Novel One-Pot Synthesis of Diverse $\gamma,\delta$-Unsaturated $\beta$-Ketoesters by Thermal Cascade Reactions of Diazodicarbonyl Compounds and Enol Ethers: Transformation into Substituted 3,5-Diketoesters

Rameshwar Prasad Pandit and Yong Rok Lee*
School of Chemical Engineering, Yeungnam University, Gyeongsan 712-749, Korea

yrlee@yu.ac.kr
Phone: 82-53-810-2529. Fax: 82-53-810-4631

Supplimentary Information

Contents

1. General Remarks
2. General Experimental Procedure and Characterization Data of New Compounds
3. Copies of NMR spectra of New Compounds
General Remarks

All the experiments were carried out under nitrogen. Merck precoated silica gel plates (Art. 5554) with fluorescent indicator were used for analytical TLC. Flash column chromatography was performed using silica gel 9385 (Merck). $^1$H NMR and $^{13}$C NMR spectra were recorded on a Varian VNS (300 and 75 MHz, respectively) spectrometer in CDCl$_3$ using $\delta = 7.24$ and 77.23 ppm as solvent chemical shift. Multiplicities are abbreviated as follows; s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet and dd = doublet of doublets. IR spectra were recorded on a FTIR (BIO-RAD), and HRMS was carried out at the Korean Basic Science Institute.

General Experimental procedure and Characterization Data for $\gamma$,\$-unsaturated $\beta$-ketoester (3a-3o).

The solution of $\alpha$-diazo-$\beta$-ketoesters (1.0 mmol) and enol ether (5.0 mmol) in $p$-xylene (5.0 mL) was refluxed for 6-12 h under the nitrogen gas atmosphere until the completion of reaction as indicated by thin layer chromatography. The excess solvent was removed at rotary evaporator and purified by silica gel column chromatography (Hexane: EtOAc = 20:1) to yield the expected product.

(E)-Methyl 5-ethoxy-2-methyl-3-oxopent-4-enoate (3a): Prepared from methyl 2-diazo-3-oxobutanoate 1a and ethyl vinyl ether according to general procedure in 6 h. Oil (111 mg, 60%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.60$ (1H, d, $J = 12.3$ Hz), 5.66 (1H, d, $J = 12.3$ Hz), 3.93 (2H, q, $J = 6.9$ Hz), 3.67 (3H, s), 3.52 (1H, q, $J = 7.2$ Hz), 1.33-1.28 (6H, m); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 194.3$, 171.3, 163.3, 103.4, 67.5, 52.2, 51.8, 14.4, 13.1; IR (neat): 2955, 1736, 1446, 1216, 870 cm$^{-1}$; HRMS-FAB: m/z [M+H]$^+$ calcd for C$_9$H$_{15}$O$_4$: 187.0970; found: 187.0973.

(E)-Methyl 2-methyl-3-oxo-5-propoxypent-4-enoate (3b): Prepared from methyl 2-diazo-3-oxobutanoate 1a and $n$-propyl vinyl ether according to general procedure in 6 h. Oil (112 mg, 56%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.61$ (1H, d, $J = 12.6$ Hz), 5.65 (1H, d, $J = 12.3$ Hz), 3.67 (3H, s), 3.52 (1H, q, $J = 6.9$ Hz), 1.75-1.63 (2H, m), 1.31 (3H, d, $J = 7.2$ Hz), 0.93 (3H, t, $J = 7.5$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 194.3$, 171.2, 163.5, 103.4, 77.4, 52.1, 51.6, 22.2, 13.1, 10.0; IR (neat): 2956, 1737, 1602, 1449, 1213, 1109 cm$^{-1}$; HRMS-FAB: m/z [M+H]$^+$ calcd for C$_{10}$H$_{17}$O$_4$: 201.1127; found: 201.1125.

