Supporting Information

Application of Cu(I)/TEMPO/O₂ Catalytic System for Aerobic Oxidative Dehydrogenative Aromatization of Pyrrolidines
Zheng Luo, Yan Liu, Chao Wang, Danjun Fang, Junyu Zhou and Huayou Hu*

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 GENERAL INFORMATION

Unless otherwise noted, all commercial reagents and solvents were obtained from
the commercial provider and used without further purification. $^1$H NMR and $^{13}$C NMR spectra were recorded onBruker 400 MHz spectrometers. Chemical shifts were reported relative to internal tetramethylsilane (δ 0.00 ppm), CDCl$_3$ (δ 7.26 ppm) or DMSO-d$_6$ (δ 2.49 ppm) for $^1$H NMR, CDCl$_3$ (δ 77.0 ppm) or DMSO-d$_6$ (δ 39.5 ppm) for $^{13}$C NMR. Flash column chromatography was performed on 300-400 mesh silica gels. Analytical thin layer chromatography was performed with pre-coated glass baked plates (250 μ) and visualized by fluorescence. HRMS were recorded on a Aglient 6540 Q-TOF LC/MS spectrometer. IR spectra were recorded by using a Thermo Scientific Nicolet iS50 FT-IR spectrometer.

**Experimental procedure**

**General procedure for synthesis of pyrrolidines 1a-1z.$^{1-3}$**
Synthesis of α-Iminoesters. In a 100 mL round-bottomed flask, methyl, ethyl or tert-butyl glycinate hydrochloride (12 mmol, 1.2 equiv.), excess magnesium sulfate anhydrous, and Et$_3$N (12 mmol, 1.2 equiv.) in CH$_2$Cl$_2$ (10 mL) was stirred at r.t. for 1 h. Aldehyde (10 mmol, 1.0 equiv.) was added, and the mixture was stirred at r.t. overnight. The reaction was monitored by TLC. The reaction was finished, MgSO$_4$ was removed by filtration and the filtrate was washed with H$_2$O (30 mL). The aqueous phase was extracted with CH$_2$Cl$_2$ (10 mL x 3), and the combined organic layers were washed with brine. The organic phase was dried over anhydrous Na$_2$SO$_4$, filtered, and concentrated in vacuum. The crude product was used without any further purification.

Synthesis of pyrrolidines. Et$_3$N (1.53 mL, 11 mmol) was added dropwise to the mixture of α-Iminoesters, electron-deficient olefin (11 mmol, 1.1 equiv.), AgOAc (0.17g, 1.1 mmol) in toluene (10 mL). The mixture was stirred at r.t. for 12 - 24 h. The reaction was monitored by TLC. After the reaction was finished, toluene was removed by evaporation. The solid residue was suspended in CHCl$_3$ (30 mL), and the precipitate was removed by filtration. The organic phase was washed with 50 mL of water, and 50 mL of brine, dried over Na$_2$SO$_4$, and filtered, and volatiles were evaporated. The product was purified by recrystallization or column chromatography on silica gel (petroleum ether/ethyl acetate).

Synthetic procedure for N-substituted pyrrolidine 3a, 3b.

Synthetic Procedure for 3a: A mixture of 1-bromobutane (0.47 mL, 4.4 mmol), pyrrolidine 1a (0.64 g, 2 mmol), potassium carbonate (0.33 g, 2.4 mmol), and potassium iodide (66.4 mg, 0.40 mmol) in acetonitrile (5.0 mL) was stirred at 100 °C
for 8 h, and to the reaction mixture was added a saturated NaHCO₃ aqueous solution. The mixture was then extracted with ethyl acetate (15 mL) for three times. The combined organic layers were dried over anhydrous Na₂SO₄, filtered, and concentrated in vacuum. The residue was purified by flash column chromatography on silica gel (PE/EA = 2/1) to give the title compound 3a (0.75 g, 73%) as a white solid.

**Synthetic Procedure for 3b:** The compound 1e (2.0 mmol) was dissolved in 5.0 mL of methylene chloride. p-Toluene-sulfonyl chloride (572.0 mg, 3.0 mmol) and triethyl amine (810 μL, 5.0 mmol) were added subsequently, and the resulting mixture was stirred for 8 h at room temperature. To the reaction mixture was added saturated brine. The mixture was extracted with CHCl₃ (15 mL) for three times, dried over Na₂SO₄, and filtered, and volatiles were evaporated. The crude product was purified by column chromatography on silica gel (PE/EA = 3/2) to afford the compound 3b (84%) as a white solid.

