

# The Michael Addition Reaction of Indoles and $\alpha$ , $\beta$ -Unsaturated Ketones Catalyzed by Brønsted Acidic Ionic Liquid

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## Abstract

The Michael addition reaction of indoles with  $\alpha$ ,  $\beta$ -unsaturated ketones was studied using brønsted acidic ionic liquid [ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>] as catalyst. A series of  $\beta$ -indolone derivatives were obtained in up to 99% yield. The catalyst ionic liquid used in the approach can be easily recycled and reused for at least three cycles without decreasing its catalytic activity. The approach is characterized by mild condition and simple operation. It provides a new method for the synthesis of  $\beta$ -indole derivatives.

## Keywords

Ionic Liquid, Catalysis, Indole,  $\alpha$ ,  $\beta$ -Unsaturated Ketone, Michael Addition

# Brønsted酸性离子液体催化吲哚与 $\alpha$ , $\beta$ -不饱和酮的Michael加成反应

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## 摘要

本文以Brønsted酸性离子液体[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]催化吡啶与 $\alpha$ ,  $\beta$ -不饱和酮发生Michael加成反应, 得到了一系列 $\beta$ -吡啶酮化合物, 最高产率可达99%。离子液体催化剂循环使用3次以上, 催化活性没有明显下降。该方法具有条件温和、操作简单的特点, 为 $\beta$ -吡啶酮化合物的合成提供了一种新的方法。

## 关键词

离子液体, 催化, 吡啶,  $\alpha$ ,  $\beta$ -不饱和酮, Michael加成

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## 1. 引言

众所周知, 吡啶作为一类具有独特结构和生物活性的化合物, 在药物、功能材料和香料等领域应用广泛[1] [2] [3] [4] [5]。 $\beta$ -吡啶酮化合物在吡啶化学的研究中具有重要地位, 迈克尔加成反应是合成该类化合物的有效途径之一[6] [7] [8] [9] [10]。

近年来, 离子液体因具有低毒、低挥发性、良好的溶解性能和可循环使用等优点被广泛关注[11] [12] [13] [14]。离子液体作为反应溶剂、催化剂或促进剂应用于有机合成反应, 可以高效、高选择性且条件温和的实现化合物之间的转化, 符合绿色化学的理念[15] [16]。基于本课题组在离子液体领域的研究基础[17] [18], 本文采用 Brønsted 酸性功能化噻唑硫酮离子液体[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]催化吡啶与  $\alpha$ ,  $\beta$ -不饱和酮发生迈克尔加成反应, 以 82%~99%的产率得到了一系列  $\beta$ -吡啶酮化合物。本方法优点在于底物普适性好、产物产率高, 催化剂可以循环使用 3 次以上催化活性无明显下降。

## 2. 实验部分

### 2.1. 仪器与试剂

瑞士 Buchi B-540 型熔点仪; 德国 Bruker Equinox 55 红外光谱仪(KBr 压片); 美国 Varian inova-400 型核磁共振仪(TMS 为内标, CDCl<sub>3</sub>、D<sub>2</sub>O 或 DMSO-*d*<sub>6</sub> 为溶剂); 美国 HP1100 液相色谱质谱仪。所有试剂均为市售分析纯, 用前未经处理直接使用。

### 2.2. Brønsted 酸性离子液体[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]合成

Brønsted 酸性离子液体[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]的合成参照文献[19]

### 2.3. $\alpha$ , $\beta$ -不饱和酮的合成

$\alpha$ ,  $\beta$ -不饱和酮的合成参照文献[20]。

### 2.4. $\beta$ -吡啶酮化合物 3a-3z 的合成及结构分析

吡啶化合物(1 mmol)、 $\alpha$ ,  $\beta$ -不饱和酮化合物(1 mmol)、Brønsted 酸性离子液体催化剂

[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>] (10 mol%)和乙腈(5 mL)在 80℃下磁力搅拌反应 5 h。反应结束后,待反应混合物冷至室温,加入碎冰搅拌至碎冰溶化并析出固体,过滤,用蒸馏水洗涤固体得到粗产物。粗产物经硅胶柱层析分离纯化得到目标产物纯品,反应式如式 1 所示。所得化合物结构经 <sup>1</sup>H NMR, <sup>13</sup>C NMR, IR 和 MS 确证。