(E)-Methyl 2-methyl-3-oxo-5-butoxypent-4-enoate (3c): Prepared from methyl 2-diazo-3-oxobutanoate 1a and $n$-butyl vinyl ether according to general procedure in 6 h. Oil (96 mg, 45%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.63$ (1H, d, $J = 12.3$ Hz), 5.67 (1H, d, $J = 12.3$ Hz), 3.69 (3H, s), 3.54 (1H, q, $J = 7.2$ Hz), 1.71-1.62 (2H, m), 1.42-1.63 (5H, m), 0.92 (3H, t, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 194.2$, 171.2, 163.5, 103.4, 71.6, 52.0, 51.6, 30.8, 18.8, 13.5, 13.1; IR (neat): 2947, 1739, 1601, 1450, 1219, 1108 cm$^{-1}$; HRMS-FAB: m/z [M+H]$^+$ calcd for C$_{11}$H$_{19}$O$_4$: 215.1283; found: 215.1284.

(E)-Methyl 5-methoxy-2-methyl-3-oxohex-4-enoate (3d): Prepared from methyl 2-diazo-3-oxobutanoate 1a and 2-methoxypropene according to general procedure in 6 h. Oil (122 mg, 66%);
$^1$H NMR (300 MHz, CDCl$_3$): $\delta = 5.47$ (1H, s), 3.66 (3H, s), 3.61 (3H, s), 3.45 (1H, q, $J = 7.2$ Hz), 2.24 (3H, s), 1.30 (3H, d, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 193.6$, 175.1, 171.8, 97.1, 55.6, 53.9, 52.1, 20.0, 13.4; IR (neat): 2952, 1739, 1443, 1212, 1085, 896 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_9$H$_{14}$O$_4$: 186.0892; found: 186.0894.

($E$)-Ethyl 5-ethoxy-2-methyl-3-oxopent-4-enoate (3e): Prepared from ethyl 2-diazo-3-oxobutanoate 1b and ethyl vinyl ether according to general procedure in 6 h. Oil (118 mg, 59%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.61$ (1H, d, $J = 12.6$ Hz), 5.67 (1H, d, $J = 12.3$ Hz), 4.14 (2H, q, $J = 7.2$ Hz), 3.93 (2H, q, $J = 7.2$ Hz), 3.51 (1H, q, $J = 6.9$ Hz), 1.34-1.29 (6H, m), 1.22 (3H, t, $J = 6.9$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 194.6, 171.1, 163.3, 103.7, 67.7, 61.3, 52.2, 14.6, 14.2, 13.3$; IR (neat): 2980, 1731, 1609, 1195, 1102 cm$^{-1}$; HRMS-FAB: $m/z$ [M+H]$^+$ calcd for C$_{10}$H$_{17}$O$_4$: 201.1127; found: 201.1129.

($E$)-Ethyl 5-methoxy-2-methyl-3-oxohex-4-enoate (3f): Prepared from ethyl 2-diazo-3-oxobutanoate 1b and 2-methoxypropene according to general procedure in 6 h. Oil (140 mg, 70%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 5.51$ (1H, s), 4.15 (2H, q, $J = 7.2$ Hz), 3.63 (3H, s), 3.45 (1H, q, $J = 6.9$ Hz), 2.27 (3H, s), 1.32 (3H, d, $J = 7.2$ Hz), 1.22 (3H, t, $J = 6.9$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 193.6, 174.8, 171.3, 97.1, 60.9, 55.5, 54.1, 19.9, 14.1, 13.3$; IR (neat): 2978, 1730, 1584, 1445, 1181, 821 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{10}$H$_{16}$O$_4$: 200.1049; found: 200.1050.

($E$)-Allyl 5-methoxy-2-methyl-3-oxohex-4-enoate (3g): Prepared from methyl 3-methylbut-2-enyl 2-diazo-3-oxobutanoate 1c and 2-methoxypropene according to general procedure in 10 h. Oil (161 mg, 76%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 5.94-5.81$ (1H, m), 5.51 (1H, s), 5.32-5.18 (2H, m), 4.60 (2H, dd, $J = 5.7, 1.5$ Hz), 3.64 (3H, s), 3.50 (1H, q, $J = 7.2$ Hz), 2.28 (3H, s), 1.34 (3H, d, $J = 6.9$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 193.3, 174.9, 170.8, 131.8, 118.1, 97.1, 65.4, 55.5, 53.9, 19.9, 13.2$; IR (neat): 2976, 1736, 1582, 1438, 1264, 1183, 910, 820 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{11}$H$_{16}$O$_4$: 212.1049; found: 212.1045.