**General Procedure for Synthesis of Pyrroles.**

**Condition A:** Pyrrolidine (0.3 mmol), CuCl (3.0 mg, 0.03 mmol), TEMPO (14.0 mg, 0.09 mmol) and dimethyl carbonate (1.0 mL) were added into a 15 mL glass test tube, and then the mixture was stirred under O₂ atmosphere (balloon), at 80 °C for 19h. After the reaction was finished, the mixture was cooled down to r.t. Then, the mixture was evaporated under vacuum and the crude mixture was purified by flash chromatography (silica gel, petroleum ether / ethyl acetate).

**Condition B:** Pyrrolidine (0.3 mmol), CuCl (6.0 mg, 0.06 mmol), TEMPO (14.0 mg, 0.09 mmol) and dimethyl carbonate (1.0 mL) were added into a 15 mL glass test tube, and then the mixture was stirred under air atmosphere (balloon), at 80 °C for
19h. After the reaction was finished, the mixture was cooled down to r.t. Then, the mixture was evaporated under vacuum and the crude mixture was purified by flash chromatography (silica gel, petroleum ether / ethyl acetate).

Procedure for the Gram-Scale Experiment.

\[
\begin{align*}
\text{Pyrrolidine (1a) (1.6067 g, 5.0 mmol), CuCl (49.5 mg, 0.5 mmol), TEMPO (234.4 mg, 1.5 mmol) and dimethyl carbonate (16.7 mL) were added into a 100 mL glass test tube, and then the mixture was stirred under O}_2 \text{ atmosphere (balloon), at 80 }^\circ\text{C for 19h. When the reaction was finished, the mixture was cooled down to r.t. Then, the mixture was evaporated under vacuum and the crude mixture was purified by flash chromatography (silica gel, petroleum ether / ethyl acetate). The pyrrole (2a) was isolated as a white solid in the yield of 74\% (1.18 g).}
\end{align*}
\]

One-pot Reaction for Synthesis of Pyrrole (2b).

\[
\begin{align*}
\alpha\text{-Iminoester (5) (0.36 mmol, 1.2 equiv), dimethyl maleate (6) (0.3 mmol, 1.0 equiv), AgOAc (5.0 mg, 10 mol \%) , LiOH (1.3 mg, 18 mol \%) and 0.5 mL DMC was added into a 15 mL glass test tube stirred at 40 }^\circ\text{C for 24 h, The reaction was monitored by TLC. After the reaction was finished, CuCl (3.0 mg, 10 mol \%) and TEMPO (14.0 mg, 30 mol \%) were added, followed by another 0.5 mL DMC, and then the mixture was stirred under O}_2 \text{ atmosphere (balloon), at 80 }^\circ\text{C for 19h. When the reaction was finished, the mixture was cooled down to r.t. Then, the mixture was evaporated under vacuum and the crude mixture was purified by flash chromatography (silica gel, petroleum ether / ethyl acetate). The pyrrole (2b) was isolated as a white solid in the yield of 73\% (73.5 mg).}
\end{align*}
\]
Control experiments.

In three 25-mL Schlenk tubes, pyrrolidine (1a) (0.3 mmol, 0.0964g) and Cu(OAc)$_2$·H$_2$O (1.5 mmol, 0.2995 g) or TEMPO (1.5 mmol, 0.2334g) or TEMPO$^+$BF$_4^-$ (0.75 mmol, 0.1824g) were added separately. The air in the Schlenk tube was evacuated and backfilled with Ar three times. DMC (1 mL) was added and the contents were stirred at 80 °C for 19h. After the mixture cooled down to r.t., the mixture was filtered with silica gel and washed the filter cake with CH$_2$Cl$_2$ (10 X 3 mL). The combined filtrate was concentrated in vacuo. The NMR yield of the desired product was determined by using CH$_2$Br$_2$ as an internal standard.

Table S-1: Optimized reaction conditions.
Table S-1: Optimization of reaction conditions

![Chemical structures of 1a and 2a](image)

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<tr>
<th>Entry</th>
<th>Cu salt (mol%)</th>
<th>Cocatalyst (mol%)</th>
<th>Solvent</th>
<th>Yield(%)a</th>
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Reaction conditions: copper salt and TEMPO derivatives as the catalyst, 0.2 mmol 1a, 2 mL solvent, were stirred under O₂ (balloon) at 80 °C for 19 h. a Yields were determined by ¹H NMR using CH₃Br₂ as an internal standard. b air, 80 °C, 27 h. c O₂, 60 °C, 44 h. d 1 mL solvent. e 0.3 mmol of 1a in 1 mL solvent. f Isolated yield. g 1a was recovered in 68%. h 1a was recovered in 44%. i 1a was recovered in 72%.

Table S-2: Re-optimization of reaction conditions.
Table S-2 Re-optimization of reaction condition.