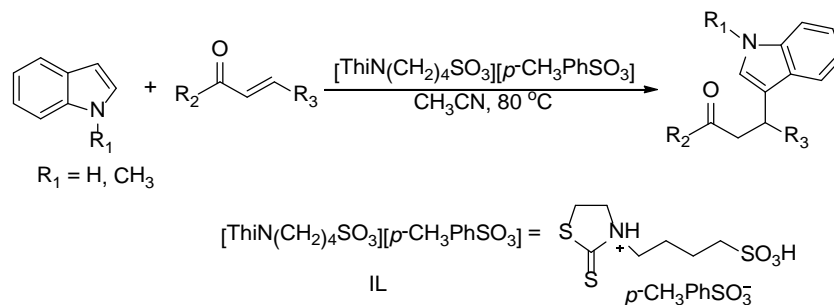
未知化合物的结构表征如下:

化合物 **3h**: 粉色粉末; <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz): δ (ppm): 7.99 (s, 1H), 7.90-7.92 (m, 2H), 7.92 (d, *J* = 7.6 Hz, 2H), 7.46-7.52 (m, 1H), 7.39 (d, *J* = 7.6 Hz, 1H), 7.27-7.32 (m, 1H), 7.14 (t, *J* = 8.0 Hz, 1H), 6.88-7.03 (m, 6H), 5.03 (t, *J* = 8.0 Hz, 1H), 3.84 (s, 3H), 3.60-3.76 (m, 2H); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz): δ (ppm) : 196.91, 163.47, 162.53, 160.10, 140.01, 139.98, 136.63, 130.37, 130.12, 129.29, 129.21, 126.48, 122.23, 121.29, 119.47, 119.44, 119.33, 115.24, 115.03, 113.73, 111.15, 76.70, 55.47, 44.80, 37.64; IR (KBr), ν<sub>max</sub>/cm<sup>-1</sup>: 3390, 3048, 2908, 2838, 1659, 1598, 1507, 1419, 1355, 1253, 1218, 1180, 1020, 980, 837, 742, 591, 534; ESI-MS: *m/z* (%) = 396 (100) [M+Na]<sup>+</sup>.

化合物 **3j**: 土黄色粉末; <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz): δ (ppm): 7.88 (d, *J* = 12.0 Hz, 3H), 6.86-7.48 (m, 10H), 4.98 (t, *J* = 8.0 Hz, 1H), 4.04-4.09 (m, 2H), 3.59-3.77 (m, 2H), 2.17 (s, 6H), 1.40 (t, *J* = 4.0 Hz, 3H); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz): δ (ppm) : 197.16, 162.76, 141.82, 136.59, 136.38, 134.27, 130.38, 130.10, 129.59, 129.17, 126.74, 124.97, 121.99, 121.34, 119.73, 119.61, 119.28, 114.08, 111.01, 76.69, 63.71, 44.97, 37.89, 19.89, 19.32, 14.66; IR (KBr), ν<sub>max</sub>/cm<sup>-1</sup>: 3335, 3041, 2982, 2936, 2889, 1649, 1592, 1420, 1357, 1259, 1171, 1041, 816, 741, 610; ESI-MS: *m/z* (%) = 420 (100) [M+Na]<sup>+</sup>.

化合物 **3k**: 紫红色粉末; <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz): δ (ppm): 8.05 (s, 1H), 7.87-7.91 (m, 2H), 6.86-7.50 (m, 10H), 5.01 (s, 1H), 4.04-4.10 (m, 2H), 3.56-3.75 (m, 2H), 1.41 (t, *J* = 8.0 Hz, 3H); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz): δ (ppm) : 196.46, 163.02, 158.75, 156.30, 141.95, 141.92, 136.63, 132.64, 130.37, 129.77, 128.45, 128.37, 126.33, 122.36, 121.31, 119.59, 119.28, 118.67, 116.29, 116.07, 114.22, 111.24, 108.93, 108.72, 76.71, 63.79, 44.57, 37.34, 14.65; IR (KBr), ν<sub>max</sub>/cm<sup>-1</sup>: 3331, 3058, 2983, 2935, 2895, 1645, 1598, 1493, 1334, 1246, 1172, 1042, 980, 813, 738, 612; ESI-MS: *m/z* (%) = 490 (100) [M+Na]<sup>+</sup>.