($E$)-Methyl 5-methoxy-3-oxo-2-phenylhex-4-enoate (3h): Prepared from methyl 2-diazo-3-oxo-3-phenylpropanoate 1d and 2-methoxypropene according to general procedure in 12 h. Oil (164 mg, 66%); this compound was isolated as an inseparable mixture of keto enol tautomer (keto:enol = 90:10). The characterization of keto tautomer is as follows. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.39-7.30$ (5H, m), 5.39 (1H, s), 4.70 (1H, s), 3.74 (3H, s), 3.54 (3H, s), 2.28 (3H, s); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 191.3, 175.2, 169.4, 133.6, 129.1, 129.1, 128.3, 128.3, 127.6, 97.4, 65.4, 55.5, 53.9, 19.7$; IR (neat): 2951, 1742, 1581, 1438, 1273 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{14}$H$_{16}$O$_4$: 248.1049; found: 248.1045.

($E$)-Methyl 5-methoxy-3-oxo-2-p-tolylhex-4-enoate (3i): Prepared from methyl 2-diazo-3-oxo-3-p-tolylpropanoate 1e and 2-methoxypropene according to general procedure in 12 h. Oil (184 mg, 70%); this compound was isolated as an inseparable mixture of keto enol tautomer (keto:enol = 88:22). The characterization of keto tautomer is as follows. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.19$ (2H, d, $J = 8.1$ Hz), 7.09 (2H, d, $J = 8.4$ Hz), 5.33 (1H, s), 4.59 (1H, s), 3.66 (3H, s), 3.47 (3H, s), 2.48 (3H, s), 1.29 (3H, s), 1.22 (3H, t, $J = 6.9$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 193.3, 175.2, 169.4, 133.6, 129.1, 129.1, 128.3, 128.3, 127.6, 97.4, 65.4, 55.5, 53.9, 19.7$; IR (neat): 2951, 1742, 1581, 1438, 1273 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{14}$H$_{16}$O$_4$: 248.1049; found: 248.1045.
2.26 (3H, s), 2.21 (3H, s); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ = 192.0, 175.6, 170.1, 137.8, 131.1, 129.5, 129.4, 129.4, 97.8, 65.8, 55.7, 52.5, 21.3, 20.2; IR (neat): 2948, 1740, 1586, 1436, 1222 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{15}$H$_{18}$O$_4$: 278.1154; found: 178.1150.

(E)-Methyl 5-methoxy-2-(4-methoxyphenyl)-3-oxohex-4-enoate (3j): Prepared from methyl 2-diazo-3-(4-methoxyphenyl)-3-oxopropanoate 1f and 2-methoxypropene according to general procedure in 12 h. Oil (192 mg, 69%); this compound was isolated as an inseparable mixture of keto enol tautomer (keto:enol = 92:8). The characterization of keto tautomer is as follows. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 7.31 (2H, d, $J$ = 8.4 Hz), 6.90 (2H, d, $J$ = 8.4 Hz), 5.41 (1H, s), 4.67 (1H, s), 3.80 (3H, s), 3.75 (3H, s), 3.56 (3H, s), 2.30 (3H, s); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ = 192.1, 175.5, 170.2, 159.5, 130.6, 130.6, 126.2, 114.2, 114.2, 97.8, 65.3, 55.7, 55.4, 52.5, 20.1; IR (neat): 2951, 1739, 1594, 1443, 1252, 1173, 1033, 827 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{15}$H$_{18}$O$_4$: 278.1154; found: 278.1150.

(E)-Ethyl 5-methoxy-3-oxo-2-phenylhex-4-enoate (3k): Prepared from ethyl 2-diazo-3-oxo-3-phenylpropanoate 1g and 2-methoxypropene according to general procedure in 12 h. Oil (189 mg, 72%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 7.38-7.28 (5H, m), 5.40 (1H, s), 4.66 (1H, s), 4.19 (2H, q, $J$ = 7.2 Hz), 3.52 (3H, s), 2.27 (3H, s), 1.25 (3H, t, $J$ = 7.2 Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ = 191.7, 175.4, 169.3, 134.1, 129.5, 129.5, 128.6, 128.6, 127.9, 97.8, 66.1, 61.3, 55.6, 20.1, 14.1; IR (neat): 2950, 2350, 1741, 1597, 1452, 1162 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{15}$H$_{18}$O$_4$: 262.1205; found: 262.1205.