![Reaction condition diagram]

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<th>Entry</th>
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<th>TEMPO (mol %)</th>
<th>Atmosphere</th>
<th>Temp (°C)</th>
<th>Yield (%)</th>
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<td>air</td>
<td>80</td>
<td>73 (68b)</td>
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</table>

Reaction conditions: CuCl and TEMPO as the catalyst, 0.3 mmol 1q, 1 mL DMC, were stirred for 19h. a Yields were determined by 1H NMR using CH₃Br₂ as an internal standard. b Isolated yield.

Characterization data of pyrrole.

Trimethyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2a).

Known compound

Yield: 76% (72.3 mg).

1H NMR (400 MHz, CDCl₃): 9.34 (br, 1H), 7.58 - 7.52 (m, 2H), 7.48 - 7.42 (m, 3H), 3.97 (s, 3H), 3.86 (s, 3H), 3.73 (s, 3H).

Trimethyl 5-(2-fluorophenyl)-1H-pyrrole-2,3,4-tricarboxylate (2b).

Known compound

Yield: 87% (87.6 mg).

1H NMR (400 MHz, CDCl₃): 10.31 (br, 1H), 7.47 (dt, J = 7.5, 1.7 Hz, 1H), 7.43 - 7.38 (m, 1H), 7.21 - 7.11 (m, 2H), 3.94 (s, 3H), 3.70 (s, 3H), 3.69 (s, 3H).

Trimethyl 5-(3-nitrophenyl)-1H-pyrrole-2,3,4-tricarboxylate (2c).

Known compound

Yield: 99% (107.5 mg).

1H NMR (400 MHz, CDCl₃): 10.54 (br, 1H), 8.45 (s, 1H), 8.25 (d, J = 8.1 Hz, 1H), 7.93 (d, J = 7.5 Hz, 1H), 7.60 (t, J = 7.8 Hz, 1H), 3.94 (s, 3H), 3.73 (s, 3H), 3.72 (s,
Trimethyl 5-(4-(methoxycarbonyl)phenyl)-1H-pyrrole-2,3,4-tricarboxylate (2d).

Physical state: white solid.

M.P: 172 - 173 °C.

Yield: 74% (82.8 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.09 (br, 1H), 8.06 (d, $J = 8.0$ Hz, 2H), 7.63 (d, $J = 8.1$ Hz, 2H), 3.95 (s, 3H), 3.93 (s, 3H), 3.78 (s, 3H), 3.71 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 166.5, 165.7, 163.0, 160.1, 138.6, 134.3, 130.8, 129.41, 129.38, 125.0, 120.2, 112.9, 52.8, 52.5, 52.3, 51.7.

IR (KBr) ν: 3289, 3027, 2957, 1721, 1691, 1577, 1566, 1496, 1453, 1438, 1405, 1355 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{18}$H$_{18}$NO$_8$: 376.1027, found 376.1033.

Trimethyl 5-(4-bromophenyl)-1H-pyrrole-2,3,4-tricarboxylate (2e).

Physical state: white solid.

M.P: 129 - 131 °C.

Yield: 83% (98.9 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.22 (br, 1H), 7.53 (d, $J = 8.4$ Hz, 2H), 7.43 (d, $J = 8.5$ Hz, 2H), 3.94 (s, 3H), 3.712 (s, 3H), 3.708 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 165.8, 163.0, 160.3, 139.0, 131.4, 131.0, 128.9, 124.9, 123.9, 119.8, 112.4, 52.8, 52.5, 51.7.

IR (KBr) ν: 3295, 2954, 1741, 1719, 1689, 1483, 1452, 1355 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{16}$H$_{15}$BrNO$_6$: 396.0077, found 396.0077.

Trimethyl 5-(naphthalen-2-yl)-1H-pyrrole-2,3,4-tricarboxylate (2f).

Physical state: yellow solid.

M.P: 126 - 128 °C.

Yield: 87% (96.0 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.37 (br, 1H), 7.98 (s, 1H), 7.89 - 7.86 (m, 3H), 7.60
(dd, J = 8.5, 1.6 Hz, 1H), 7.51 - 7.48 (m, 2H), 3.93 (s, 3H), 3.68 (s, 3H), 3.53 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 166.0, 163.2, 160.4, 140.3, 133.4, 132.7, 128.9, 128.3, 127.7, 127.6, 127.5, 127.1, 126.9, 126.6, 125.1, 119.7, 112.4, 52.8, 52.3, 51.6.

IR (KBr) v: 3269, 2952, 1697, 1571, 1526, 1499, 1469, 1450, 1365 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{20}$H$_{18}$NO$_6$: 368.1129, found 368.1133.

Trimethyl 5-(p-tolyl)-1H-pyrrole-2,3,4-tricarboxylate (2g).

