Alkynyl Acylammoniums as Electrophilic 3C Synthons in a Formal [3+3] Annulation: Access to Functionalized 4H-Pyran-4-ones

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General Methods and Materials. All reactions were carried out in dry glassware, and were monitored by analytical thin-layer chromatography (TLC), which was visualized by ultraviolet light (254 nm). All solvents were obtained from commercial sources and were purified according to standard procedures. Alkynyl carboxylic acids 1\textsuperscript{[1]} and substrates 2\textsuperscript{[2]} are commercially available or prepared according to known procedures. Compound 12 was prepared from acyl chloride and imidazole according to the known procedure.\textsuperscript{[3]} Purification of the products was accomplished by flash chromatography using silica gel (200-300 mesh). All NMR spectra were recorded on Bruker spectrometers, running at 300 MHz or 500 MHz for \(^1\)H and 75 MHz or 125 MHz for \(^13\)C respectively. Chemical shifts (\(\delta\)) and coupling constants (\(J\)) are reported in ppm and Hz respectively. The solvent signals were used as references (residual CHCl\(_3\) in CDCl\(_3\): \(\delta_H = 7.26\) ppm, \(\delta_c = 77.0\) ppm). The following abbreviations are used to indicate the multiplicity in NMR spectra: s (singlet); d (doublet); t (triplet); q (quartet); m (multiplet). High resolution mass spectrometry (HRMS) was recorded on TOF perimer for ESI\(^+\).

General procedure for the synthesis of \(\gamma\)-pyrones 3/5 or \(\alpha\)-pyrones 4:

![Reaction Scheme]

To an oven-dried 25 mL round-bottom flask was charged with acid 1 (0.35 mmol), substrate 2 (0.7 mmol), CDI (97 mg, 0.6 mmol), DMAP (51 mg, 0.385 mmol), Sc(OTf)\(_3\) (30 mg, 0.06 mmol), 200 mg of 4 Å MS and NaOH (28 mg, 0.7 mmol). Then anhydrous 1,2-DCE (4 mL) was added to the flask and the resulting mixture was heated at 80 °C in air for a period time until the completion of the reaction as monitored by TLC. The mixture was cooled to room temperature. The mixture was filtered and the filtrate was concentrated under reduced pressure. The residue was purified by chromatography on silica gel using hexane/EtOAc (10:1) as the eluent to afford products 3/5 or 4.

Ethyl 2-methyl-4-oxo-6-phenyl-4\(H\)-pyran-3-carboxylate (3a). 59 mg, 65% yield, white solid, mp: 105-106 °C. \(^1\)H NMR (300 MHz, CDCl\(_3\)): \(\delta\) 7.74 (d, \(J = 6.3\) Hz, 2H), 7.44-7.54 (m, 3H), 6.77...
(s, 1H), 4.40 (q, J = 6.9 Hz, 2H), 2.49 (s, 3H), 1.38 (t, J = 6.9 Hz, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 175.7, 165.4, 164.5, 162.8, 131.4, 130.5, 128.9, 125.6, 121.6, 111.0, 61.6, 18.5, 14.0. HRMS (ESI) calcd for C$_{15}$H$_{15}$O$_4$ (M+H)$^+$: 259.0965, found 259.0964.

**Methyl 2-methyl-4-oxo-6-phenyl-4H-pyran-3-carboxylate (3b).** 48 mg, 56% yield, white solid, mp: 130-131 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.75 (d, J = 6.7 Hz, 2H), 7.47-7.54 (m, 3H), 6.81 (s, 1H), 3.93 (s, 3H), 2.51 (s, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 175.7, 166.2, 165.1, 162.9, 131.6, 130.6, 129.1, 125.7, 121.3, 111.2, 52.6, 18.8. HRMS (ESI) calcd for C$_{14}$H$_{13}$O$_4$ (M+H)$^+$: 245.0808, found 245.0805.