(E)-Methyl 5-methoxy-2-(4-methylphenethyl)-3-oxohex-4-enoate (3l): Prepared from methyl 2-diazo-3-oxo-5-$p$-tolylpentanoate 1i and 2-methoxypropene according to general procedure in 12 h. Oil (197 mg, 68%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 7.04-7.06 (4H, m), 5.45 (1H, s), 3.66 (3H, s), 3.62 (3H, s), 3.39 (1H, t, $J$ = 7.2 Hz), 2.56 (2H, t, $J$ = 7.5 Hz), 2.29 (3H, s), 2.28 (3H, s), 2.20-2.01 (2H, m); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ = 192.9, 175.3, 171.1, 138.0, 135.5, 129.1, 129.1, 128.4, 128.4, 97.6, 59.4, 55.7, 52.2, 33.1, 30.5, 21.0, 20.2; IR (neat): 2942, 1738, 1679, 1580, 1437, 1265, 813 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{17}$H$_{22}$O$_4$: 290.1518; found: 290.1521.

(E)-Methyl 5-methoxy-2-(4-methoxyphenethyl)-3-oxohex-4-enoate (3m): Prepared from methyl 2-diazo-5-(4-methoxyphenyl)-3-oxopentanoate 1j and 2-methoxypropene according to general procedure in 12 h. Oil (186 mg, 61%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 7.07 (2H, d, $J$ = 7.8 Hz), 6.80 (2H, d, $J$ = 8.4 Hz), 5.45 (1H, s), 3.76 (3H, s), 3.68 (3H, s), 3.62 (3H, s), 3.38 (1H, t, $J$ = 6.9 Hz), 2.54 (2H, t, $J$ = 7.5 Hz), 2.28 (3H, s), 2.18-2.09 (2H, m); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ = 192.9, 175.3, 171.1, 158.1, 133.2, 129.5, 129.5, 113.9, 113.9, 97.6, 59.4, 55.7, 55.3, 52.2, 32.7, 30.7, 20.1; IR (neat): 2944, 1734, 1584, 1444, 1249, 1045, 822 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{17}$H$_{22}$O$_5$: 306.1467; found: 306.1469.

(E)-Methyl 3-(3,4-dihydro-$2H$-pyran-5-yl)-2-methyl-3-oxopropanoate (3n): Prepared from methyl 2-diazo-3-oxobutanoate 1a and 3,4-dihydro-$2H$-pyran according to general procedure in 6 h. Oil (114 mg, 58%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 7.66 (1H, s), 4.07 (2H, t, $J$ = 6.0 Hz), 3.87 (1H,
q, $J = 7.2$ Hz), 3.67 (3H, s), 2.28-2.24 (2H, m), 1.87-1.81 (2H, m), 1.34 (3H, d, $J = 6.9$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 194.1, 171.5, 158.0, 115.9, 67.2, 52.3, 46.4, 20.9, 18.5, 14.2$; IR (neat): 2945, 1738, 1622, 1447, 1181, 905 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{10}$H$_{14}$O$_4$: 198.0892; found: 198.0891.

**Ethyl 3-(3,4-dihydro-2H-pyran-5-yl)-3-oxo-2-phenylpropanoate (3o):** Prepared from ethyl 2-diazo-3-oxo-3-phenylpropanoate 1g and 3,4-dihydro-2H-pyran according to general procedure in 12 h. Off-white solid; mp 70-72 °C (167 mg, 61%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 7.64$ (1H, s), 7.32-7.25 (5H, m), 5.06 (1H, s), 4.17 (2H, q, $J = 7.2$ Hz), 4.01 (2H, t, $J = 5.4$ Hz), 2.31-2.17 (2H, m), 1.83-1.76 (2H, m), 1.23 (3H, t, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 194.6, 169.0, 158.4, 134.0, 129.3, 129.3, 128.5, 128.5, 127.7, 115.6, 67.1, 61.4, 59.0, 20.8, 18.6, 14.0$; IR (KBr): 2962, 1743, 1617, 1243, 1178 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{16}$H$_{18}$O$_4$: 274.1205; found: 274.1203.