化合物 **3l**: 淡黄色粉末; <sup>1</sup>H NMR (CDCl<sub>3</sub>, 400 MHz): δ (ppm): 7.92-7.99 (m, 2H), 6.80-7.39 (m, 9H), 5.46 (t, *J* = 8.0 Hz, 1H), 4.06-4.11 (m, 2H), 3.72-3.84 (m, 1H), 3.53-3.76 (m, 2H), 1.55 (s, 1H), 1.41 (t, *J* = 8.0 Hz, 3H); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 100 MHz): δ (ppm) : 196.56, 141.28, 137.40, 137.29, 136.69, 136.58, 134.57, 133.14, 130.17, 129.69, 129.07, 127.10, 126.87, 126.14, 124.83, 121.72, 119.48, 118.90, 117.74, 109.31, 109.21, 76.69, 45.42, 37.78, 32.69, 19.91, 19.34; IR (KBr), ν<sub>max</sub>/cm<sup>-1</sup>: 3384, 3059, 2980, 1652, 1598, 1484, 1340, 1248, 1173, 1041, 907, 844, 742, 640; ESI-MS: *m/z* (%) = 444 (100) [M+Na]<sup>+</sup>.



**Scheme 1.** Synthesis of  $\beta$ -indolone compounds  
**式 1.**  $\beta$ -吲哚酮化合物的合成

化合物 **3m**: 褐色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.94 (s, 2H), 7.71 (d,  $J = 8.0$  Hz, 1H), 7.00-7.06 (m, 9H), 4.98 (t,  $J = 8.0$  Hz, 1H), 3.61-3.75 (m, 2H), 2.18 (s, 6H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 196.57, 196.02, 141.09, 137.43, 136.68, 136.57, 134.62, 133.15, 130.61, 130.15, 129.69, 129.06, 127.09, 126.51, 124.88, 122.20, 121.28, 119.46, 111.10, 58.49, 45.27, 37.89, 19.90, 19.33; IR (KBr),  $\nu_{\text{max}}/\text{cm}^{-1}$ : 3393, 3040, 2922, 1677, 1580, 1453, 1387, 1276, 1190, 1026, 880, 802, 741, 523; ESI-MS:  $m/z$  (%) = 444 (45)  $[\text{M}+\text{Na}]^+$ .

化合物 **3o**: 淡粉色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.91-7.94 (m, 2H), 7.16-7.57 (m, 7H), 7.24 (t,  $J = 3.6$  Hz, 1H), 6.99-7.03 (m, 1H), 6.90-6.95 (m, 2H), 6.83 (s, 1H), 5.02 (t,  $J = 8.0$  Hz, 1H), 3.75 (d,  $J = 9.6$  Hz, 2H), 3.74 (s, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 196.57, 141.09, 137.43, 136.68, 136.57, 134.62, 133.15, 130.61, 130.15, 129.69, 129.06, 127.09, 126.51, 124.88, 122.20, 121.28, 119.46, 119.27, 111.10, 76.69, 45.27, 37.89, 19.90, 19.33; IR (KBr),  $\nu_{\text{max}}/\text{cm}^{-1}$ : 3058, 2878, 1673, 1569, 1505, 1448, 1308, 1223, 1155, 1012, 976, 830, 742, 690; ESI-MS:  $m/z$  (%) = 380 (100)  $[\text{M}+\text{Na}]^+$ .

化合物 **3q**: 草绿色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.92 (d,  $J = 7.6$  Hz, 2H), 7.46-7.52 (m, 4H), 7.19-7.32 (m, 5H), 7.11-7.15 (m, 1H), 7.01 (t,  $J = 1.6$  Hz, 1H), 6.84 (s, 1H), 5.12-5.16 (m, 1H), 3.74 (s, 3H), 3.32-3.35 (m, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 188.35, 164.42, 163.01, 161.89, 138.54, 138.53, 136.34, 136.23, 130.92, 130.50, 129.86, 129.83, 129.07, 128.98, 124.37, 124.34, 117.69, 117.44, 114.81, 114.59, 114.31, 76.69, 63.80, 14.67.; IR (KBr),  $\nu_{\text{max}}/\text{cm}^{-1}$ : 3056, 2909, 2823, 1673, 1592, 1471, 1371, 1237, 1196, 1071, 998, 881, 737, 686; ESI-MS:  $m/z$  (%) = 442 (100)  $[\text{M}+\text{Na}]^+$ .