**tert-Butyl 2-methyl-4-oxo-6-phenyl-4H-pyran-3-carboxylate (3c).** 41 mg, 41% yield, white solid, mp: 145-146 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 7.71-7.74 (m, 2H), 7.42-7.51 (m, 3H), 6.72 (s, 1H), 2.45 (s, 3H), 1.59 (s, 9H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 175.9, 164.1, 163.8, 162.8, 131.4, 130.8, 129.0, 123.0, 111.3, 82.8, 28.1, 18.4. HRMS (ESI) calcd for C$_{17}$H$_{19}$O$_4$ (M+H)$^+$: 287.1278, found 287.1281.

**Benzyl 2-methyl-4-oxo-6-phenyl-4H-pyran-3-carboxylate (3d).** 65 mg, 58% yield, white solid, mp: 123-124 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 7.73-7.75 (m, 2H), 7.46-7.54 (m, 5H), 7.37-7.40 (m, 2H), 7.33 (m, 1H), 6.81 (s, 1H), 5.38 (s, 2H), 2.44 (s, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 175.8, 165.9, 164.5, 162.9, 135.4, 131.6, 130.6, 129.1, 128.6, 128.3, 125.8, 121.4, 111.2, 67.4, 18.7. HRMS (ESI) calcd for C$_{20}$H$_{17}$O$_4$ (M+H)$^+$: 321.1121, found 321.1118.

**Ethyl 2-ethyl-4-oxo-6-phenyl-4H-pyran-3-carboxylate (3e).** 48 mg, 50% yield, colorless liquid. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.79-7.78 (m, 2H), 7.58-7.52 (m, 3H), 6.81 (s, 1H), 4.43 (q, J = 7.1 Hz, 2H), 2.81 (q, J = 7.6 Hz, 2H), 1.41 (t, J = 7.3 Hz, 6H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 175.79, 168.79, 164.26, 162.71, 131.31, 130.46, 128.82, 125.41, 120.81, 110.68, 61.41, 25.73, 13.84, 11.38. HRMS (ESI) calcd for C$_{16}$H$_{17}$O$_4$ (M+H)$^+$: 273.1121, found 273.1125.
**Ethyl 4-oxo-2,6-diphenyl-4H-pyran-3-carboxylate (3f).** 78 mg, 70% yield, colorless liquid. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.81 (d, $J = 6.5$ Hz, 2H), 7.73 (d, $J = 7.5$ Hz, 2H), 7.50-7.58 (m, 6H), 4.28 (q, $J = 7.0$ Hz, 2H), 1.17 (t, $J = 7.0$ Hz, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 176.0, 164.3, 163.0, 161.9, 131.4, 131.2, 131.0, 130.3, 128.8, 128.5, 127.5, 125.5, 121.4, 110.5, 61.5, 13.4. HRMS (ESI) calcd for C$_{20}$H$_{17}$O$_4$ (M+H)$^+$: 321.1121, found 321.1117.

**Methyl 4-oxo-2,6-diphenyl-4H-pyran-3-carboxylate (3g).** 84 mg, 78% yield, white solid, mp: 153-154 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 7.81 (d, $J = 6.6$ Hz, 2H), 7.71 (d, $J = 6.9$ Hz, 2H), 7.52-7.57 (m, 6H), 6.90 (s, 1H), 3.80 (s, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 176.3, 165.2, 163.4, 162.4, 131.7, 131.6, 131.4, 130.7, 129.1, 128.9, 127.7, 125.9, 121.5, 110.9, 52.7. HRMS (ESI) calcd for C$_{19}$H$_{15}$O$_4$ (M+H)$^+$: 307.0965, found 307.0962.

**Methyl 2-(4-chlorophenyl)-4-oxo-6-phenyl-4H-pyran-3-carboxylate (3h).** 73 mg, 61% yield, white solid, mp: 128-129 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 7.79 (d, $J = 6.6$ Hz, 2H), 7.65 (d, $J = 8.4$ Hz, 2H), 7.49-7.54 (m, 5H), 6.89 (s, 1H), 3.82 (s, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 176.1, 165.1, 163.5, 161.2, 138.0, 131.8, 130.6, 129.8, 129.3, 129.1, 129.1, 125.9, 121.7, 111.0, 52.9. HRMS (ESI) calcd for C$_{19}$H$_{14}$ClO$_4$ (M+H)$^+$: 341.0575, found 341.0578.