**General Experimental procedure and Characterization Data for 3,5-diketoesters (9a-9i).**

To the solution of enone (0.5 mmol) in alcohol (3.0 mL) was added $p$-toluenesulfonic acid monohydrate (0.5 mmol) and refluxed for 2-10 h until completion of reaction as indicated by thin layer chromatography. The excess solvent was removed at rotary evaporator and purified by silica gel column chromatography (Hexane: EtOAc = 20:1) to yield the expected product.

**Methyl 2-methyl-3,5-dioxohexanoate (9a):** Prepared from 3d according to general procedure in 10 h. Oil (61 mg, 71%). This compound was isolated as an inseparable mixture of tautomers in a ratio (keto:enol =14:86). The characterization of enol tautomer is as follows. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 5.54$ (1H, s), 3.68 (3H, s), 3.34 (1H, q, $J = 7.2$ Hz), 2.02 (3H, s), 1.35 (3H, d, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 192.5, 189.4, 171.3, 99.0, 52.5, 49.3, 24.1, 14.0$; IR (neat): 1742, 1610, 1450 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_8$H$_{12}$O$_4$: 172.0736; found: 172.0733.

**Ethyl 2-methyl-3,5-dioxohexanoate (9b):** Prepared from 3f according to general procedure in 6 h. Oil (68 mg, 73%). This compound was isolated as an inseparable mixture of tautomers in a ratio (keto:enol =12:88). The characterization of enol tautomer is as follows. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 5.51$ (1H, s), 4.12 (2H, q, $J = 7.2$ Hz), 3.29 (1H, q, $J = 7.2$ Hz), 2.00 (3H, s), 1.31 (3H, d, $J = 7.2$ Hz), 1.20 (3H, t, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 192.7, 189.3, 170.9, 98.9, 61.4, 49.5, 24.2, 14.2, 14.0$; IR (neat): 2990, 2344, 1740, 1618, 1453, 1453, 1240, 1088 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_9$H$_{14}$O$_4$: 186.0892; found: 186.0889.

**Allyl 2-methyl-3,5-dioxohexanoate (9c):** Prepared from 3g according to general procedure in 5 h. Oil (59 mg, 60%). This compound was isolated as an inseparable mixture of tautomers in a ratio (keto:enol =15:85). The characterization of enol tautomer is as follows. $^1$H NMR (300 MHz, CDCl$_3$): $\delta = 5.94-5.81$ (1H, m), 5.56 (1H, s), 5.31-5.19 (2H, m), 4.60 (2H, d, $J = 5.7$ Hz), 3.37 (1H, q, $J = 7.2$ Hz), 2.03 (3H, s), 1.37 (3H, d, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta = 192.4, 189.5, 170.7, 131.8, 118.7, 99.0, 66.0, 49.5, 24.3, 14.1$; IR (neat): 2944, 1738, 1614, 1445, 1188, 1086, 934 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{10}$H$_{14}$O$_4$: 198.0892; found: 198.0891.
Methyl 3,5-dioxo-2-p-tolylhexanoate (9d): Prepared from 3i according to general procedure in 6 h. Oil (67 mg, 54%). This compound was isolated as an inseparable mixture of tautomers in a ratio (keto:enol = 22:78). The characterization of enol tautomer is as follows. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \(\delta = 7.19 (2H, d, J = 8.1 \text{ Hz}), 7.10 (2H, d, J = 8.4 \text{ Hz}), 5.42 (1H, s), 4.48 (1H, s), 3.67 (3H, s), 2.27 (3H, s), 1.93 (3H, s); \(^13\)C NMR (75 MHz, CDCl\(_3\)): \(\delta = 191.5, 188.7, 169.7, 138.3, 130.7, 129.7, 129.2, 99.8, 61.1, 52.8, 24.0, 21.3\); IR (neat): 2945, 1740, 1612, 1438, 1225 cm\(^{-1}\); HRMS (EI): \(m/z [M^+]\) calcd for C\(_{14}\)H\(_{16}\)O\(_4\): 248.1049; found: 248.1050.

