PLATINUM-CATALYZED REGIOSELECTIVE HYDRATION OF 1-(2-PROPYNYL)-2-FORMYL PYRROLES

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Abstract – The hydration reaction of 1-(2-propynyl)-2-formylpyrroles with a platinum catalyst in aqueous media is described. Various 1-(2-oxopropyl)-2-formylpyrroles were regioselectively synthesized via the platinum-promoted intramolecular 6-exo-dig cyclization pathway.

INTRODUCTION
Hydration of alkynes is a useful protocol for introduction of carbonyl component within the molecules, and various methodologies for the application in organic synthesis have been reported. 1,2 Among them, transition metal-catalyzed hydration of alkynes utilizing neighboring group participation is one of the useful protocol to obtain the desired product in high regioselectivity. 3 For example, Sahoo recently reported a gold-catalyzed hydration of propargyl acetates, in which α-acyloxy methyl ketones were regioselectively produced by assisting a neighboring carbonyl group. 3d During the course of our studies on the platinum-catalyzed reactions using alkynyl compounds, 4 we focused on a regioselective hydration of 1-(2-propynyl)pyrroles utilizing neighboring group participation. We report herein a platinum-catalyzed hydration of 1-(2-propynyl)-2-formylpyrroles, in which various 1-(2-oxopropyl)-2-formylpyrroles can be synthesized in a regioselective manner.

RESULTS AND DISCUSSION
The initial attempts were carried out using 1-(2-propynyl)-2-formylpyrrole (1a) (Scheme 1). When the substrate 1a was treated with 10 mol % of PtCl₂ in dioxane/H₂O (2/1) at 100 °C for 10 min, 4a,b the reaction successfully proceeded to afford 1-(2-oxopropyl)-2-formylpyrrole (2a) in 77% yield. 5 The reaction also proceeded when 10 mol % AuCl₃ was used as the catalyst, but the reaction time was prolonged to 10 h and the yield was decreased to 65%.

‡ This paper is dedicated to Prof. Ei-ichi Negishi on the occasion of his 77th birthday.
We next attempted the reactions using various substrates 1b–1i having an aryl group at the alkynyl position (Scheme 2). When phenyl-substituted substrate 1b was subjected to the reaction with PtCl₂, the hydrated product 2b was obtained in 82% yield together with the regioisomer 3b in 12% yield (Table 1, entry 1). The tolyl- and p-methoxyphenyl-substituted substrates 1c and 1d were transformed to the ketones 2c and 2d, but considerable amount of the regioisomers 3c and 3d were also produced, respectively (entries 2 and 3). The reactions of 1e and 1f, having a fluoro and a chloro group on the aromatic ring, afforded the corresponding products 2e and 2f in moderate yields with good regioselectivity (entries 4 and 5). When the substrates 1g and 1h having an electron-withdrawing group were subjected to the reactions, the corresponding products 2g and 2h were obtained in low yields (entries 6 and 7). On the other hand, the reaction of the substrate 1i which contains an ester moiety on the phenyl group successfully afforded the corresponding ketone 2i and the regioisomer 3i in 63% and 11% yields, respectively (entry 8). Interestingly, the observed regioselectivity for the production of 2 was contrary to the literature reports that p-Lewis acid-promoted hydrations of aryl-substituted alkynes prefer to add water at the RC≡CAr carbon atom (R = alkyl). These results imply that the reactions proceed by assisting a neighboring formyl group.

Scheme 1

![Scheme 1]

<table>
<thead>
<tr>
<th>catalyst</th>
<th>time</th>
<th>yield of 2a</th>
</tr>
</thead>
<tbody>
<tr>
<td>PtCl₂</td>
<td>10 min</td>
<td>77%</td>
</tr>
<tr>
<td>AuCl₃</td>
<td>10 h</td>
<td>65%</td>
</tr>
</tbody>
</table>

Scheme 2

![Scheme 2]
Table 1. Platinum-catalyzed hydration of aryl-substituted substrates 1b–i.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate 1</th>
<th>Time (h)</th>
<th>2 (Yield /%)$^a$</th>
<th>3 (Yield /%)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R = H (1b)</td>
<td>0.5</td>
<td>2b (82)</td>
<td>3b (12)</td>
</tr>
<tr>
<td>2</td>
<td>R = Me (1c)</td>
<td>2.5</td>
<td>2c (52)</td>
<td>3c (25)</td>
</tr>
<tr>
<td>3</td>
<td>R = OMe (1d)</td>
<td>5</td>
<td>2d (33)</td>
<td>3d (26)</td>
</tr>
<tr>
<td>4</td>
<td>R = F (1e)</td>
<td>1</td>
<td>2e (66)</td>
<td>3e (11)</td>
</tr>
<tr>
<td>5</td>
<td>R = Cl (1f)</td>
<td>2</td>
<td>2f (51)</td>
<td>3f (13)</td>
</tr>
<tr>
<td>6</td>
<td>R = Ac (1g)</td>
<td>1</td>
<td>2g (28)</td>
<td>3g (9)</td>
</tr>
<tr>
<td>7</td>
<td>R = CN (1h)</td>
<td>5</td>
<td>2h (28)</td>
<td>3h (6)</td>
</tr>
<tr>
<td>8</td>
<td>R = CO$_2$Me (1i)</td>
<td>1</td>
<td>2i (63)</td>
<td>3i (11)</td>
</tr>
</tbody>
</table>

$^a$Isolated yields.