**Methyl 4-oxo-6-phenyl-2-(p-tolyl)-4H-pyran-3-carboxylate (3i).** 93 mg, 83% yield, white solid, mp: 137-138 °C. $^1$H NMR (300 MHz, CDCl$_3$): $\delta$ 7.81 (d, $J = 6.9$ Hz, 2H), 7.61 (d, $J = 8.1$ Hz, 2H), 7.50-7.53 (m, 3H), 7.32 (d, $J = 7.8$ Hz, 2H), 6.89 (s, 1H), 3.81 (s, 3H), 2.44 (s, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 176.4, 165.5, 163.3, 162.6, 142.2, 131.7, 130.8, 129.7, 129.1, 128.5, 127.7, 125.9, 121.0, 110.8, 52.8, 21.5. HRMS (ESI) calcd for C$_{20}$H$_{17}$O$_4$ (M+H)$^+$: 321.1121, found 321.1121.

**3-Acetyl-2-methyl-6-phenyl-4H-pyran-4-one (3j).** 29 mg, 36% yield, white solid, mp: 140-141 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.76 (d, $J = 7.3$ Hz, 2H), 7.56-7.46
(m, 3H), 6.78 (s, 1H), 2.61 (s, 3H), 2.50 (s, 3H). $^{13}$C NMR (125MHz, CDCl$_3$): $\delta$ 200.25, 177.49, 167.22, 162.71, 131.60, 130.57, 129.08, 126.93, 125.77, 111.80, 31.93, 18.87. HRMS (ESI) calcd for C$_{14}$H$_{13}$O$_3$ (M+H)$^+$: 229.0859, found 229.0864.

3-Benzoyl-2,6-diphenyl-4$H$-pyran-4-one (3k). 38 mg, 31% yield, white solid, mp: 183-184 $^\circ$C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.93 (d, $J$ = 7.7 Hz, 2H), 7.87 (d, $J$ = 6.8 Hz, 2H), 7.63 (d, $J$ = 7.5 Hz, 2H), 7.57-7.52 (m, 4H), 7.44-7.40 (m, 3H), 7.37 (t, $J$ = 7.5 Hz, 2H), 6.93 (s, 1H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 193.13, 177.89, 163.59, 161.60, 136.58, 133.80, 131.69, 131.27, 131.18, 130.84, 129.30, 129.16, 128.80, 128.69, 128.19, 126.14, 125.91, 110.98. HRMS (ESI) calcd for C$_{24}$H$_{17}$O$_3$ (M+H)$^+$: 353.1172, found 353.1178.

Methyl 6-(4-fluorophenyl)-4-oxo-2-phenyl-4$H$-pyran-3-carboxylate (3l). 52 mg, 46% yield, white solid, mp: 166-167 $^\circ$C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.79 (s, 3H). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.80-7.82 (m, 2H), 7.69-7.71 (m, 2H), 7.57 (m, 1H), 7.50-7.53 (m, 2H), 7.20 (t, $J$ = 8.5 Hz, 2H), 6.84 (s, 1H), 3.80 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 193.13, 177.89, 163.59, 161.60, 136.58, 133.80, 131.69, 131.27, 131.18, 130.84, 129.30, 129.16, 128.80, 128.69, 128.19, 126.14, 125.91, 110.98. HRMS (ESI) calcd for C$_{19}$H$_{14}$FO$_4$ (M+H)$^+$: 325.0871, found 325.0869.

Methyl 6-(4-chlorophenyl)-4-oxo-2-phenyl-4$H$-pyran-3-carboxylate (3m). 73 mg, 61% yield, white solid, mp: 170-171 $^\circ$C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.79 (s, 3H). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.79 (s, 3H). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 176.06, 165.05, 162.42, 162.24, 138.03, 131.65, 131.18, 129.48, 129.15, 128.95, 127.70, 127.16, 121.56, 111.00, 52.74. HRMS (ESI) calcd for C$_{19}$H$_{14}$ClO$_4$ (M+H)$^+$: 341.0575, found 341.0570.