化合物 **3t**: 土黄色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.75-7.79 (m, 2H), 7.54-7.57 (m, 2H), 7.43 (d,  $J = 8.0$  Hz, 1H), 7.14-7.35 (m, 7H), 6.99-7.03 (m, 1H), 6.81 (s, 1H), 5.02 (t,  $J = 8.0$  Hz, 1H), 3.73-3.79 (m, 2H), 3.72 (s, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 197.54, 144.10, 137.30, 135.80, 131.83, 129.61, 128.45, 128.12, 127.72, 126.87, 126.33, 126.18, 121.73, 119.50, 118.89, 117.58, 109.30, 109.22, 45.22, 38.17, 32.71; IR (KBr),  $\nu_{\text{max}}/\text{cm}^{-1}$ : 3054, 2885, 1679, 1580, 1481, 1397, 1243, 1194, 1069, 972, 828, 740, 697; ESI-MS:  $m/z$  (%) = 442 (75)  $[\text{M}+\text{Na}]^+$ .

化合物 **3u**: 粉色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz, TMS):  $\delta$  (ppm) : 7.83-7.85 (m, 2H), 7.16-7.43 (m, 7H), 7.01 (t,  $J = 7.6$  Hz, 1H), 6.77-6.80 (m, 3H), 4.97 (t,  $J = 8.0$  Hz, 1H), 3.74 (s, 3H), 3.71 (s, 3H), 3.62-3.70 (m, 2H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 188.07, 146.42, 140.47, 137.96, 137.35, 137.09, 133.19, 132.12, 130.68, 130.41, 130.32, 129.77, 127.48, 126.38, 119.66, 76.68, 19.95, 19.77; IR (KBr),  $\nu_{\text{max}}/\text{cm}^{-1}$ : 3050, 2934, 2834, 1677, 1585, 1508, 1466, 1250, 1173, 1092, 1035, 1009, 976, 829, 802, 740; 7.88-7.92 (d, 2H, CH), 7.18-7.21 (d, 2H, CH), 7.04-7.06 (d, 2H, CH); ESI-MS:  $m/z$  (%) = 426 (98)  $[\text{M}+\text{Na}]^+$ .

化合物 **3v**: 粉色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.75 (d,  $J = 8.8$  Hz, 2H), 7.53 (d,  $J = 8.8$  Hz, 2H), 7.46 (d,  $J = 8.0$  Hz, 1H), 6.99-7.25 (m, 7H), 6.79 (s, 1H), 3.62-3.66 (m, 2H), 3.76 (s, 3H), 2.18 (s, 6H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 197.64, 141.50, 137.27, 136.47, 135.86, 134.42, 131.77, 129.62, 129.08, 128.00, 126.92, 126.12, 124.82, 121.63, 119.50, 118.81, 117.89, 109.15, 77.30, 77.19, 76.99, 76.67, 45.36, 37.71, 32.67, 19.89, 19.32; IR (KBr),  $\nu_{\text{max}}/\text{cm}^{-1}$ : 3044, 2915, 1677, 1580, 1478, 1377, 1248, 1197, 1069, 1004, 975, 816, 744; ESI-MS:  $m/z$  (%) = 468 (100)  $[\text{M}+\text{Na}]^+$ .

化合物 **3w**: 粉色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.92-7.96 (m, 2H), 6.80-7.41 (m, 10H), 5.46 (t,  $J = 8.0$  Hz, 1H), 4.09 (dd, 2H,  $J = 12.0, 7.2$  Hz), 3.73-3.75 (m, 1H), 3.72 (s, 3H), 3.54-3.60 (m, 1H), 1.45 (s, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 196.30, 162.91, 162.01, 159.54, 137.87, 137.83, 137.29, 133.97, 133.87, 130.40, 129.89, 129.81, 129.69, 126.92, 126.55, 121.79, 119.42, 118.94, 116.94, 116.70, 116.16,

114.14, 113.93, 109.19, 76.66, 63.73, 43.95, 34.36, 32.75, 14.65; IR (KBr),  $\nu_{\max}/\text{cm}^{-1}$ : 3051, 2981, 2902, 1668, 1599, 1483, 1315, 1244, 1177, 1040, 904, 846, 745, 600; ESI-MS:  $m/z$  (%) = 458 (100)  $[\text{M}+\text{Na}]^+$ .