Known compound$^4$

Yield: 78% (77.8 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.90 (br, 1H), 7.44 (d, J = 7.8 Hz, 2H), 7.21 (d, J = 7.8 Hz, 2H), 3.94 (s, 3H), 3.74 (s, 3H), 3.71 (s, 3H), 2.38 (s, 3H).

Trimethyl 5-(2-methoxyphenyl)-1H-pyrrole-2,3,4-tricarboxylate (2h).

Physical state: yellow solid.

M.P: 128 - 130 °C.

Yield: 79% (82.3 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.10 (br, 1H), 7.44 (d, J = 7.6, 1.7 Hz, 1H), 7.36 (dt, J = 7.9, 1.7 Hz, 1H), 7.00 - 6.94 (m, 2H), 3.94 (s, 3H), 3.76 (s, 3H), 3.73 (s, 3H), 3.68 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 166.1, 163.4, 160.3, 156.9, 136.3, 131.9, 130.9, 124.2, 120.3, 119.1, 118.6, 113.3, 111.0, 55.6, 52.7, 52.2, 51.5.

IR (KBr) v: 3306, 3002, 2950, 2840, 1733, 1712, 1686, 1608, 1584, 1566, 1523, 1499, 1470, 1447, 1359, 1301 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{17}$H$_{18}$NO$_7$: 348.1078, found 348.1086.

Trimethyl 5-(4-methoxyphenyl)-1H-pyrrole-2,3,4-tricarboxylate (2i).

Known compound$^4$

Yield: 81% (84.5 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.86 (br, 1H), 7.50 (d, J = 8.2 Hz, 2H), 6.92 (d, J = 8.2 Hz, 2H), 3.94 (s, 3H), 3.83 (s, 3H), 3.76 (s, 3H), 3.71 (s, 3H).
Trimethyl 5-(2,3,4-trimethoxyphenyl)-1H-pyrrole-2,3,4-tricarboxylate (2j).

Physical state: yellow solid.

M.P: 191 - 193°C.

Yield: 64% (77.5 mg).

\[^1\text{H} \text{NMR} \text{ (400 MHz, CDCl}_3\text{): } 9.68\text{(br, 1H), 7.32(d, } J = 8.8 \text{ Hz, 1H), 6.74(d, } J = 8.8 \text{ Hz, 1H), 3.97(s, 3H), 3.91(s, 6H), 3.88(s, 3H), 3.74(s, 6H).} \]

\[^{13}\text{C NMR} \text{ (100 MHz, CDCl}_3\text{): } 166.1, 163.4, 159.8, 154.9, 151.6, 142.1, 135.8, 126.7, 124.2, 119.1, 115.8, 112.7, 107.2, 61.5, 61.1, 56.0, 52.8, 52.3, 51.6. \]

IR (KBr) v: 3424, 3294, 2954, 1750, 1735, 1711, 1686, 1654, 1617, 1603, 1577, 1560, 1493, 1458, 1420, 1383, 1357 cm\(^{-1}\).

HRMS (ESI-TOF) m/z: [M+H]^+ calcd for C\(_{19}\)H\(_{22}\)NO\(_9\): 408.1289, found 408.1296.

Trimethyl 5-(furan-2-yl)-1H-pyrrole-2,3,4-tricarboxylate (2k).

Physical state: yellow solid.

M.P: 122 - 123 °C.

Yield: 59% (53.9 mg).

\[^1\text{H} \text{NMR} \text{ (400 MHz, CDCl}_3\text{): } 9.69\text{(br, 1H), 7.57 (d, } J = 3.6 \text{ Hz, 1H), 7.50 (d, } J = 1.8 \text{ Hz, 1H), 6.54 (dd, } J = 3.5, 1.8 \text{ Hz, 1H), 3.94 (s, 3H), 3.89(s, 3H), 3.84 (s, 3H).} \]

\[^{13}\text{C NMR} \text{ (100 MHz, CDCl}_3\text{): } 165.7, 162.7, 159.7, 143.9, 143.1, 129.8, 124.9, 119.2, 113.8, 112.6, 110.2, 52.7, 52.4, 51.8. \]

IR (KBr) v: 3375, 3278, 2954, 1750, 1735, 1711, 1701, 1686, 1654, 1617, 1603, 1577, 1560, 1493, 1458, 1420, 1383, 1357 cm\(^{-1}\).

HRMS (ESI-TOF) m/z: [M+H]^+ calcd for C\(_{14}\)H\(_{14}\)NO\(_7\): 308.0765, found 308.0767.

Trimethyl 5-(pyridin-3-yl)-1H-pyrrole-2,3,4-tricarboxylate (2l).