Methyl 6-(4-bromophenyl)-4-oxo-2-phenyl-4$H$-pyran-3-carboxylate (3n). 58 mg, 43% yield, white solid, mp: 191-192 $^\circ$C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.70-7.68 (m,
2H), 7.66-7.64 (m, 4H), 7.58 (t, J = 6.8 Hz, 1H), 7.53-7.51 (m, 2H), 6.88 (s, 1H), 3.79 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 176.10, 165.06, 162.49, 162.36, 132.50, 131.68, 131.22, 129.66, 128.99, 127.75, 127.34, 126.48, 121.64, 111.08, 52.79. HRMS (ESI) calcd for C$_{19}$H$_{14}$BrO$_4$ (M+H)$^+$: 385.0070, found 385.0076.

**Methyl 4-oxo-2-phenyl-6-(p-tolyl)-4H-pyran-3-carboxylate (3o).** 74 mg, 66% yield, white solid, mp: 149-150 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 6.89-7.72 (m, 4H), 7.50-7.57 (m, 3H), 7.30 (d, J = 7.5 Hz, 2H), 6.85 (s, 1H), 3.79 (s, 3H), 2.43 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 176.35, 165.31, 163.57, 162.24, 142.41, 131.50, 131.43, 129.85, 128.89, 127.87, 125.83, 121.39, 110.20, 52.69, 21.43. HRMS (ESI) calcd for C$_{20}$H$_{17}$O$_4$ (M+H)$^+$: 321.1121, found 321.1118.

**Methyl 6-(3-chlorophenyl)-4-oxo-2-phenyl-4H-pyran-3-carboxylate (3p).** 68 mg, 57% yield, white solid, mp: 96-97 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.78 (s, 1H), 7.71-7.67 (m, 3H), 7.58 (t, J = 7.3 Hz, 1H), 7.55-7.50 (m, 3H), 7.45 (t, J = 7.9 Hz, 1H), 6.88 (s, 1H), 3.80 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 176.02, 165.01, 162.58, 161.87, 135.41, 132.51, 131.70, 131.14, 130.47, 129.00, 127.75, 125.96, 124.05, 121.71, 111.59, 52.78. HRMS (ESI) calcd for C$_{19}$H$_{14}$ClO$_4$ (M+H)$^+$: 341.0575, found 341.0579.

**Methyl 4-oxo-2-phenyl-6-(m-tolyl)-4H-pyran-3-carboxylate (3q).** 49 mg, 44%, yield, white solid, mp: 132-133 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.71 (d, J = 7.2 Hz, 2H), 7.62-7.58 (m, 2H), 7.58-7.49 (m, 3H), 7.39 (t, J = 7.6 Hz, 1H), 7.35 (d, J = 7.5 Hz, 1H), 6.88 (s, 1H), 3.80 (s, 3H), 2.43 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 176.31, 165.26, 163.61, 162.37, 138.98, 132.52, 131.51, 131.39, 130.65, 129.02, 128.90, 127.73, 126.41, 123.12, 121.48, 110.83, 52.69, 21.40. HRMS (ESI) calcd for C$_{20}$H$_{17}$O$_4$ (M+H)$^+$: 321.1121, found 321.1124.
Methyl 6-(2-chlorophenyl)-4-oxo-2-phenyl-4H-pyran-3-carboxylate (3r). 50 mg, 42% yield, white solid, mp: 153-154 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.70 (d, $J = 7.5$ Hz, 2H), 7.56-7.51 (m, 3H), 7.50-7.44 (m, 3H), 7.40 (t, $J = 7.5$ Hz, 1H), 6.74 (s, 1H), 3.81 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 175.96, 165.19, 163.00, 162.58, 132.74, 132.05, 131.60, 131.09, 130.81, 130.58, 128.82, 127.76, 127.22, 121.43, 116.48, 52.76. HRMS (ESI) calcd for C$_{19}$H$_{14}$ClO$_4$ (M+H)$^+$: 341.0575, found 341.0575.