Methyl 2-(4-methoxyphenyl)-3,5-dioxohexanoate (9e): Prepared from 3j according to general procedure in 6 h. Oil (68 mg, 52%). This compound was isolated as an inseparable mixture of tautomers in a ratio (keto:enol = 25:75). The characterization of enol tautomer is as follows. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \(\delta = 7.23 (2H, d, J = 8.7 \text{ Hz}), 6.82 (2H, d, J = 8.7 \text{ Hz}), 5.41 (1H, s), 4.46 (1H, s), 3.73 (3H, s), 3.67 (3H, s), 1.93 (3H, s); \(^13\)C NMR (75 MHz, CDCl\(_3\)): \(\delta = 191.7, 188.6, 169.8, 132.2, 130.5, 130.5, 125.7, 114.4, 114.4, 99.7, 60.6, 55.4, 52.8, 24.0\); IR (neat): 2952, 1739, 1610, 1513, 1444, 1250, 1029 cm\(^{-1}\); HRMS (EI): \(m/z [M^+]\) calcd for C\(_{14}\)H\(_{16}\)O\(_5\): 264.0998; found: 264.0999.

Ethyl 3,5-dioxo-2-phenylhexanoate (9f): Prepared from 3k according to general procedure in 2 h. Semisolid (122 mg, 50%). This compound was isolated as an inseparable mixture of tautomers in a ratio (keto:enol = 27:73). The characterization of enol tautomer is as follows. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \(\delta = 7.39-7.29 (5H, m), 5.49 (1H, s), 4.56 (1H, s), 4.20 (2H, q, J = 7.2 \text{ Hz}), 1.98 (3H, s), 1.25 (3H, t, J = 7.2 \text{ Hz}); \(^13\)C NMR (75 MHz, CDCl\(_3\)): \(\delta = 191.2, 188.5, 168.8, 133.5, 129.1, 129.1, 128.7, 128.7, 128.1, 99.6, 61.6, 61.3, 23.8, 14.0\); IR (neat): 2982, 1736, 1611, 1233, 1031, 712 cm\(^{-1}\); HRMS (EI): \(m/z [M^+]\) calcd for C\(_{14}\)H\(_{16}\)O\(_4\): 248.1049; found: 248.1051.

Methyl 2-(4-methylphenethyl)-3,5-dioxohexanoate (9g): Prepared from 3m according to general procedure in 6 h. Oil (85 mg, 62%). This compound was isolated as an enol (keto:enol = 0:100). The characterization of enol tautomer is as follows. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \(\delta = 7.08-7.01 (4H, m), 5.44 (1H, s), 3.70 (3H, s), 3.24 (1H, t, J = 7.2 \text{ Hz}), 2.57 (2H, t, J = 7.5 \text{ Hz}), 2.29 (3H, s), 2.21-2.09 (2H, m), 2.04 (3H, s); \(^13\)C NMR (75 MHz, CDCl\(_3\)): \(\delta = 191.4, 189.6, 170.7, 137.7, 135.8, 129.3, 129.3, 128.5, 128.5, 99.7, 54.6, 52.6, 33.0, 31.0, 24.3, 21.1\); IR (neat): 2941, 1736, 1610, 1439, 1221, 1157, 1033, 801 cm\(^{-1}\); HRMS (EI): \(m/z [M^+]\) calcd for C\(_{16}\)H\(_{20}\)O\(_4\): 276.1362; found: 276.1362.