A plausible mechanism for the hydration of the 1-(2-propynyl)-2-formylpyrroles 1 is shown in Scheme 3. The platinum catalyst activates the carbon-carbon triple bond in 1 by coordination as shown in 4. Intramolecular 6-exo-dig cyclization of the internal formyl oxygen occurs to form the cyclized intermediate 5, which produces a ketone 2 upon hydrolysis followed by proto-demetalation process. It is expected that the regioisomers 3 are produced via the intermediate 5’, derived from intramolecular 7-endo-dig cyclization of 4.
Information on the reaction mechanism was gained by carrying out the reaction using formyl-free substrates (Scheme 4). When the 1-(2-propynyl)pyrrole (6) was subjected to the reaction, the yield of the hydrated product 7 was dramatically decreased to 4%. Furthermore, the reaction of vinyl-substituted substrate 8 did not give the corresponding product 9. These results support the hypothesis that the reaction proceeds via the intramolecular 6-exo-dig cyclization pathway by assisting a neighboring formyl group.

\[
\begin{align*}
\text{6} & \quad \text{10 mol} \, \% \text{ PtCl}_2 \\
& \quad \text{dioxane/H}_2\text{O (2/1)} \\
& \quad 100 \, ^\circ\text{C, 6 h}} \\
\text{7} & \quad 4\% \\
\text{8} & \quad \text{10 mol} \, \% \text{ PtCl}_2 \\
& \quad \text{dioxane/H}_2\text{O (2/1)} \\
& \quad 100 \, ^\circ\text{C, 10 h}} \\
& \quad \text{N.R. (not obtained)}
\end{align*}
\]

Scheme 4

In conclusion, we have developed a methodology for the synthesis of 1-(2-oxopropyl)-2-formylpyrroles by platinum-catalyzed hydration reactions. By introducing a formyl group on the pyrrole ring, regioselective hydration has been accomplished via the intramolecular 6-exo-dig cyclization pathway. Functionalization of pyrroles is an important research area of heterocyclic chemistry for synthesizing a variety of biologically active natural products and industrially useful compounds in an efficient and selective manner.\(^7\) Our reaction would provide a useful methodology for the selective functionalization of 1-(2-oxopropyl) pyrroles. Efforts to extend the scope of these reactions and their subsequent application to the syntheses of biologically active heterocyclic molecules are currently in progress.

**EXPERIMENTAL**

Solvents were dried and distilled according to standard protocols. The phrase ‘residue upon workup’ refers to the residue obtained when the organic layer was separated and dried over anhydrous MgSO\(_4\) and the solvent was evaporated under reduced pressure.

**Starting Materials.** 1-(2-Propynyl)-2-formylpyrroles 1a–1i were prepared according to the procedures described in the literature.\(^8\)
Typical Procedure for the Preparation of 1-(2-Propynyl)-2-formylpyrrole 1.

Synthesis of 1d: To a stirred solution of NaH (44.0 mg, 1.10 mmol) in DMF (20 mL) was added dropwise 2-formylpyrrole (95.1 mg, 1.00 mmol) in DMF (2 mL) at 0 °C and stirring was continued for 30 min at the same temperature. Then 1-(3-bromo-1-propyl)-4-methoxybenzene (247 mg, 1.10 mmol) in DMF (2 mL) was added to the solution at 0 °C. After stirring was continued for 20 min at the same temperature, the reaction mixture was quenched with water and extracted with Et₂O. The combined extracts were washed with 0.5 N HCl, and the residue upon workup was chromatographed on silica gel with hexane-AcOEt (90/10 v/v) as eluent to give 1-[3-(4-Methoxyphenyl)-2-propynyl]-2-formylpyrrole 1d (218 mg, 91%) as a colorless solid.

1-(3-Phenyl-2-propynyl)-2-formylpyrrole (1b): Colorless plates; mp 54.2–56.3 °C (recrystallized from AcOEt-hexane); IR (KBr) 2977, 2808, 1660, 788, 754 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 5.43 (2H, s), 6.30 (1H, dd, J = 2.4 and 4.0 Hz), 6.98 (1H, dd, J = 1.6 and 4.0 Hz), 7.30–7.34 (3H, m), 7.36–7.38 (1H, m), 7.44–7.47 (2H, m), 9.59 (1H, s); ¹³C-NMR (100MHz, CDCl₃) δ 39.0 (CH₂), 82.7 (Cq), 86.1 (Cq), 110.0 (CH), 122.2 (Cq), 124.9 (CH), 128.3 (CH), 128.7 (CH), 130.4 (CH), 131.2 (Cq), 131.8 (CH), 179.5 (CH); HRMS (ESI) m/z calcd for C₁₄H₁₁NNaO [M+Na]⁺ 232.0738, found 232.0740.