化合物 **3x**: 砖红色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.89-7.92 (m, 2H), 7.46 (d,  $J = 8.0$  Hz, 1H), 6.86-7.25 (m, 8H), 6.80 (s, 1H), 4.97 (t,  $J = 8.0$  Hz, 1H), 4.07 (d,  $J = 7.2$  Hz, 2H), 3.61-3.75 (m, 5H), 2.18 (s, 6H), 1.42 (t,  $J = 7.2$  Hz, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 197.08, 162.73, 141.97, 137.28, 136.37, 134.21, 130.37, 130.08, 129.58, 129.16, 127.06, 126.16, 124.90, 121.51, 119.64, 118.70, 118.24, 114.04, 109.08, 76.68, 63.69, 45.08, 37.73, 32.67, 19.91, 19.34, 14.67; IR (KBr),  $\nu_{\max}/\text{cm}^{-1}$ : 3044, 2974, 2929, 1667, 1599, 1472, 1309, 1247, 1174, 1045, 838, 742, 610; ESI-MS:  $m/z$  (%) = 434 (100)  $[\text{M}+\text{Na}]^+$ .

化合物 **3y**: 粉色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.51 (d,  $J = 7.6$  Hz, 1H), 7.12-7.37 (m, 7H), 7.00-7.04 (m, 3H), 6.83 (s, 1H), 4.92 (t,  $J = 8.0$  Hz, 1H), 3.74 (s, 3H), 3.54-3.70 (m, 1H), 2.34 (s, 3H), 2.29 (s, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 201.35, 144.80, 141.99, 138.65, 137.30, 134.91, 132.90, 132.26, 130.25, 130.05, 129.77, 128.64, 127.35, 126.66, 126.26, 126.15, 121.93, 119.27, 119.08, 116.67, 109.31, 76.68, 47.58, 37.76, 32.74, 21.36, 21.10; IR (KBr),  $\nu_{\max}/\text{cm}^{-1}$ : 3051, 2958, 2917, 1668, 1561, 1466, 1347, 1290, 1199, 1124, 1029, 978, 818, 741, 6890; ESI-MS:  $m/z$  (%) = 437 (100)  $[\text{M}+\text{H}^+]$ , 458 (93)  $[\text{M}+\text{Na}]^+$ .

化合物 **3z**: 黄色粉末;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz):  $\delta$  (ppm) : 7.94 (d,  $J = 1.6$  Hz, 1H), 7.70 (dd,  $J = 12, 2.0$  Hz, 1H), 7.45-7.49 (m, 3H), 7.16-7.26 (m, 5H), 7.00-7.09 (m, 5H), 6.79 (s, 1H), 4.94 (t,  $J = 8.0$  Hz, 1H), 3.66-3.73 (m, 3H), 2.18 (s, 3H);  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 100 MHz):  $\delta$  (ppm) : 196.54, 141.27, 137.40, 137.28, 136.68, 136.56, 134.56, 133.13, 130.59, 130.16, 129.69, 129.06, 127.09, 126.86, 126.13, 124.83, 121.71, 119.47, 118.89, 117.73, 109.20, 45.42, 37.78, 32.70, 19.91, 19.34; IR (KBr),  $\nu_{\max}/\text{cm}^{-1}$ : 3085, 3013, 2934, 2891, 1678, 1579, 1463, 1387, 1243, 1197, 1027, 815, 744, 677; ESI-MS:  $m/z$  (%) = 458 (100)  $[\text{M}+\text{Na}]^+$ .

### 3. 结果讨论

#### 3.1. 优化反应条件

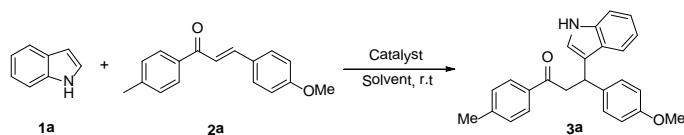
以吡啶和 3-(4-甲基苯基)-1-(4-甲氧基苯基)-1-丙酮在乙腈中的反应为模型, 对反应条件进行了优化, 实验结果见表 1。首先考察了催化剂 Brønsted 酸性离子液体  $[\text{ThiN}(\text{CH}_2)_4\text{SO}_3][p\text{-CH}_3\text{PhSO}_3]$  的用量对反应的影响 (Table 1, entries 1-4)。当不加催化剂时, 无法得到目标产物 (Table 1, entry 1)。当催化剂用量为 15 mol% 时, 催化效率最高, 产率可达 98% (Table 1, entry 4), 考虑到反应的经济性, 确定催化剂的用量为 10 mol% (Table 1, entry 3)。其次考察了反应时间、溶剂种类等对该反应的影响 (Table 1, entries 5-10)。通过筛选, 确定反应的最佳条件为: 离子液体催化剂  $[\text{ThiN}(\text{CH}_2)_4\text{SO}_3][p\text{-CH}_3\text{PhSO}_3]$  用量 10 mol%, 乙腈为反应溶剂, 反应时间 5 h, 反应温度 80°C。

