$H NMR (400 MHz, CDCl$_3$) δ 7.01 (d, $J = 8.8$ Hz, 2H), 6.83 (d, $J = 8.8$ Hz, 2H), 4.13 (m, 3H), 3.73 (s, 3H), 3.71 (s, 3H), 3.24 (d, $J = 2.4$ Hz, 1H), 2.10(m, 2H), 1.90(m, 2H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 193.0, 168.7, 158.9, 149.5, 147.8, 131.5, 128.2, 114.4, 66.9, 59.3, 55.2, 52.6, 46.8, 22.0, 22.1; IR (NaCl plate, cm$^{-1}$): 1738, 1713, 1648, 1512, 1250, 1162, 1122; HRMS calculated for C$_{19}$H$_{22}$O$_7$ (M+H)$^+$ 303.1216, Found : 303.1227.

5-(3-Methoxy-phenyl)-7-oxo-2,3,4,5,6,7-hexahydro-cyclopenta[b]pyran-6-carboxylic acid methyl ester

4c $^1$H NMR (400 MHz, CDCl$_3$) δ 7.23 (t, $J = 8$ Hz, 1H), 6.78 (dd, $J_1 = 8$ Hz, $J_2 = 6$ Hz, 1H), 6.69 (d, $J = 7.6$ Hz, 1H), 6.64 (d, $J = 1.6$ Hz, 1H), 4.16 (br. s, 1H), 4.08 (m, 2H), 3.75 (s, 3H), 3.73 (s, 3H), 3.29 (br. s, 1H), 2.10 (m, 2H), 1.88 (m, 2H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 192.8, 168.6, 160.0, 149.7, 147.3, 141.3, 130.1, 119.4, 113.2, 112.6, 66.9, 58.9, 58.9, 55.1, 47.5, 22.1, 21.1; IR (NaCl plate, cm$^{-1}$): 1736, 1714, 439.3; Elemental analysis calculated for C$_{17}$H$_{16}$O$_5$: C 67.54%; H 6.00%. Found : C 67.62%; H 5.94%.

7-Oxo-5-phenyl-2,3,4,5,6,7-hexahydro-cyclopenta[b]pyran-6-carboxylic acid methyl ester

4d $^1$H NMR (400 MHz, CDCl$_3$) δ 7.33 (t, $J = 7.2$ Hz, 2H), 7.28 (d, $J = 7.2$ Hz, 1H), 7.13 (d, $J = 7.2$ Hz, 2H), 4.20 (br. s, 1H), 4.15 (m, 2H), 3.75 (s, 3H), 3.32 (br. s, 1H), 2.13 (m, 1H), 2.08 (m, 1H), 1.93 (m, 2H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 192.8, 168.6, 149.7, 147.4, 139.7, 128.8, 127.6, 127.2, 66.9, 59.1, 52.8, 47.5, 22.1, 21.1; IR (NaCl plate, cm$^{-1}$): 1739, 1714, 1648, 1263, 1161, 1123; Elemental analysis calculated for C$_{16}$H$_{16}$O$_4$: C 70.57%; H 5.92%. Found : C 70.70%; H 5.78%.

5-Furan-2-yl-7-oxo-2,3,4,5,6,7-hexahydro-cyclopenta[b]pyran-6-carboxylic acid methyl ester

4e $^1$H NMR (400 MHz, CDCl$_3$) δ 7.33 (d, $J = 1.2$ Hz, 1H), 6.31 (t, $J = 1.2$ Hz, 1H), 6.17 (d, $J = 3.2$ Hz, 1H), 4.35 (d, $J = 2$ Hz, 1H), 4.13 (m, 2H), 3.76 (s, 3H), 3.52 (d, $J = 2$ Hz, 1H), 2.27 (m, 1H), 2.19 (m, 1H), 1.94 (m, 2H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 192.0, 168.4, 151.7, 149.4, 144.7, 142.4, 110.3, 107.2, 66.9, 55.5, 52.8, 40.8, 22.2, 21.1; IR (NaCl plate, cm$^{-1}$): 1715, 1649, 524; Elemental analysis calculated for C$_{14}$H$_{14}$O$_5$: C 64.12%; H 5.38%. Found : C 64.00%; H 5.51%.
5-Cyclohexyl-7-oxo-2,3,4,5,6,7-hexahydro-cyclopenta[b]pyran-6-carboxylic acid methyl ester