Methyl 6-(naphthalen-1-yl)-4-oxo-2-phenyl-4H-pyran-3-carboxylate (3s). 34 mg, 27% yield, white solid, mp: 153-154 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 8.10-8.09 (m, 1H), 8.03 (d, $J = 8.2$ Hz, 1H), 7.96-7.94 (m, 1H), 7.72-7.68 (m, 3H), 7.60-7.56 (m, 3H), 7.52 (t, $J = 7.3$ Hz, 1H), 7.46 (t, $J = 7.4$ Hz, 2H), 6.79 (s, 1H), 3.85 (s, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta$ 176.12, 165.34, 164.96, 162.89, 133.64, 131.66, 131.56, 131.09, 130.14, 129.37, 128.81, 128.73, 127.85, 127.67, 127.55, 126.60, 124.95, 124.32, 121.48, 116.46, 52.77. HRMS (ESI) calcd for C$_{23}$H$_{17}$O$_4$ (M+H)$^+$: 357.1121, found 357.1120.

Methyl 6-(furan-2-yl)-4-oxo-2-phenyl-4H-pyran-3-carboxylate (3t). 19 mg, 18% yield, colorless liquid. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.69-7.65 (m, 2H), 7.61 (d, $J = 1.0$ Hz, 1H), 7.57-7.53 (m, 1H), 7.50 (t, $J = 7.4$ Hz, 2H), 7.01 (d, $J = 3.5$ Hz, 1H), 6.77 (s, 1H), 6.58 (dd, $J = 3.5$, 1.7 Hz, 1H), 3.78 (s, 3H). $^{13}$C NMR (75 MHz, CDCl$_3$): $\delta$ 175.78, 165.16, 161.79, 155.31, 145.91, 145.42, 131.62, 131.20, 128.92, 127.74, 121.63, 112.87, 112.45, 108.64, 52.80. HRMS (ESI) calcd for C$_{17}$H$_{13}$O$_5$ (M+H)$^+$: 297.0757, found 297.0761.

Methyl 4-cyclopropyl-2-oxo-6-phenyl-2H-pyran-5-carboxylate (3u). 41 mg, 43% yield, colorless liquid. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 7.53 (d, $J = 8.0$ Hz, 2H), 7.49 (d, $J = 7.1$ Hz, 1H), 7.44 (t, $J = 7.5$ Hz, 2H), 6.27 (s, 1H), 3.74 (s, 3H), 1.90-1.82 (m, 1H), 1.11-1.04 (m, 4H).
$^{13}$C NMR (125 MHz, CDCl$_3$): δ 175.73, 169.61, 165.32, 161.72, 131.34, 131.22, 128.77, 127.41, 121.19, 111.09, 52.59, 13.83, 8.33. HRMS (ESI) calcd for C$_{18}$H$_{15}$O$_4$ (M+H)$^+$: 271.0965, found 271.0965.

**Methyl 4-oxo-6-pentyl-2-phenyl-4H-pyran-3-carboxylate (3v).** 19 mg, 18% yield, colorless liquid. $^1$H NMR (500 MHz, CDCl$_3$): δ 7.60 (d, $J = 7.5$ Hz, 2H), 7.52 (t, $J = 7.5$ Hz, 1H), 7.47 (t, $J = 7.5$ Hz, 2H), 6.26 (s, 1H), 3.77 (s, 3H), 2.59 (t, $J = 7.5$ Hz, 2H), 1.74-1.68 (m, 2H), 1.39-1.36 (m, 4H), 0.92 (t, $J = 7.0$ Hz, 3H).

$^{13}$C NMR (125 MHz, CDCl$_3$): δ 176.34, 169.26, 165.41, 162.57, 131.42, 131.38, 128.80, 127.63, 121.14, 113.37, 52.72, 33.52, 30.96, 26.28, 22.22, 13.79. HRMS (ESI) calcd for C$_{18}$H$_{21}$O$_4$ (M+H)$^+$: 301.1434, found 301.1438.