1-[3-(4-Methoxyphenyl)-2-propynyl]-2-formylpyrrole (1d): Colorless needles; mp 42.4–44.6 °C (recrystallized from AcOEt-hexane); IR (KBr) 2977, 2808, 1660, 788, 754 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 3.81 (3H, s), 5.41 (2H, s), 6.29 (1H, dd, J = 2.4 and 3.6 Hz), 6.82–6.86 (2H, m), 6.97 (1H, dd, J = 2.0 and 3.6 Hz), 7.37–7.40 (3H, m), 9.58 (1H, d, J = 0.4 Hz); ¹³C-NMR (100MHz, CDCl₃) δ 39.1 (CH₂), 55.3 (CH₃), 81.3 (Cq), 109.9 (CH), 119.1 (Cq), 124.8 (CH), 129.1 (CH), 130.4 (CH), 131.1 (Cq), 131.7 (CH), 138.9 (CH), 179.5 (CH); HRMS (ESI) m/z calcd for C₁₅H₁₃NNaO₂ [M+Na]⁺ 262.0844, found 262.0844.
Hz), 124.8 (CH), 130.3 (CH), 131.1 (Cq), 133.7 (CH, d, J = 8.3 Hz), 162.6 (Cq, d, J = 248.7 Hz), 179.4 (CH); HRMS (ESI) m/z calcld for C_{14}H_{10}FNNaO [M+Na]^+ 250.0644, found 250.0639.

1-[3-(4-Chlorophenyl)-2-propynyl]-2-formylpyrrole (1f): Colorless needles; mp 90.3–91.0 °C (recrystallized from AcOEt-hexane); IR (KBr) 3099, 2813, 2362, 1651, 1335, 1037, 792, 750 cm–1; 1H-NMR (400 MHz, CDCl3) δ 5.42 (2H, s), 6.30 (1H, dd, J = 2.4 and 4.0 Hz), 6.98 (1H, dd, J = 1.6 and 4.0 Hz), 7.28–7.32 (3H, m), 7.35–7.38 (2H, m), 9.59 (1H, d, J = 0.8 Hz); 13C-NMR (100MHz, CDCl3) δ 38.9 (CH2), 83.8 (Cq), 84.8 (Cq), 110.1 (CH), 120.7 (Cq), 124.9 (CH), 128.7 (CH), 130.4 (CH), 131.2 (Cq), 133.0 (CH), 134.8 (Cq), 179.6 (CH); HRMS (ESI) m/z calcld for C_{14}H_{10}ClNNaO [M+Na]^+ 266.0349, found 266.0355.

1-[3-(4-Acetylphenyl)-2-propynyl]-2-formylpyrrole (1g): Thin yellow needles; mp 69.6–70.8 °C (recrystallized from AcOEt-hexane); IR (KBr) 3010, 2824, 2387, 2359, 1683, 1661, 1404, 838, 748 cm–1; 1H-NMR (400 MHz, CDCl3) δ 2.60 (3H, s), 5.46 (2H, s), 6.32 (1H, dd, J = 2.0 and 4.0 Hz), 6.90 (1H, d, J = 1.2 Hz); 13C-NMR (100MHz, CDCl 3) δ 26.6 (CH 3), 38.8 (CH 2), 85.0 (Cq), 86.1 (Cq), 110.2 (CH), 124.9 (CH), 127.0 (Cq), 128.2 (CH), 130.4 (CH), 131.1 (Cq), 131.9 (CH), 136.7 (Cq), 179.6 (CH), 197.2 (Cq); HRMS (ESI) m/z calcld for C_{16}H_{13}NNaO 274.0844, found 274.0844.

1-[3-(4-Cyanophenyl)-2-propynyl]-2-formylpyrrole (1h): Colorless needles; mp 126.3–128.6 °C (recrystallized from AcOEt-hexane); IR (KBr) 2816, 2225, 1651, 1335, 840 cm–1; 1H-NMR (400 MHz, CDCl3) δ 5.46 (2H, s), 6.30 (1H, dd, J = 2.4 and 4.0 Hz), 6.98 (1H, d, J = 2.0 and 4.0 Hz), 7.25–7.27 (1H, m), 7.51–7.53 (2H, m), 7.60–7.62 (2H, m), 9.59 (1H, d, J = 0.8 Hz); 13C-NMR (100MHz, CDCl3) δ 38.7 (CH2), 84.0 (Cq), 87.4 (Cq), 110.3 (CH), 112.2 (Cq), 118.2 (Cq), 124.9 (CH), 127.1 (Cq), 130.4 (CH), 131.1 (Cq), 132.0 (CH), 132.3 (CH), 179.6 (CH); HRMS (ESI) m/z calcld for C_{15}H_{11}N_{2}O 235.0871, found 235.0865.