Known compound\(^4\)

Yield: 87% (83.1 mg).

\[^1\text{H} \text{NMR} \text{ (400 MHz, CDCl}_3\text{): } 11.60 \text{(br, 1H), 8.61 - 8.55 (m, 2H), 7.99 (dt, } J = 8.0, 1.9 \text{ Hz, 1H), 7.36 (dd, } J = 8.0, 3.1 \text{ Hz, 1H), 3.96 (s, 3H), 3.81 (s, 3H), 3.71 (s, 3H).} \]

Trimethyl 5-(thiophen-2-yl)-1H-pyrrole-2,3,4-tricarboxylate (2m).
Physical state: yellow solid.

M.P.: 118 - 120 °C.

Yield: 77% (74.7 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.87 (br, 1H), 7.55 (dd, $J = 3.8$, 1.2 Hz, 1H), 7.44 (dd, $J = 5.1$, 1.2 Hz, 1H), 7.11 - 7.05 (m, 1H), 3.94 (s, 3H), 3.81 (s, 3H), 3.78 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 165.7, 163.0, 160.0, 133.1, 130.4, 129.5, 128.2, 127.2, 125.0, 119.6, 112.2, 52.8, 52.5, 51.7.

IR (KBr) ν: 3278, 2956, 1706, 1571, 1541, 1521, 1489, 1411, 1404 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{14}$H$_{14}$NO$_6$S: 324.0536, found 324.0541.

Trimethyl 5-(1-(tert-butoxycarbonylpiperidin-4-yl))-1H-pyrrole-2,3,4-tricarboxylate (2n).

Physical state: yellow solid.

M.P.: 147 - 149 °C.

Yield: 77% (97.7 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.10 (br, 1H), 4.40 - 4.15 (m, 2H), 3.93 (s, 3H), 3.83 (s, 3H), 3.81 (s, 3H), 3.76 - 3.66 (m, 1H), 2.95 - 2.70 (m, 2H), 1.89 (dd, $J = 12.3$, 3.3 Hz, 2H), 1.80 - 1.62 (m, 2H), 1.47 (s, 9H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 166.2, 163.5, 160.1, 154.5, 145.9, 124.1, 118.7, 110.9, 79.8, 52.7, 52.4, 51.5, 44.1, 34.2, 30.8, 28.4.

IR (KBr) ν: 3304, 2955, 2856, 1744, 1716, 1686, 1576, 1522, 1489, 1411, 1404 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{20}$H$_{29}$N$_2$O$_8$: 425.1918, found 425.1934.

Trimethyl 5-(heptan-3-yl))-1H-pyrrole-2,3,4-tricarboxylate (2o).

Known compound$^4$

Yield: 84% (85.7 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.70 (br, 1H), 3.94 (s, 3H), 3.86 (s, 3H), 3.80 (s, 3H), 3.65 - 3.55 (m, 1H), 1.80 - 1.55 (m, 4H), 1.33 - 1.16 (m, 4H), 0.85 - 0.78 (m, 6H).

Trimethyl 5-(cyclohex-3-en-1-yl))-1H-pyrrole-2,3,4-tricarboxylate (2p).

Physical state: white solid.
M.P: 142 - 144 °C.
Yield: 71% (68.2 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.66 (br, 1H), 5.85 - 5.75 (m, 2H), 3.93 (s, 3H), 3.84 (s, 3H), 3.80 (s, 3H), 2.41 (dd, $J = 16.2, 5.5$ Hz, 1H), 2.27 - 2.15 (m, 2H), 2.13 - 1.77 (m, 4H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 166.3, 163.5, 160.2, 147.1, 127.8, 125.6, 124.1, 118.2, 111.1, 52.7, 52.3, 51.5, 31.1, 30.0, 27.2, 24.4.

IR (KBr) v: 3298, 2952, 2836, 1748, 1714, 1686, 1654, 1576, 1457, 1420, 1376 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{16}$H$_{20}$NO$_6$: 322.1285, found 322.1288.

Dimethyl 5-phenyl-1$H$-pyrrole-2,4-dicarboxylate (2q).

Known compound$^5$
Yield: 68% (52.9 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.92 (br, 1H), 7.69 - 7.61 (m, 2H), 7.49 - 7.42 (m, 3H), 7.41 (d, $J = 2.8$ Hz, 1H), 3.79 (s, 3H), 3.77 (s, 3H).

4-Ethyl 2-methyl 5-phenyl-1$H$-pyrrole-2,4-dicarboxylate (2r).

Physical state: white solid.

M.P: 125 - 127 °C.

Yield: 76% (62.3 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.89 (br, 1H), 7.62 (dd, $J = 7.4, 3.2$ Hz, 2H), 7.46 - 7.36 (m, 4H), 4.22 (q, $J = 7.1$ Hz, 2H), 3.77 (s, 3H), 1.26 (t, $J = 7.1$ Hz, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 164.0, 161.5, 140.9, 130.8, 129.3, 129.1, 128.1, 121.9, 118.6, 114.2, 60.0, 51.8, 14.2.