**Methyl 6-methyl-4-oxo-2-phenyl-4H-pyran-3-carboxylate (3w).** 34 mg, 40% yield, colorless liquid. $^1$H NMR (300 MHz, CDCl$_3$): δ 7.62-7.59 (m, 2H), 7.75-7.43 (m, 3H), 6.26 (s, 1H), 3.76 (s, 3H), 2.35 (s, 3H).

$^{13}$C NMR (125 MHz, CDCl$_3$): δ 176.21, 165.62, 165.35, 162.71, 131.44, 131.28, 128.78, 127.66, 121.11, 114.13, 52.69, 19.82. HRMS (ESI) calcd for C$_{14}$H$_{13}$O$_4$ (M+H)$^+$: 245.0808, found 245.0815.

**Methyl 4-methyl-2-oxo-6-phenyl-2H-pyran-5-carboxylate (4a).** 20 mg, 23% yield, white solid, mp: 99-100 °C. $^1$H NMR (500 MHz, CDCl$_3$): δ 7.57 (d, $J = 7.4$ Hz, 2H), 7.52-7.41 (m, 3H), 6.16 (s, 1H), 3.66 (s, 3H), 2.25 (s, 3H).

$^{13}$C NMR (125 MHz, CDCl$_3$): δ 166.60, 161.04, 160.32, 153.69, 131.88, 128.52, 127.80, 113.26, 112.44, 52.46, 20.16. HRMS (ESI) calcd for C$_{14}$H$_{13}$O$_4$ (M+H)$^+$: 245.0808, found 245.0811.

**Methyl 2-oxo-6-phenyl-2H-pyran-5-carboxylate (4b).** 39 mg, 48% yield, colorless liquid. $^1$H NMR (300 MHz, CDCl$_3$): δ 7.86 (d, $J = 9.7$ Hz, 1H), 7.58-7.43 (m, 5H), 6.34 (d, $J = 9.7$ Hz, 1H), 3.71 (s, 3H).

$^{13}$C NMR (75MHz, CDCl$_3$): δ 167.2, 164.9, 160.1, 144.1, 132.1, 131.2, 129.1, 128.0, 113.2, 109.4, 52.2. HRMS (ESI) calcd for C$_{13}$H$_{11}$O$_4$ (M+H)$^+$: 231.0652, found 231.0656.

**4-Oxo-2,6-diphenyl-4H-pyran-3-carbonitrile (5).** 49 mg, 51% yield, white solid,
mp: 177-178 °C. $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 8.09 (d, $J = 7.5$ Hz, 2H), 7.82 (d, $J = 7.0$ Hz, 2H), 7.68 (t, $J = 7.5$ Hz, 1H), 7.54-7.64 (m, 5H), 6.91 (s, 1H). $^{13}$C NMR (75MHz, CDCl$_3$): $\delta$ 175.1, 170.3, 163.7, 133.3, 132.4, 129.8, 129.6, 129.4, 129.2, 128.4, 126.0, 113.4, 109.9, 102.0. HRMS (ESI) calcd for C$_{18}$H$_{13}$NO$_2$ (M+H)$^+$: 274.0863, found 274.0859.

Procedure for the synthesis of compound 6 from 3a or 3g.

To a 10 mL round-bottom flask was charged with 3a/3g (0.1 mmol) and 3 mL of EtOH. Then 5 mL of 1M NaOH (aq) was added and the resulting mixture was stirred for a period of time until the completion of the reaction as monitored by TLC. The solution was acidified to pH = 3 with 1M HCl, and was subsequently extracted with DCM. Then, the organic phase was dried over anhydrous MgSO$_4$. The mixture was filtered and the filtrate was concentrated under reduced pressure. The residue was purified by chromatography on silica gel using hexane/EtOAc (1:2) as the eluent to afford product 6.

5-Hydroxy-3-oxo-5-phenylpent-4-enoic acid (6). 20 mg from 3a and 10 mg from 3g. Colorless liquid. Know compound.$^{[3]}$ $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 15.44 (brs, 1H), 7.89 (d, $J = 8.0$ Hz, 2H), 7.56 (t, $J = 7.3$ Hz, 1H), 7.47 (t, $J = 7.6$ Hz, 2H), 6.28 (s, 1H), 3.57 (s, 2H).