1-[3-(4-Methoxycarbonylphenyl)-2-propynyl]-2-formylpyrrole (1i): Colorless needles; mp 102.4–103.5 °C (recrystallized from AcOEt-hexane); IR (KBr) 2952, 2360, 1721, 1661, 1405, 1277, 1108, 786 cm–1; 1H-NMR (400 MHz, CDCl3) δ 3.92 (3H, s), 5.46 (2H, s), 6.31 (1H, dd, J = 2.8 and 4.0 Hz), 6.99 (1H, dd, J = 2.0 and 4.0 Hz), 7.31–7.33 (1H, m), 7.49–7.52 (2H, m), 7.97–8.00 (2H, m), 9.59 (1H, d, J = 0.8 Hz); 13C-NMR (100MHz, CDCl3) δ 38.7 (CH2), 52.1 (CH3), 85.0 (Cq), 85.8 (Cq), 110.1 (CH), 124.8 (CH), 126.7 (Cq), 129.4 (CH), 129.9 (Cq), 130.3 (CH), 131.1 (Cq), 131.6 (CH), 166.2 (Cq), 179.5 (CH); HRMS (ESI) m/z calcld for C_{16}H_{13}NNaO3 [M+Na]^+ 290.0793, found 290.0800.

General Procedure for Platinum–Catalyzed Hydration of 1: To a stirred solution of 1b (50.0mg, 0.24 mmol) in dioxane/H2O (2:1, 2 mL) was added PtCl2 (6.4 mg, 0.024 mmol) at rt. After stirring was continued for 30 min at 100 °C, the resulting mixture was cooled to rt and diluted with minimum amount of Et2O. The solution was dried over anhydrous MgSO4 and filtered through a small amount of silica gel.
Concentration at reduced pressure gave the residue, which was chromatographed on silica gel with hexane-AcOEt (90/10 v/v) as eluent to give 2b (44.5 mg, 82%) as a colorless solid and 3b (6.7 mg, 12%) as a colorless solid.

1-(2-Oxopropyl)-2-formylpyrrole (2a): Yield 77%; colorless needles; mp 59.0–61.0 °C (recrystallized from AcOEt-hexane); IR (KBr) 1731, 1659, 1482, 1406, 762 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 2.23 (3H, s), 5.10 (2H, s), 6.32 (1H, dd, J = 2.4 and 4.4 Hz), 6.85–6.87 (1H, m), 7.00 (1H, dd, J = 2.0 and 4.4 Hz), 9.50 (1H, d, J = 1.2 Hz); ¹³C-NMR (100MHz, CDCl₃) δ 26.9 (CH₃), 57.9 (CH₂), 110.2 (CH), 124.6 (CH), 131.4 (Cq), 132.1 (CH), 179.7 (CH), 201.6 (Cq); HRMS (ESI) m/z calcd for C₈H₉NNaO₂ [M+Na]⁺ 174.0531, found 174.0526.

1-(3-Phenyl-2-oxopropyl)-2-formylpyrrole (2b): Yield 82%; colorless needles; mp 66.6–69.4 °C (recrystallized from AcOEt-hexane); IR (KBr) 2929, 2807, 1734, 1659, 1405, 759 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 3.85 (2H, s), 5.09 (2H, s), 6.28 (1H, dd, J = 2.4 and 4.4 Hz), 6.77–6.79 (1H, m), 6.99 (1H, dd, J = 1.2 Hz); ¹³C-NMR (100MHz, CDCl₃) δ 47.4 (CH₂), 57.0 (CH₂), 110.2 (CH), 124.6 (CH), 127.3 (CH), 128.8 (CH), 129.6 (CH), 131.4 (Cq), 132.2 (CH), 133.0 (Cq), 179.7 (CH), 201.3 (Cq); HRMS (ESI) m/z calcd for C₁₄H₁₄NO₂ [M+H]+ 228.1025, found 228.1026.

1-(3-Phenyl-3-oxopropyl)-2-formylpyrrole (3b): Yield 12%; colorless plates; mp 55.7–57.4 °C (recrystallized from AcOEt-hexane); IR (KBr) 2923, 2360, 1684, 1660, 1404, 743 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 3.50 (2H, t, J = 6.4 Hz), 4.73 (2H, t, J = 6.4 Hz), 6.19 (1H, dd, J = 2.4 and 4.0 Hz), 6.94 (1H, dd, J = 2.0 and 4.0 Hz), 7.14–7.16 (1H, m), 7.42–7.46 (2H, m), 7.54–7.58 (1H, m), 7.92–7.95 (2H, m), 9.54 (1H, d, J = 1.2 Hz); ¹³C-NMR (100MHz, CDCl₃) δ 39.7 (CH₂), 44.2 (CH₂), 109.6 (CH), 125.3 (CH), 128.1 (CH), 128.6 (CH), 131.1 (Cq), 132.9 (CH), 133.4 (CH), 136.5 (Cq), 179.2 (CH), 197.7 (Cq); HRMS (ESI) m/z calcd for C₁₄H₁₃NNaO₂ [M+Na]⁺ 250.0844, found 250.0833.