IR (KBr) v: 3310, 2977, 1720, 1696, 1567, 1473, 1431, 1347 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{15}$H$_{16}$NO$_4$: 274.1074, found 274.1073.

4-Butyl 2-methyl 5-phenyl-1$H$-pyrrole-2,4-dicarboxylate (2s).

Physical state: yellow solid.

M.P: 92 - 94 °C.
Yield: 69% (62.4 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.90 (br, 1H), 7.65 - 7.58 (m, 2H), 7.45 - 7.36 (m, 4H), 4.16 (t, $J = 6.5$ Hz, 2H), 3.77 (s, 3H), 1.65 - 1.55 (m, 2H), 1.37-1.26 (m, 2H), 0.90 (t, $J = 7.4$ Hz, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 164.1, 161.5, 140.9, 130.9, 129.3, 129.0, 128.1, 121.9, 118.5, 114.3, 64.0, 51.9, 30.7, 19.2, 13.7.

IR (KBr) $\nu$: 3280, 2964, 1713, 1691, 1465, 1446, 1432, 1345 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{17}$H$_{20}$NO$_4$: 302.1387, found 302.1391.

Methyl 4-(dimethylcarbamoyl)-5-phenyl-$1^H$-pyrrole-2-carboxylate (2t).

Physical state: white solid.

M.P: 167 - 169 °C.

Yield: 60% (49.0 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 9.78 (br, 1H), 7.52 (dd, $J = 8.2$, 1.5 Hz, 2H), 7.43 - 7.33 (m, 3H), 7.00 (d, $J = 2.6$ Hz, 1H), 3.84 (s, 3H), 3.03 (s, 3H), 2.72 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 167.6, 161.5, 134.6, 130.9, 129.0, 128.5, 126.7, 122.4, 118.4, 116.3, 51.8, 38.7, 35.0.

IR (KBr) $\nu$: 3452, 3114, 1712, 1597, 1561, 1512, 1462, 1437, 1333 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{15}$H$_{17}$N$_2$O$_3$: 273.1234, found 273.1236.

Methyl 4-((4-chlorophenyl)carbamoyl)-5-phenyl-$1^H$-pyrrole-2-carboxylate (2u).

Physical state: yellow solid.

M.P: 226 - 227 °C.

Yield: 59% (62.8 mg).

$^1$H NMR (400 MHz, DMSO-$d_6$): 12.51 (br, 1H), 9.97 (s, 1H), 7.72 (d, $J = 8.9$ Hz, 2H), 7.63 -7.57 (m, 2H), 7.47 (d, $J = 2.3$ Hz, 1H), 7.42 - 7.36 (m, 3H), 7.34 (d, $J = 8.8$ Hz, 2H), 3.83 (s, 3H).

$^{13}$C NMR (100 MHz, DMSO-$d_6$): 163.2, 161.0, 139.6, 138.9, 131.3, 129.8, 128.8, 128.7, 128.1, 127.0, 121.9, 121.8, 118.1, 116.9, 51.8.

IR (KBr) $\nu$: 3311, 1685, 1655, 1593, 1513, 1494, 1470, 1447, 1395, 1305 cm$^{-1}$.
HRMS (ESI-TOF) m/z: [M+Na]^+ calcd for C_{19}H_{15}ClN_{2}O_{3}Na: 377.0663, found 377.0669.

Methyl 4-cyano-5-phenyl-1H-pyrrole-2-carboxylate (2v).

Physical state: white solid.
M.P: 215 - 216 °C.
Yield: 70% (47.5 mg).

$^1$H NMR (400 MHz, DMSO-d$_6$): 13.12 (br, 1H), 7.83 (d, $J = 7.2$ Hz, 2H), 7.58 - 7.45 (m, 3H), 7.35 (s, 1H), 3.84 (s, 3H).

$^{13}$C NMR (100 MHz, DMSO-d$_6$): 160.3, 143.0, 130.0, 129.3, 129.1, 127.8, 124.3, 120.0, 116.9, 91.4, 52.3.

IR (KBr) $\nu$: 3266, 2960, 2224, 1690, 1519, 1472, 1445, 1429, 1416, 1346, 1317 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+Na]^+ calcd for C$_{13}$H$_{10}$N$_2$O$_2$: 249.0634, found 249.0640.

3,4-Dibutyl 2-methyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2w).