$4f^1$H NMR (400 MHz, CDCl$_3$) δ 4.16 (m, 1H), 4.03 (m, 1H), 3.72 (s, 3H), 3.17 (d, $J = 2.4$ Hz, 1H), 3.03 (d, $J = 2.4$ Hz, 1H), 2.33 (m, 2H), 1.93 (m, 2H), 1.69-1.74 (m, 4H), 1.07-1.24 (m, 7H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 194.1, 170.0, 149.1, 147.8, 66.8, 52.6, 51.5, 47.4, 38.2, 31.0, 26.6, 26.3, 26.1, 26.0, 22.7, 21.2; IR (NaCl plate, cm$^{-1}$): 2359, 2337, 1711, 1033, 824, 614; Elemental analysis calculated for C$_{16}$H$_{22}$O$_4$: C 69.04%; H 7.97%. Found : C 68.84%; H 7.93%.

3-Cyclohexyl-1-oxo-2,3,3a,4,5,6-hexahydro-1H-indene-2-carboxylic acid methyl ester

$6f$-1 (53% isolated yield) $^1$H NMR (400 MHz, CDCl$_3$) δ 6.79 (t, $J = 3.6$ Hz, 1H), 3.76 (s, 3H), 3.16 (d, $J = 11.6$, 1H), 2.36 (m, 2H), 2.20 (m, 2H), 2.12 (m, 1H), 1.67 (m, 1H), 1.65(m, 5H), 1.55(m, 2H), 1.15 (m, 6H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 199.2, 171.2, 140.2, 135.4, 57.8, 52.4, 51.1, 39.7, 38.7, 31.7, 29.3, 28.4, 26.7, 26.5, 26.3, 21.7; IR (NaCl plate, cm$^{-1}$): 2925, 2853, 1744, 1713, 1651, 1447, 1336, 1259, 1149, 979, 422; Elemental analysis calculated for C$_{17}$H$_{24}$O$_3$: C 73.88%; H 8.75%. Found : C 73.98%; H 8.69%.

1-Cyclohexyl-3-oxo-2,3,4,5,6,7-hexahydro-1H-indene-2-carboxylic acid methyl ester

$6f$-2 (17% isolated yield) $^1$H NMR (400 MHz, CDCl$_3$) δ 3.75 (s, 3H), 3.22 (d, $J = 2.4$ Hz, 1H), 3.11 (br, s, 1H), 2.29 (m, 2H), 2.12 (m, 2H), 1.71 (m, 9H), 1.26 (m, 5H), 0.83 (m, 1H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 200.9, 175.6, 170.5, 137.6, 53.3, 52.3, 51.8, 37.9, 31.5, 26.7, 26.4, 26.2, 26.1, 26.0, 22.0, 21.4, 20.1; IR (NaCl plate, cm$^{-1}$) 2925, 2853, 1738, 1702, 1644, 1439, 1263, 1155, 897, 730; Elemental analysis calculated for C$_{17}$H$_{24}$O$_3$: C 73.88%; H 8.75%. Found : C 74.07%; H 8.60%.