1-[3-(4-Methylphenyl)-2-oxopropyl]-2-formylpyrrole (2c): Yield 52%; colorless needles; mp 69.9–70.8 °C (recrystallized from AcOEt-hexane); IR (KBr) 2929, 2820, 1733, 1659, 1405, 764 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 2.34 (3H, s), 3.80 (2H, s), 5.08 (2H, s), 6.27 (1H, dd, J = 2.4 and 4.0 Hz), 6.76–6.78 (1H, m), 6.98 (1H, dd, J = 1.6 and 4.0 Hz), 7.13–7.16 (3H, m), 7.42–7.46 (2H, m), 9.49 (1H, d, J = 0.8 Hz); ¹³C-NMR (100MHz, CDCl₃) δ 21.0 (CH₃), 47.0 (CH₂), 56.9 (CH₂), 110.1 (CH), 124.6 (CH), 129.4 (CH), 129.5 (CH), 129.9 (Cq), 131.4 (Cq), 132.2 (CH), 137.0 (Cq), 179.7 (CH), 201.6 (Cq); HRMS (ESI) m/z calcd for C₁₅H₁₅NNaO₂ [M+Na]⁺ 264.1000, found 264.0996.

1-[3-(4-Methylphenyl)-3-oxopropyl]-2-formylpyrrole (3c): Yield 25%; colorless needles; mp 40.5–42.7 °C (recrystallized from AcOEt-hexane); IR (KBr) 2922, 1660, 1404, 815, 759 cm⁻¹; ¹H-NMR (400 MHz, CDCl₃) δ 2.39 (3H, s), 3.46 (2H, t, J = 6.4 Hz), 4.71 (2H, t, J = 6.4 Hz), 6.19 (1H, dd, J = 2.4 and 4.0 Hz), 6.93 (1H, dd, J = 2.0 and 4.0 Hz), 7.13–7.15 (1H, m), 7.22–7.24 (2H, m), 7.82–7.84 (2H, m), 7.92–7.95 (2H, m), 9.54 (1H, d, J = 1.2 Hz); ¹³C-NMR (100MHz, CDCl₃) δ 21.0 (CH₃), 47.0 (CH₂), 56.9 (CH₂), 110.1 (CH), 124.6 (CH), 129.4 (CH), 129.5 (CH), 129.9 (Cq), 131.4 (Cq), 132.2 (CH), 137.0 (Cq), 179.7 (CH), 201.6 (Cq); HRMS (ESI) m/z calcd for C₁₅H₁₃NNaO₂ [M+Na]⁺ 264.1000, found 264.0996.
9.54 (1H, d, J = 1.2 Hz); $^{13}$C-NMR (100MHz, CDCl$_3$) δ 21.6 (CH$_3$), 39.6 (CH$_2$), 44.3 (CH$_2$), 109.5 (CH), 125.3 (CH), 128.2 (CH), 129.3 (CH), 131.1 (Cq), 132.9 (CH), 134.1 (Cq), 144.2 (Cq), 179.2 (CH), 197.3 (Cq); HRMS (ESI) m/z calcd for C$_{15}$H$_{16}$NO$_2$ [M+H]$^+$ 242.1181, found 242.1180.

1-[3-(4-Methoxyphenyl)-2-oxopropyl]-2-formylpyrrole (2d): Yield 33%; colorless needles; mp 72.6–73.7 °C (recrystallized from AcOEt-hexane); IR (KBr) 2930, 2845, 1732, 1653, 1246, 1030, 831, 763 cm$^{-1}$; $^1$H-NMR (400 MHz, CDCl$_3$) δ 3.78 (2H, s), 3.80 (3H, s), 5.08 (2H, s), 6.28 (1H, dd, J = 2.4 and 4.0 Hz), 6.77–6.79 (1H, m), 6.87–6.90 (2H, m), 6.98 (1H, dd, J = 1.6 and 4.0 Hz), 7.15–7.18 (2H, m), 9.49 (1H, d, J = 1.2 Hz); $^{13}$C-NMR (100MHz, CDCl$_3$) δ 46.5 (CH$_2$), 55.3 (CH$_3$), 56.9 (CH$_2$), 110.2 (CH), 114.3 (CH), 124.6 (CH), 125.0 (Cq), 130.6 (CH), 131.4 (Cq), 132.2 (CH), 158.9 (Cq), 179.7 (CH), 201.7 (Cq); HRMS (ESI) m/z calcd for C$_{15}$H$_{15}$NNaO$_3$ [M+Na]$^+$ 280.0950, found 280.0951.