Physical state: white solid.
M.P: 56 - 58 °C.
Yield: 75% (90.3 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.06 (br, 1H), 7.54 (dd, $J = 6.7$, 3.0, 2H), 7.44 - 7.36 (m, 3H), 4.35 (t, $J = 6.7$ Hz, 2H), 4.11 (t, $J = 6.5$ Hz, 2H), 3.70 (s, 3H), 1.80 - 1.70 (m, 2H), 1.57 - 1.40 (m, 4H), 1.28 - 1.17 (m, 2H), 0.97 (t, $J = 7.4$ Hz, 3H), 0.85 (t, $J = 7.3$ Hz, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 165.6, 162.8, 160.5, 140.2, 130.3, 129.5, 129.3, 128.1, 125.2, 119.3, 112.5, 65.7, 64.4, 52.2, 30.6, 30.5, 19.2, 19.0, 13.7, 13.6.

IR (KBr) $\nu$: 3269, 2958, 2874, 1735, 1719, 1686, 1485, 1459, 1357 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]^+ calcd for C$_{22}$H$_{28}$NO$_6$: 402.1911, found 402.1919.

2-Ethyl 3,4-dimethyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2x).

Known compound$^6$
Yield: 75% (74.6 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.40 (br, 1H), 7.55 (dd, $J = 6.7$, 3.0 Hz, 2H), 7.42 - 7.37 (m, 3H), 4.05 (q, $J = 7.1$ Hz, 2H), 3.92 (s, 3H), 3.69 (s, 3H), 1.23 (t, $J = 7.1$ Hz, 3H).

2-(Tert-butyl) 3,4-dimethyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2y).

Known compound

Yield: 76% (82.4 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.02 (br, 1H), 7.53 - 7.51 (m, 2H), 7.41 - 7.40 (m, 3H), 3.92 (s, 3H), 3.69 (s, 3H), 1.39 (s, 9H).

Dimethyl 2-cyano-5-phenyl-1H-pyrrole-3,4-dicarboxylate (2z).

Known compound

Yield: 30% (25.6 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 10.41 (br, 1H), 7.49 - 7.43 (m, 2H), 7.43 - 7.37 (m, 3H), 3.89 (s, 3H), 3.82 (s, 3H).

Characterization Data of 3.

Trimethyl 1-butyl-5-phenylpyrrolidine-2,3,4-tricarboxylate (3a).

Physical state: white solid.

M.P: 84 - 85°C.

$^1$H NMR (400 MHz, CDCl$_3$): 7.44 (d, $J = 6.9$ Hz, 2H), 7.30 (t, $J = 7.2$ Hz, 2H), 7.24 (t, $J = 7.3$ Hz, 1H), 4.20 (d, $J = 6.8$ Hz, 1H), 3.95 (d, $J = 9.6$ Hz, 1H), 3.80 (s, 3H), 3.72 (s, 3H), 3.53 (dd, $J = 9.6$, 6.7 Hz, 1H), 3.36 (t, $J = 6.8$ Hz, 1H), 3.20 (s, 3H), 2.77 - 2.67 (m, 1H), 2.62 - 2.51 (m, 1H), 1.53 - 1.41 (m, 1H), 1.41 - 1.22 (m, 2H), 1.22 - 1.11 (m, 1H), 0.82 (t, $J = 7.1$ Hz, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 172.6, 170.2, 169.9, 138.5, 128.0, 127.8, 127.6, 70.0, 65.3, 53.7, 52.0, 51.9, 51.6, 51.0, 47.9, 29.0, 20.4, 13.9.

IR (KBr) v: 3456, 2951, 2871, 1760, 1750, 1701, 1494, 1455, 1437, 1384, 1352, 1318 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{20}$H$_{28}$NO$_6$: 378.1911, found 378.1918.
Trimethyl 5-phenyl-1-tosylpyrrolidine-2,3,4-tricarboxylate (3b).

Physical state: white solid.

M.P: 166 - 167 °C.

$^1$H NMR (400 MHz, CDCl$_3$): 7.54 (d, $J = 8.3$ Hz, 2H), 7.22 (d, $J = 8.4$ Hz, 2H), 7.16 (d, $J = 8.4$ Hz, 2H), 7.07 (d, $J = 8.4$ Hz, 2H), 5.28 (d, $J = 8.9$ Hz, 1H), 5.08 (d, $J = 7.8$ Hz, 1H), 3.81 (s, 3H), 3.76 (s, 3H), 3.49 (dd, $J = 7.8$, 6.5 Hz, 1H), 3.37 (dd, $J = 8.9$, 6.5 Hz, 1H), 3.19 (s, 3H), 2.40 (s, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 169.6, 169.5, 167.9, 144.2, 135.2, 134.7, 130.8, 129.5, 129.2, 128.3, 121.9, 65.2, 61.7, 52.7, 52.3, 51.6, 51.2, 48.3, 21.5.