3-Methyl-2-oxo-5-(2,4,6-trimethoxy-phenyl)-cyclopent-3-ene-carboxylic acid methyl ester

$8a$ $^1$H NMR (400 MHz, CDCl$_3$) δ 7.20 (t, $J = 1.2$ Hz, 1H), 6.08 (s, 2H), 4.90 (q, $J = 2.4$ Hz, 1H), 3.76(s, 3H), 3.73 (s, 3H), 3.71 (s, 6H), 3.63 (d, $J = 2.4$ Hz, 1H), 1.80(s, 3H); $^{13}$C NMR (CDCl$_3$, 100 MHz) δ 203.6, 170.2, 161.6, 160.4, 159.1, 137.3, 107.2, 90.7, 57.4, 55.5, 55.2, 52.2, 38.4, 9.9; IR (NaCl plate, cm$^{-1}$): 1738, 1704, 1636, 1605, 1459, 1436, 1333, 1256, 1221, 1204, 1151, 1119; Elemental analysis calculated for C$_{17}$H$_{20}$O$_6$: C 63.74%; H 6.29%. Found : C 63.57%; H 6.13%.
5-Oxo-7-(2,4,6-trimethoxy-phenyl)-6,7-dihydro-5H-indeno[5,6-d][1,3]dioxole-6-carboxylic acid methyl ester
10a  $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.11 (s, 1H), 6.55 (s, 1H), 6.21 (s, 1H), 6.03(s, 3H), 5.42 (d, $J$ = 3.6 Hz, 1H), 4.00 (d, $J$ = 3.6 Hz, 1H), 3.89 (s, 3H), 3.82 (s, 3H), 3.77 (s, 3H), 3.47 (s, 3H), $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 197.9, 170.2, 160.5, 156.2, 154.3, 147.9, 129.0, 109.0, 104.4, 102.0, 91.1, 90.6, 59.8, 56.0, 55.2, 55.1, 52.3, 37.6; IR (NaCl plate, cm$^{-1}$): 1738, 1700, 1607, 1497, 1467, 1329, 1294, 1248, 1205, 1151, 1118, 1035, 815, 734; Elemental analysis calculated for C$_{21}$H$_{20}$O$_6$: C 63.00%; H 5.03%. Found: C 62.99%; H 5.22%.

3a-Methyl-1-oxo-3-(2,4,6-trimethoxy-phenyl)-2,3,3a,4,5,6-hexahydro-1H-indene-2-carboxylic acid methyl ester
12a  $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.74 (t, $J$ = 4 Hz, 1H), 6.15 (s, 2H), 4.90 (d, $J$ = 13.2 Hz, 1H), 4.05 (d, $J$ = 13.2 Hz, 1H), 3.81 (s, 3H), 3.77 (s, 6H), 3.66 (s, 3H), 2.21 (m, 2H), 1.63-1.71 (m, 4H), 1.24 (s, 3H); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 200.0, 170.6, 159.9, 144.8, 134.4, 105.9, 91.5, 55.1, 52.1, 45.6, 41.9, 34.1, 25.5, 20.6, 18.1; IR (NaCl plate, cm$^{-1}$): 1740, 1707, 1646, 1606, 1459, 1203, 1152, 1115; X-ray crystallography please see attached cif file.

3-Methyl-5-oxo-2-(2,4,6-trimethoxy-phenyl)-cyclopent-3-ene-carboxylic acid ethyl ester
14a  $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.15 (d, $J$ = 2.1 Hz, 1H), 6.06 (s, 1H), 5.92 (s, 1H), 4.92 (br. s, 1H), 4.18 (m, 2H), 3.80 (s, 6H), 3.63 (m, 4H), 1.88 (s, 3H), 1.25 (t, $J$ = 7.2 Hz, 3H); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 202.6, 182.4, 169.9, 160.6, 159.6, 159.2, 127.0, 106.4, 90.7, 90.5, 61.2, 59.1, 56.0, 55.3, 55.2, 43.8, 17.3, 14.2; IR (NaCl plate, cm$^{-1}$): 2939, 1732, 1700, 1606, 1461, 1420, 1331, 1205, 1150, 1120, 1058, 1035, 815; Elemental analysis calculated for C$_{18}$H$_{22}$O$_6$: C 64.66%; H 6.63%. Found: C 64.75%; H 6.52%.
5-(2,4,6-Trimethoxy-phenyl)-3,4,5,6-tetrahydro-2H-cyclopenta[b]pyran-7-one