1-[3-(4-Methoxyphenyl)-3-oxopropyl]-2-formylpyrrole (3d): Yield 26%; colorless needles; mp 71.1–72.6 °C (recrystallized from AcOEt-hexane); IR (KBr) 2966, 2926, 2852, 2816, 1660, 1600, 1256, 1170, 836, 761 cm$^{-1}$; $^1$H-NMR (400 MHz, CDCl$_3$) δ 3.43 (2H, t, J = 6.4 Hz), 3.86 (3H, s), 4.71 (2H, t, J = 6.4 Hz), 6.19 (1H, dd, J = 2.4 and 4.0 Hz), 6.89–6.92 (2H, m), 6.93 (1H, dd, J = 2.0 and 4.0 Hz), 7.13–7.15 (1H, m), 7.90–7.93 (2H, m), 9.54 (1H, d, J = 0.8 Hz); $^{13}$C-NMR (100MHz, CDCl$_3$) δ 39.4 (CH$_2$), 44.4 (CH$_2$), 55.4 (CH$_3$), 109.5 (CH), 113.8 (CH), 125.3 (CH), 129.7 (Cq), 130.4 (CH), 131.1 (Cq), 132.9 (CH), 163.7 (Cq), 179.2 (CH), 196.2 (Cq); HRMS (ESI) m/z calcd for C$_{15}$H$_{15}$NNaO$_3$ [M+Na]$^+$ 280.0950, found 280.0950.

1-[3-(4-Fluorophenyl)-2-oxopropyl]-2-formylpyrrole (2e): Yield 66%; colorless needles; mp 63.8–65.6 °C (recrystallized from AcOEt-hexane); IR (KBr) 2931, 2809, 1735, 1659, 1407, 1223, 836, 765 cm$^{-1}$; $^1$H-NMR (400 MHz, CDCl$_3$) δ 3.82 (2H, s), 5.09 (2H, s), 6.29 (1H, dd, J = 2.4 and 4.0 Hz), 6.80–6.82 (1H, m), 7.00 (1H, dd, J = 1.6 and 4.0 Hz), 7.01–7.06 (2H, m), 7.19–7.23 (2H, m), 9.49 (1H, d, J = 0.8 Hz); $^{13}$C-NMR (100MHz, CDCl$_3$) δ 46.1 (CH$_2$), 57.1 (CH$_2$), 110.2 (CH), 124.6 (CH), 128.6 (Cq, d, J = 3.3 Hz), 131.2 (CH, d, J = 7.4 Hz), 131.3 (Cq), 132.2 (CH), 162.1 (Cq, d, J = 244.6 Hz), 179.7 (CH), 201.1 (Cq); HRMS (ESI) m/z calcd for C$_{14}$H$_{13}$FNO$_2$ [M+H]$^+$ 246.0930, found 246.0922.

1-[3-(4-Fluorophenyl)-3-oxopropyl]-2-formylpyrrole (3e): Yield 11%; colorless needles; mp 125.7–126.8 °C (recrystallized from AcOEt-hexane); IR (KBr) 2931, 2849, 1677, 1656, 1404, 1373, 852, 764 cm$^{-1}$; $^1$H-NMR (400 MHz, CDCl$_3$) δ 3.46 (2H, t, J = 6.4 Hz), 4.71 (2H, t, J = 6.4 Hz), 6.20 (1H, dd, J = 2.4 and 3.6 Hz), 6.94 (1H, dd, J = 2.0 and 3.6 Hz), 7.09–7.13 (3H, m), 7.95–7.98 (2H, m), 9.54 (1H, d, J = 0.8 Hz); $^{13}$C-NMR (100MHz, CDCl$_3$) δ 39.7 (CH$_2$), 44.3 (CH$_2$), 109.6 (CH), 115.8 (CH, d, J = 22.3 Hz), 125.4 (CH), 130.7 (CH, d, J = 9.0 Hz), 131.1 (Cq), 132.9 (CH), 133.0 (Cq, d, J = 3.3 Hz), 165.9 (Cq, d, J = 254.4 Hz), 179.3 (CH), 196.1 (Cq); HRMS (ESI) m/z calcd for C$_{14}$H$_{13}$FNO$_2$ [M+H]$^+$ 246.0930, found 246.0930.
1-[3-(4-Chlorophenyl)-2-oxopropyl]-2-formylpyrrole (2f): Yield 51%; colorless needles; mp 84.5–87.3 °C (recrystallized from AcOEt-hexane); IR (KBr) 2927, 2807, 1734, 1656, 1492, 1323, 1092, 1066, 801, 760 cm\(^{-1}\); \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 3.81 (2H, s), 5.09 (2H, s), 6.30 (1H, dd, \(J = 2.8\) and 4.4 Hz), 6.80–6.82 (1H, m), 7.00 (1H, dd, \(J = 2.0\) and 4.4 Hz), 7.16–7.19 (2H, m), 7.31–7.33 (2H, m), 9.49 (1H, d, \(J = 0.8\) Hz); \(^1^3\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 46.3 (CH\(_2\)), 57.1 (CH\(_2\)), 110.3 (CH), 124.7 (CH), 128.9 (CH), 131.0 (CH), 131.3 (Cq), 131.4 (Cq), 132.2 (CH), 133.3 (Cq), 179.8 (CH), 200.8 (Cq); HRMS (ESI) \(m/z\) calcd for C\(_{14}\)H\(_{13}\)ClNO\(_2\) [M+H]\(^{+}\) 262.0635, found 262.0623.