Procedure for the synthesis of compound 9.

To a 10 mL round-bottom flask was charged with 3g (31 mg, 0.1 mmol) and 3 mL of THF. Then 5 mL of 1M NaOH (aq) was added and the resulting mixture was stired
for a period of time until the completion of the reaction as monitored by TLC. The solution was acidified to pH = 3 with 1M HCl, and was subsequently extracted with DCM. Then, the organic phase was dried over anhydrous MgSO₄. The mixture was filtered and the filtrate was concentrated under reduced pressure. The residue was purified by chromatography on silica gel using hexane/EtOAc (1:2) as the eluent to afford 22 mg of compound 9.

**4-Oxo-2,6-diphenyl-4H-pyran-3-carboxylic acid (9).** White solid, mp: 202-203 °C.  

\[ \text{\begin{array}{c}
\text{Ph} \\
\begin{array}{c}
\text{O} \\
\text{O}
\end{array}
\begin{array}{c}
\text{O} \\
\text{OH}
\end{array}
\begin{array}{c}
\text{Ph} \\
\end{array}
\end{array} \]

\[ \delta \begin{array}{l}
7.84-7.81 (m, 2H), 7.69-7.66 (m, 2H), 7.61-7.51 (m, 6H), 7.11 (s, 1H).
\end{array} \]

\[ \text{13C NMR (125 MHz, CDCl₃): } \delta \begin{array}{l}
181.97, 173.18, 165.01, 163.06, 132.83, 131.87, 131.75, 
129.45, 129.31, 128.21, 126.33, 113.41, 110.17.
\end{array} \]

HRMS (ESI) calcd for C₁₈H₁₃O₄ (M+H)+: 293.0808, found 293.0815.

**Procedure for the synthesis of compound 10 from 9.**

\[ \text{\begin{array}{c}
\text{Ph} \\
\begin{array}{c}
\text{O} \\
\text{O}
\end{array}
\begin{array}{c}
\text{O} \\
\text{OH}
\end{array}
\begin{array}{c}
\text{Ph} \\
\end{array}
\end{array} \]

\[ \begin{array}{c}
\text{4-OMePhNH₂} \\
\text{BOP, DIPEA} \\
\text{THF} \\
\text{99%}
\end{array} \]

\[ \text{\begin{array}{c}
\text{Ph} \\
\begin{array}{c}
\text{O} \\
\text{O}
\end{array}
\begin{array}{c}
\text{O} \\
\text{N}
\end{array}
\begin{array}{c}
\text{Ph} \\
\end{array}
\end{array} \]

\[ \begin{array}{c}
\text{OMe} \\
\text{O}\end{array} \]

To a 10 mL round-bottom flask was charged with 9 (29 mg, 0.1 mmol), BOP (66 mg, 0.15 mmol), 3 mL of THF and DIPEA (26 mg, 0.2 mmol). After 5 mins, 4-OMePhNH₂ (15 mg, 0.12 mmol) was added to the solution, and the resulting mixture was stirred for a period of time until the completion of the reaction as monitored by TLC. Then, the reaction mixture was concentrated under reduced pressure. The residue was purified by chromatography on silica gel using hexane/EtOAc (3:1) as the eluent to afford 39 mg of compound 10.

**N-(4-methoxyphenyl)-4-oxo-2,6-diphenyl-4H-pyran-3-carboxamide (10).** White solid, mp: 177-178 °C. \[ \text{1H NMR (500 MHz, CDCl₃): } \delta \begin{array}{l}
10.94 (brs, 1H), 7.82 (d, J = 7.5 Hz, 2H), 7.68 (d, J = 7.0 Hz, 2H), 7.49-7.57 (m, 8H), 6.99 (s, 1H), 6.84 (d, J = 9.0 Hz, 2H), 3.78 (s, 3H).
\end{array} \]

\[ \text{13C NMR (75 MHz, CDCl₃): } \delta \begin{array}{l}
179.47, 169.65, 163.09, 160.27, 156.32, 133.18, 131.99, 131.43, 131.05, 130.13, 129.21, 128.77, 128.26, 126.02, 122.03, 118.69, 113.99, 111.24, 55.43.
\end{array} \]

HRMS (ESI) calcd for C₂₅H₂₀NO₄ (M+H)+: 393.1402, found 393.1395.
(M+H)^+: 398.1387, found 398.1395.