Methyl 2-(4-methoxyphenethyl)-3,5-dioxohexanoate (9h): Prepared from 3n according to general procedure in 6 h. Oil (77 mg, 53%). This compound was isolated as an enol (keto:enol = 0:100). The characterization of enol tautomer is as follows. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \(\delta = 7.08-7.01 (4H, m), 5.54 (1H, s), 3.70 (3H, s), 3.24 (1H, t, J = 7.2 \text{ Hz}), 2.57 (2H, t, J = 7.5 \text{ Hz}), 2.29 (3H, s), 2.21-2.09 (2H, m), 2.04 (3H, s); \(^13\)C NMR (75 MHz, CDCl\(_3\)): \(\delta = 191.4, 189.6, 170.7, 137.7, 135.8, 129.3, 129.3, 128.5, 128.5, 99.7, 54.6, 52.6, 33.0, 31.0, 24.3, 21.1\); IR (neat): 2941, 1736, 1610, 1439, 1221, 1157, 1033, 801 cm\(^{-1}\); HRMS (EI): \(m/z [M^+]\) calcd for C\(_{16}\)H\(_{20}\)O\(_5\): 292.1311; found: 292.1312.
**Methyl 5,5-dimethoxy-2-methyl-3-oxopentanoate (9i):** Prepared from 3a according to general procedure in 12 h. Oil (56 mg, 55%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 4.76 (1H, d, $J = 5.7$ Hz), 3.71 (3H, s), 3.56 (1H, q, $J = 6.9$ Hz), 3.34 (3H, s), 3.33 (3H, s), 2.83 (2H, d, $J = 5.4$ Hz), 1.31 (3H, d, $J = 7.2$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 202.7, 167.0, 101.8, 54.5, 54.0, 53.6, 52.6, 45.5, 12.6; IR (neat): 2947, 1735, 1449, 1244, 1113 cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_9$H$_{16}$O$_5$:204.0998; found: 204.0994.

**4-Hydroxy-3,6-dimethyl-2H-pyran-2-one (10):**$^{28a}$ To a solution of ester 9a (53 mg, 0.31 mmol) in benzene (1 mL) was added DBU (48 mg, 0.31 mmol). The mixture was stirred under reflux for 1 h. After cooling to room temperature, 1M HCl solution (20 mL) was added and resulting solution was extracted with EtOAc. The combined organic layers were washed with brine and dried over anhydrous Na$_2$SO$_4$, filtered and concentrated in vacuo. The residue was crystallized from CHCl$_3$ and MeOH to afford 10 as white solid; mp: 105-107 $^\circ$C (35 mg, 81%). $^1$H NMR (300 MHz, CDCl$_3$+CD$_3$OD): $\delta$ = 5.77 (1H, s), 2.08(3H, s), 1.79 (3H, s); $^{13}$C NMR (75 MHz, CDCl$_3$+CD$_3$OD): $\delta$ = 167.8, 166.1, 159.5, 100.7, 98.3, 19.5, 7.9; IR (KBr): 2902, 2675, 1647, 1576, 1397, 1248, 862 cm$^{-1}$.

**Ethyl 2-hydroxy-4-methyl-1-naphthoate (11):** To the solution of 9f (0.5 mmol) in toluene (3.0 mL) was added trifluoroacetic acid (0.5 mmol) and refluxed for 12 h until completion of reaction as indicated by thin layer chromatography. The excess solvent was removed at rotary evaporator and purified by silica gel column chromatography (Hexane: EtOAc = 20:1) to yield 11 as a off-white solid; mp: 40-41$^\circ$C (51 mg, 45%); $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ = 12.2 (1H, s, OH), 8.82 (1H, d, $J = 8.7$ Hz), 7.92 (1H, d, $J = 8.4$ Hz), 7.56-7.51 (1H, m), 7.40-7.35 (1H, m), 7.03 (1H, s), 4.56 (2H, q, $J = 7.2$ Hz), 2.65 (3H, s), 1.50 (3H, t, $J = 6.9$ Hz); $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ = 172.5, 164.1, 144.2, 132.3, 128.4, 128.1, 125.9, 124.9, 123.6, 120.3, 103.5, 61.9, 20.4, 14.5; IR (KBr): 2974, 1642, 1232, cm$^{-1}$; HRMS (EI): $m/z$ [M$^+$] calcd for C$_{14}$H$_{14}$O$_3$:230.0943; found: 230.0942.
$^1$H NMR of 3b

$n$-PrO\[\begin{array}{c}
\text{\(\text{O}\)}
\end{array}\]
\[\begin{array}{c}
\text{\(\text{O}\)}
\end{array}\]
\[\begin{array}{c}
\text{\(\text{OMe}\)}
\end{array}\]