1-[3-(4-Chlorophenyl)-3-oxopropyl]-2-formylpyrrole (3f): Yield 13%; colorless needles; mp 110.9–113.5 °C (recrystallized from AcOEt-hexane); IR (KBr) 2961, 2915, 1687, 1660, 1588, 1259, 1089, 1029, 801, 756 cm\(^{-1}\); \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 3.46 (2H, t, \(J = 6.4\) Hz), 4.70 (2H, t, \(J = 6.4\) Hz), 6.20 (1H, dd, \(J = 2.8\) and 4.0 Hz), 6.94 (1H, dd, \(J = 2.0\) and 4.0 Hz), 7.12–7.14 (1H, m), 7.40–7.43 (2H, m), 7.85–7.89 (2H, m), 9.54 (1H, d, \(J = 0.8\) Hz); \(^1^3\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 39.7 (CH\(_2\)), 44.2 (CH\(_2\)), 109.7 (CH), 125.4 (CH), 129.0 (CH), 129.5 (CH), 131.1 (Cq), 132.9 (CH), 134.9 (Cq), 139.9 (Cq), 179.3 (CH), 196.5 (Cq); HRMS (ESI) \(m/z\) calcd for C\(_{14}\)H\(_{13}\)ClNO\(_2\) [M+H]\(^{+}\) 262.0635, found 262.0624.

1-[3-(4-Acetylphenyl)-2-oxopropyl]-2-formylpyrrole (2g): Yield 28%; colorless needles; mp 90.3–93.0 °C (recrystallized from AcOEt-hexane); IR (KBr) 1735, 1681, 1656, 1407, 1268, 761 cm\(^{-1}\); \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 2.60 (3H, s), 3.91 (2H, s), 5.11 (2H, s), 6.30 (1H, dd, \(J = 2.4\) and 4.0 Hz), 6.81–6.83 (1H, m), 7.01 (1H, dd, \(J = 2.0\) and 4.0 Hz), 7.33–7.35 (2H, m), 7.92–7.95 (2H, m), 9.50 (1H, d, \(J = 1.2\) Hz); \(^1^3\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 26.6 (CH\(_3\)), 46.8 (CH\(_2\)), 57.3 (CH\(_2\)), 110.3 (CH), 124.7 (CH), 128.7 (CH), 129.9 (CH), 131.4 (Cq), 132.2 (CH), 136.2 (Cq), 138.3 (Cq), 179.8 (CH), 197.6 (Cq), 200.4 (Cq); HRMS (ESI) \(m/z\) calcd for C\(_{16}\)H\(_{15}\)NNaO\(_3\) [M+Na]\(^{+}\) 292.0950, found 292.0942.

1-[3-(4-Acetylphenyl)-3-oxopropyl]-2-formylpyrrole (3g): Yield 9%; colorless needles; mp 75.0–77.6 °C (recrystallized from AcOEt-hexane); IR (KBr) 1684, 1658, 1403, 1263, 792 cm\(^{-1}\); \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 2.63 (3H, s), 3.52 (2H, t, \(J = 6.4\) Hz), 4.72 (2H, t, \(J = 6.4\) Hz), 6.21 (1H, dd, \(J = 2.4\) and 4.0 Hz), 6.95 (1H, dd, \(J = 2.0\) and 4.0 Hz), 7.13–7.15 (1H, m), 8.01 (4H, s), 9.54 (1H, d, \(J = 1.2\) Hz); \(^1^3\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 26.8 (CH\(_3\)), 40.1 (CH\(_2\)), 44.2 (CH\(_2\)), 109.7 (CH), 125.4 (CH), 128.3 (CH), 128.5 (CH), 131.2 (Cq), 132.9 (CH), 139.6 (Cq), 140.4 (Cq), 179.3 (CH), 197.2 (Cq), 197.3 (Cq); HRMS (ESI) \(m/z\) calcd for C\(_{16}\)H\(_{15}\)NNaO\(_3\) [M+Na]\(^{+}\) 292.0950, found 292.0942.

1-[3-(4-Cyanophenyl)-2-oxopropyl]-2-formylpyrrole (2h): Yield 28%; brown needles; mp 157.3–159.8 °C (recrystallized from AcOEt-hexane); IR (KBr) 2981, 2847, 2227, 1714, 1646, 1477, 839 cm\(^{-1}\); \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 3.92 (2H, s), 5.12 (2H, s), 6.32 (1H, dd, \(J = 2.4\) and 4.0 Hz), 6.84–6.86 (1H, m), 7.02 (1H, dd, \(J = 2.0\) and 4.0 Hz), 7.33–7.35 (2H, m), 7.62–7.64 (2H, m), 9.49 (1H, d, \(J = 1.2\) Hz); \(^1^3\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 46.5 (CH\(_2\)), 57.4 (CH\(_2\)), 110.4 (CH), 111.3 (Cq), 118.6 (Cq), 124.8 (CH), 130.6 (CH), 131.3 (Cq), 132.2 (CH), 132.3 (CH), 138.3 (Cq), 179.8 (CH), 199.9 (Cq); HRMS (ESI) \(m/z\) calcd for C\(_{16}\)H\(_{15}\)NNaO\(_3\) [M+Na]\(^{+}\) 292.0950, found 292.0950.
HRMS (ESI) m/z calcd for C_{15}H_{13}N_{2}O_{2} [M+H]^+ 253.0977, found 253.0985.