#### 3.2. 反应底物普适性研究

在最佳反应条件下, 对反应底物的普适性进行研究, 结果见表 2。研究发现  $\alpha$ 、 $\beta$ -不饱和酮的苯环上连有供电子的 Me、Et、OMe 或 OEt 等基团或是吸电子的卤原子时, 反应都能够顺利的进行, 所得产物产率为 82%~99% (Table 2, 3b-3l, 3o-3x)。当  $\alpha$ 、 $\beta$ -不饱和酮的苯环上均为双取代时, 也能以优秀的产率得到相应的目标产物 (Table 2, 3m、3y、3z)。此外, 无论是吡啶还是 N-甲基吡啶都能与各种不同取代的  $\alpha$ 、 $\beta$ -不饱和酮平稳的反应。以上结果表明, 该反应底物的普适性好。

### 4. 催化剂的循环使用性研究

在最佳反应条件下, 以吡啶和 3-(4-甲基苯基)-1-(4-甲氧基苯基)-1-丙酮为模型反应, 考察了离子液体

**Table 1.** Optimization of reaction conditions<sup>a</sup>**表 1.** 反应条件优化<sup>a</sup>

Entry	Solvent	Cat. (mol%)	Time (h)	Yields (%) <sup>b</sup>
1	Acetonitrile	None	4	0
2	Acetonitrile	IL (5)	4	80
3	Acetonitrile	IL (10)	4	96
4	Acetonitrile	IL (15)	4	98
5	Acetonitrile	IL	3	89
6	Acetonitrile	IL	5	99
7	Dichloromethane	IL	4	80
8	Ethanol	IL	4	61
9	Ethyl acetate	IL	4	67
10	Toluene	IL	4	56

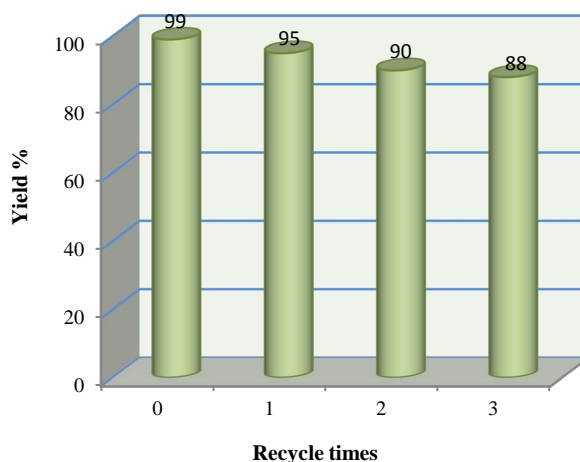
<sup>a</sup>反应条件: **1a** (1 mmol), **2a** (1 mmol), 催化剂 IL: [ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][p-CH<sub>3</sub>PhSO<sub>3</sub>], 溶剂 (5 mL), 80°C; <sup>b</sup>分离产率。