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 3b

$n$-PrO\[\begin{array}{c}
\text{\(\text{O}\)}
\end{array}\]
\[\begin{array}{c}
\text{\(\text{O}\)}
\end{array}\]
\[\begin{array}{c}
\text{\(\text{OMe}\)}
\end{array}\]

(75 MHz, CDCl$_3$)
$^1$H NMR of 3c

n-BuO\(\text{O}^{\text{O}}\text{Me}

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 3c

n-BuO\(\text{O}^{\text{O}}\text{Me}

(75 MHz, CDCl$_3$)
$^1$H NMR of 3e
\[
\text{EtO-\(\begin{array}{c}
\text{C}=\text{O} \\
\text{Et}
\end{array}\)}
\]
(300 MHz, CDCl$_3$)

$^{13}$C NMR of 3e
\[
\text{EtO-\(\begin{array}{c}
\text{C}=\text{O} \\
\text{Et}
\end{array}\)}
\]
(75 MHz, CDCl$_3$)
$^{1}H$ NMR of 3f

(300 MHz, CDCl$_3$)

$^{13}C$ NMR of 3f

(75 MHz, CDCl$_3$)
\[ ^1H \text{NMR of } 3g \]

\[
\begin{align*}
\text{MeO} & \quad \text{O} \\
\text{O} & \quad \text{MeO} \\
\text{1} & \quad \text{H} \\
\text{N} & \quad \text{M} \\
\text{Ro} & \quad \text{3g} \\
(300 \text{ MHz, CDCl}_3)
\end{align*}
\]

\[ ^{13}C \text{NMR of } 3g \]

\[
\begin{align*}
\text{MeO} & \quad \text{O} \\
\text{O} & \quad \text{MeO} \\
\text{1} & \quad \text{C} \\
\text{N} & \quad \text{M} \\
\text{Ro} & \quad \text{3g} \\
(75 \text{ MHz, CDCl}_3)
\end{align*}
\]
$^1$H NMR of 3k

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 3k

(75 MHz, CDCl$_3$)
$\text{^1H NMR of 3I}$

MeO\[-C\equiv-C\equiv-C\equiv-C\equiv\mathrm{OMe}]$

(300 MHz, CDCl$_3$)

$\text{^13C NMR of 3I}$

MeO\[-C\equiv-C\equiv-C\equiv-C\equiv\mathrm{OMe}]$

(75 MHz, CDCl$_3$)
$^1$H NMR of 3m

(300 MHz, CDCl₃)

$^{13}$C NMR of 3m

(75 MHz, CDCl₃)
$^1$H NMR of 3n

(300 MHz, CDCl$_3$)
$^{1}H$ NMR of 3o

(300 MHz, CDCl$_3$)

$^{13}C$ NMR of 3o

(75 MHz, CDCl$_3$)
$^1$H NMR of 9a

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9a

(75 MHz, CDCl$_3$)
$^1$H NMR of 9b

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9b

(75 MHz, CDCl$_3$)
$^1$H NMR of 9c

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9c

(75 MHz, CDCl$_3$)
$^1$H NMR of 9d

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9d

(75 MHz, CDCl$_3$)
$^1$H NMR of 9e

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9e

(75 MHz, CDCl$_3$)
$^{1}H$ NMR of 9g

(300 MHz, CDCl₃)

$^{13}$C NMR of 9g

(75 MHz, CDCl₃)
$^1$H NMR of 9h

![NMR spectrum of $^1$H](image)

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9h

![NMR spectrum of $^{13}$C](image)

(75 MHz, CDCl$_3$)
$^1$H NMR of 9i

(300 MHz, CDCl$_3$)

$^{13}$C NMR of 9i

(75 MHz, CDCl$_3$)
$^1$H NMR of 10

(300 MHz, CDCl$_3$+CD$_3$OD)

$^{13}$C NMR of 10

(75 MHz, CDCl$_3$+CD$_3$OD)
$\text{1}^H \text{NMR of 11}$

$\text{13C NMR of 11}$

(300 MHz, CDCl$_3$)

(75 MHz, CDCl$_3$)