1-[3-(4-Cyanophenyl)-3-oxopropyl]-2-formylpyrrole (3h): Yield 6%; colorless needles; mp 123.9–125.8 °C (recrystallized from AcOEt-hexane); IR (KBr) 3095, 2922, 2225, 1687, 1650, 1402, 765 cm⁻¹; \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 3.51 (2H, t, \(J = 6.4\) Hz), 4.71 (2H, t, \(J = 6.4\) Hz), 6.21 (1H, dd, \(J = 2.4\) and 4.0 Hz), 6.96 (1H, dd, \(J = 2.0\) and 4.0 Hz), 7.11–7.13 (1H, m), 7.74–7.76 (2H, m), 8.01–8.03 (2H, m), 9.54 (1H, d, \(J = 1.2\) Hz); \(^{13}\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 40.1 (CH\(_2\)), 44.1 (CH\(_2\)), 109.8 (CH), 116.8 (Cq), 117.8 (Cq), 125.5 (CH), 128.5 (CH), 131.2 (Cq), 132.6 (CH), 132.9 (CH), 139.4 (Cq), 179.4 (CH), 196.5 (Cq); HRMS (ESI) m/z calcd for C\(_{15}\)H\(_{13}\)N\(_{2}\)O\(_{2}\) [M+H]^+ 253.0977, found 253.0981.

1-[3-(4-Methoxycarbonylphenyl)-3-oxopropyl]-2-formylpyrrole (3i): Yield 11%; colorless needles; mp 94.1–95.8 °C (recrystallized from AcOEt-hexane); IR (KBr) 1720, 1682, 1657, 1404, 1280, 749 cm⁻¹; \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 3.52 (2H, t, \(J = 6.4\) Hz), 3.94 (3H, s), 4.72 (2H, t, \(J = 6.4\) Hz), 6.20 (1H, dd, \(J = 2.0\) and 4.0 Hz), 6.95 (1H, dd, \(J = 2.0\) and 4.0 Hz), 7.12–7.14 (1H, m), 7.96–7.98 (2H, m), 8.08–8.11 (2H, m), 9.54 (1H, d, \(J = 0.8\) Hz); \(^{13}\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 40.1 (CH\(_2\)), 44.1 (CH\(_2\)), 52.4 (CH\(_3\)), 109.7 (CH), 125.4 (CH), 128.0 (CH), 129.9 (CH), 131.1 (Cq), 132.9 (CH), 134.2 (Cq), 139.6 (Cq), 166.1 (Cq), 179.3 (CH), 197.3 (Cq); HRMS (ESI) m/z calcd for C\(_{16}\)H\(_{16}\)NO\(_{4}\) [M+H]^+ 286.1079, found 286.1083.

1-(2-Oxopropyl)-1\(^H\)-pyrrole (7): Brown oil; IR (neat) 2925, 2854, 1732, 1463, 1377 cm⁻¹; \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 2.06 (3H, s), 4.61 (2H, s), 6.24 (2H, t, \(J = 2.0\) Hz), 6.61 (2H, t, \(J = 2.0\) Hz); \(^{13}\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 26.3 (CH\(_2\)), 59.1 (CH\(_2\)), 109.5 (CH), 121.6 (CH), 204.1 (Cq); HRMS (ESI) m/z calcd for C\(_7\)H\(_9\)NONa [M+Na]^+ 146.0582, found 146.0587.

1-(2-Propynyl)-2-vinyl-1\(^H\)-pyrrole (8): According to the same procedure described for the synthesis of 1d, 8 was prepared from 2-vinylpyrrole with propargyl bromide. Yellow oil; IR (neat) 2925, 2853, 2360, 1457 cm⁻¹; \(^1\)H-NMR (400 MHz, CDCl\(_3\)) \(\delta\) 2.40 (3H, s), 4.61 (2H, s), 6.24 (2H, t, \(J = 2.0\) Hz), 6.61 (2H, t, \(J = 2.0\) Hz); \(^{13}\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 2.06 (3H, s), 4.61 (2H, s), 6.24 (2H, t, \(J = 2.0\) Hz), 6.61 (2H, t, \(J = 2.0\) Hz); \(^{13}\)C-NMR (100MHz, CDCl\(_3\)) \(\delta\) 26.3 (CH\(_2\)), 59.1 (CH\(_2\)), 109.5 (CH), 121.6 (CH), 204.1 (Cq); HRMS (ESI) m/z calcd for C\(_9\)H\(_9\)NNa [M+Na]^+ 154.0632, found 154.0629.
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REFERENCES AND NOTES


5. The yield of 2a was decreased when the catalyst loading was reduced.