IR (KBr) v: 3451, 2995, 2951, 1754, 1742, 1701, 1654, 1617, 1596, 1577, 1560, 1486, 1437, 1408, 1358 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{23}$H$_{25}$BrNO$_8$S: 554.0479, found 554.0478.

Trimethyl 1-butyl-5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (4a).

Physical state: colorless stick oil.

Yield: 25% (27.6 mg).

$^1$H NMR (400 MHz, CDCl$_3$): 7.52 - 7.41 (m, 3H), 7.31 - 7.26 (m, 2H), 4.09 (t, $J = 7.8$ Hz, 2H), 3.96 (s, 3H), 3.85 (s, 3H), 3.58 (s, 3H), 1.57 - 1.48 (m, 2H), 1.17 - 1.06 (m, 2H), 0.73 (t, $J = 7.3$ Hz, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 166.9, 163.0, 160.0, 143.0, 130.23, 130.21, 129.3, 128.2, 126.1, 119.2, 112.0, 52.7, 52.0, 51.4, 46.2, 33.4, 19.7, 13.4.

IR (NaCl) v: 2955, 2874, 1745, 1713, 1547, 1519, 1483, 1446, 1405, 1369, 1314 cm$^{-1}$.

HRMS (ESI-TOF) m/z: [M+H]$^+$ calcd for C$_{20}$H$_{24}$NO$_6$: 374.1598, found 374.1603.

Reference


**1H and 13C NMR spectra of pyrroles and pyrrolidines.**

**Trimethyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2a).**

Trimethyl 5-(2-fluorophenyl)-1H-pyrrole-2,3,4-tricarboxylate (2b).
Trimethyl 5-(3-nitrophenyl)-1H-pyrrole-2,3,4-tricarboxylate (2c).

Trimethyl 5-(4-(methoxycarbonyl)phenyl)-1H-pyrrole-2,3,4-tricarboxylate (2d).
Trimethyl 5-(4-bromophenyl)-1H-pyrrole-2,3,4-tricarboxylate (2e).
Trimethyl 5-(naphthalen-2-yl)-1H-pyrrole-2,3,4-tricarboxylate (2f).
Trimethyl 5-\((p\text{-tolyl})\)\(-1\)H-pyrrole-2,3,4-tricarboxylate (2g).
Trimethyl 5-(2-methoxyphenyl)-1H-pyrrole-2,3,4-tricarboxylate (2h).
Trimethyl 5-(4-methoxyphenyl)-1H-pyrrole-2,3,4-tricarboxylate (2i).

Trimethyl 5-(2,3,4-trimethoxyphenyl)-1H-pyrrole-2,3,4-tricarboxylate (2j).
Trimethyl 5-(furan-2-yl)-1\(H\)-pyrrole-2,3,4-tricarboxylate (2k).
Trimethyl 5-(pyridin-3-yl)-1H-pyrrole-2,3,4-tricarboxylate (2l).
Trimethyl 5-(thiophen-2-yl)-1H-pyrrole-2,3,4-tricarboxylate (2m).
Trimethyl 5-(1-(tert-butoxycarbonyl)piperidin-4-yl)-1H-pyrrole-2,3,4-tricarboxylate (2n).
Trimethyl 5-(heptan-3-yl)-1H-pyrrole-2,3,4-tricarboxylate (2o).
Trimethyl 5-(cyclohex-3-en-1-yl)-1H-pyrrole-2,3,4-tricarboxylate (2p).
Dimethyl 5-phenyl-1H-pyrrole-2,4-dicarboxylate (2q).
4-Ethyl 2-methyl 5-phenyl-1H-pyrrole-2,4-dicarboxylate (2r).
4-Butyl 2-methyl 5-phenyl-1\textit{H}-pyrrole-2,4-dicarboxylate (2s).

Methyl 4-(dimethylcarbamoyl)-5-phenyl-1\textit{H}-pyrrole-2-carboxylate (2t).
Methyl 4-((4-chlorophenyl)carbamoyl)-5-phenyl-1H-pyrrole-2-carboxylate (2u).
Methyl 4-cyano-5-phenyl-1H-pyrrole-2-carboxylate (2v).
3,4-Dibutyl 2-methyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2w).
2-Ethyl 3,4-dimethyl 5-phenyl 1H-pyrrole-2,3,4-tricarboxylate (2x)
2-(Tert-butyl) 3,4-dimethyl 5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (2y).

Dimethyl 2-cyano-5-phenyl-1H-pyrrole-3,4-dicarboxylate (2z).
Trimethyl 1-butyl-5-phenylpyrrolidine-2,3,4-tricarboxylate (3a).
Trimethyl 5-phenyl-1-tosylpyrrolidine-2,3,4-tricarboxylate (3b).
Trimethyl 1-butyl-5-phenyl-1H-pyrrole-2,3,4-tricarboxylate (4a).