16a  
$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.13 (s, 1H), 6.07 (s, 1H), 4.43 (d, $J = 5.6$ Hz, 1H), 4.06 (m, 2H), 3.80 (s, 6H), 3.63 (s, 3H), 2.66 (dd, $J_1 = 18.4$ Hz, $J_2 = 6.4$ Hz, 1H), 2.47(d, $J = 18.4$ Hz, 1H), 1.98 (m, 1H), 1.90 (m, 1H), 1.82-1.90 (m, 2H); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 200.9, 160.0, 150.0, 148.7, 108.0, 91.7, 91.9, 66.6, 56.3, 55.2, 40.3, 32.4, 22.0, 21.6; IR (NaCl plate, cm$^{-1}$): 1705, 1649, 1604, 1461, 1224, 1202, 1151, 1116; Elemental analysis calculated for C$_{17}$H$_{26}$O$_3$: C 67.09%; H 6.62%. Found : C 66.97%; H 6.80%.

5-Cyclohexyl-3,4,5,6-tetrahydro-2H-cyclopenta[b]pyran-7-one

16f  
$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 4.18 (s, 1H), 4.01 (m, 1H), 2.69 (m, 1H), 2.26 (m, 1H), 2.18 (m, 1H), 2.14 (m, 1H), 1.92 (m, 2H), 1.70 (m, 6H), 1.25-1.32(m, 5H), 1.09 (m, 1H); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 200.4, 151.2, 147.2, 66.6, 42.7, 38.6, 35.0, 31.2, 26.4, 26.3, 26.2, 26.1, 22.7, 21.4; IR (NaCl plate, cm$^{-1}$): 2922, 2851, 1708, 1644, 1117; Elemental analysis calculated for C$_{14}$H$_{20}$O$_2$: C 76.33%; H 9.15%. Found : C 76.06%; H 9.03%

3-(2,4,6-Trimethoxy-phenyl)-2,3,4,5,6,7-hexahydro-inden-1-one

18a  A mixture of stereoisomers was detected by proton NMR, but only the major product could be isolated. The yield range was determined by weighing the mass of the crude product and that of the purified major product. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.70(m, 1H), 6.16 (s, 2H), 3.80 (s, 3H), 3.78 (s, 6H), 3.45 (m, 1H), 3.14 (m, 1H), 3.05 (m, 1H), 2.31 (m, 2H), 2.29 (m, 1H), 1.87 (m, 2H), 1.83 (m, 1H), 1.43 (m, 1H); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 207.3, 159.6, 159.6, 142.4, 131.6, 109.3, 100.0, 55.6, 55.2, 41.9, 41.6, 36.6, 27.6, 25.5, 21.7; IR (NaCl plate, cm$^{-1}$): 1710, 1645, 1221, 1193, 1152, 1115, 597; HRMS calculated for C$_{18}$H$_{22}$O$_4$(M+H)$^+$ 303.1592, Found : 303.1591.

3-Cyclohexyl-2,3,3a,4,5,6-hexahydro-inden-1-one

18f A mixture of stereoisomers was detected by proton NMR, but only the major product could be isolated. The yield range was determined by weighing the mass of the crude product and that of the purified major product. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.67 (d, $J = 2.8$ Hz, 1H), 2.20-2.35 (m, 5H), 2.04 (m, 1H), 1.77 (m, 1H), 1.70(m, 3H), 1.65 (m, 2H), 1.53 (m, 3H), 1.25 (m, 3H); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 205.81, 142.0, 132.0, 47.5, 41.4, 41.0, 40.4, 32.2, 29.4, 28.6, 26.5, 26.4, 26.3, 25.2, 21.7; IR (NaCl plate, cm$^{-1}$): 2922, 2852, 1718, 1651; Elemental analysis calculated for C$_{15}$H$_{20}$O: C 82.52%; H 10.16%. Found : C 82.71%; H 9.91%.