**Table 2.** Research of substrate scope<sup>a</sup>**表 2.** 底物的普适性研究<sup>a</sup>

Entry	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	Yields (%) <sup>b</sup>	Mp (°C)	
					Found	Reported
3a	H	Ph	Ph	95	127-128	127-128 [21]
3b	H	Ph	4-F-C <sub>6</sub> H <sub>4</sub>	99	140-142	142-143 [22]
3c	H	Ph	4-Cl-C <sub>6</sub> H <sub>4</sub>	92	116-118	118-120 [23]
3d	H	Ph	4-OCH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	94	120-122	124-125 [24]
3e	H	4-Cl-C <sub>6</sub> H <sub>4</sub>	Ph	94	155-156	154-155 [25]
3f	H	4-Br-C <sub>6</sub> H <sub>4</sub>	Ph	99	173-175	174-176 [26]
3g	H	4-OCH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	Ph	93	180-181	182-183 [25]
3h	H	4-OCH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	4-F-C <sub>6</sub> H <sub>4</sub>	92	170-172	
3i	H	4-OCH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	4-CH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	92	184-185	183-186 [27]
3j	H	4-OEt-C <sub>6</sub> H <sub>4</sub>	3,4-(CH <sub>3</sub> ) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	86	146-148	
3k	H	4-OEt-C <sub>6</sub> H <sub>4</sub>	3-F-4-Br-C <sub>6</sub> H <sub>3</sub>	91	114-116	
3l	H	4-OEt-C <sub>6</sub> H <sub>4</sub>	2-Cl-4-F-C <sub>6</sub> H <sub>3</sub>	89	157-159	
3m	H	3,4-(Cl) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	3,4-(CH <sub>3</sub> ) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	88	105-107	
3n	CH <sub>3</sub>	Ph	Ph	98	125-126	127-129 [28]
3o	CH <sub>3</sub>	Ph	4-F-C <sub>6</sub> H <sub>4</sub>	84	161-163	
3p	CH <sub>3</sub>	Ph	4-Cl-C <sub>6</sub> H <sub>4</sub>	99	151-155	153-154 [29]
3q	CH <sub>3</sub>	Ph	4-Br-C <sub>6</sub> H <sub>4</sub>	92	102-104	
3r	CH <sub>3</sub>	Ph	4-OCH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	93	134-136	130-131 [30]
3s	CH <sub>3</sub>	4-Cl-C <sub>6</sub> H <sub>4</sub>	Ph	85	135-136	142-143 [24]
3t	CH <sub>3</sub>	4-Br-C <sub>6</sub> H <sub>4</sub>	Ph	96	138-140	
3u	CH <sub>3</sub>	4-Cl-C <sub>6</sub> H <sub>4</sub>	4-OCH <sub>3</sub> -C <sub>6</sub> H <sub>4</sub>	82	160-162	
3v	CH <sub>3</sub>	4-Br-C <sub>6</sub> H <sub>4</sub>	3,4-(CH <sub>3</sub> ) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	99	169-171	
3w	CH <sub>3</sub>	4-OEt-C <sub>6</sub> H <sub>4</sub>	2-Cl-4-F-C <sub>6</sub> H <sub>3</sub>	99	144-145	
3x	CH <sub>3</sub>	4-OEt-C <sub>6</sub> H <sub>4</sub>	3,4-(CH <sub>3</sub> ) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	97	135-137	
3y	CH <sub>3</sub>	2,4-(CH <sub>3</sub> ) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	3,4-(Cl)-C <sub>6</sub> H <sub>3</sub>	94	153-154	
3z	CH <sub>3</sub>	3,4-(Cl) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	3,4-(CH <sub>3</sub> ) <sub>2</sub> -C <sub>6</sub> H <sub>3</sub>	86	127-128	

<sup>a</sup>反应条件: 吲哚或取代吲哚(1 mmol), α, β-不饱和酮(1 mmol), [ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][p-CH<sub>3</sub>PhSO<sub>3</sub>] (10 mol%), 80°C, 5 h, 乙腈(5mL)。<sup>b</sup>分离产率。





**Figure 1.** Recycling research of ionic liquid [ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]  
**图 1.** 离子液体[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]的循环性研究

催化剂([ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>])的循环使用效果, 结果见图 1。具体操作是: 将 15 mL 乙酸乙酯分三次加入到除去粗产物后的滤液中萃取残留的有机物, 然后将水相中的水旋除, 真空干燥至恒重, 即得回收的离子液体催化剂, 然后直接用于下一次催化循环实验。研究发现该离子液体催化剂循环使用 3 次, 相应产物的产率分别是 95%、90%、88%, 表明离子液体具有良好的循环使用效果。

## 5. 总结

本文开展了吲哚和  $\alpha$ 、 $\beta$ -不饱和酮在 Brønsted 酸性离子液体[ThiN(CH<sub>2</sub>)<sub>4</sub>SO<sub>3</sub>][*p*-CH<sub>3</sub>PhSO<sub>3</sub>]催化下的 Michael 加成反应, 以 82%~99%的产率合成了  $\beta$ -吲哚酮化合物, 具有产物收率高、催化剂可循环使用的特点。

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