Procedure for the synthesis of compound 11.

To a 10 mL round-bottom flask was charged with 3a (26 mg, 0.1 mmol), 10 mg of NaBH₄ (0.25 mmol) and 3 mL of EtOH. The mixture was stirred at room temperature for 4h. The mixture was concentrated and the residue was purified by chromatography on silica gel using hexane/EtOAc (1:1) as the eluent to afford 25 mg of compound 11.

Ethyl 2-ethyl-5-hydroxy-3-oxo-5-phenylpent-4-enoate (11). Colorless liquid. ¹H NMR (300 MHz, CDCl₃): δ 15.85 (brs, 1H), 7.88 (d, J = 7.2 Hz, 2H), 7.56-7.42 (m, 3H), 6.28 (s, 1H), 4.21 (q, J = 7.1 Hz, 2H), 3.31 (t, J = 7.5 Hz, 1H), 2.09-1.90 (m, 2H), 1.28 (t, J = 7.2 Hz, 3H), 1.00 (t, J = 7.2 Hz, 3H). ¹³C NMR (125 MHz, CDCl₃): δ 193.41, 182.24, 170.23, 134.26, 132.49, 128.66, 127.05, 95.67, 61.29, 57.84, 22.98, 14.13, 11.94. HRMS (ESI) calcd for C₁₅H₁₉O₄ (M+H)^+: 263.1278, found 263.1284.

Procedure for the synthesis of product 3g from acid chloride.

To an oven-dried 25 mL round-bottom flask was charged with acid 1a (51 mg, 0.35 mmol) and 5 mL of SOCl₂. The resulting mixture was refluxed for 2h, and then SOCl₂ was removed under reduced pressure. Then, substrate 2g (125 mg, 0.7 mmol), DMAP (85 mg, 0.7 mmol), and Sc(OTf)₃ (30 mg, 0.06 mmol) was added to the residue followed by addition of anhydrous 1,2-DCE (4 mL). The resulting mixture was heated at 80°C in air for a period time until the completion of the reaction as monitored by TLC. The mixture was cooled to room temperature. The mixture was filtered and the filtrate was concentrated under reduced pressure. The residue was purified by chromatography on silica gel using hexane/EtOAc (10:1) as the eluent to afford 56
mg of product 3g (52%).

Procedure for the reaction of alkynyl acyl imidazole 12 with 2g.

To an oven-dried 10 mL round-bottom flask was charged with 12 (39 mg, 0.2 mmol) 2g (71 mg, 0.4 mmol), additive (none or certain amount of DMAP), Sc(OTf)₃ (17 mg, 0.034 mmol), 200 mg of 4 Å MS and NaOH (10 mg, 0.24 mmol). Then anhydrous 1,2-DCE (3 mL) was added to the flask and the resulting mixture was heated at 80 °C in air for a period time until the completion of the reaction as monitored by TLC. The mixture was cooled to room temperature. The mixture was concentrated under reduced pressure. The residue was purified by chromatography on silica gel using hexane/EtOAc (10:1) as the eluent to afford products 3g and/or 4g. 6 mg of 3g and 31 mg of 4g were obtained when none of additive was added. 32 mg of 3g and 5 mg of 4g were obtained when 20 mol % of DMAP was added. 40 mg of 3g was obtained when 1.1 equiv of DMAP was added.

Methyl 2-oxo-4,6-diphenyl-2H-pyran-5-carboxylate (4g).

Colorless liquid. Known compound. [5] ¹H NMR (300 MHz, CDCl₃): δ 7.64 (d, J = 6.6 Hz, 2H), 7.50-7.43 (m, 6H), 7.37-7.35 (m, 2H), 6.29 (s, 1H), 3.46 (s, 3H).

References:
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