Ionic-liquid-supported 1,5,7-triazabicyclo[4.4.0] dec-5-ene — An efficient and recyclable organocatalyst for Michael addition to α,β-unsaturated ketones

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Abstract: A novel ionic-liquid-supported 1,5,7-triazabicyclo[4.4.0]dec-5-ene (IL–TBD) was synthesized and investigated for its ability to act as an active organocatalyst in the Michael addition of active methylene compounds and thiophenols to chalcones under solvent-free conditions. The IL–TBD afforded Michael addition products in excellent yields (82%–94%) at room temperature, and it was simply recycled and reused at least five times without significant loss of catalytic activity.

Key words: ionic liquid, supported catalysis, organocatalyst, Michael addition, α,β-unsaturated ketones.

Résumé : On a réalisé la synthèse d'un liquide ionique supporté par du 1,5,7-triazabicyclo[4.4.0]déc-5-ène (LI–TBD) et on a étudié ses capacités d'agir comme organocatalyseur dans l'addition de Michael de composés comportant des méthylènes actifs et des thiophénols à des chalcones, dans des conditions sans solvant. Le LI–TBD permet d'obtenir des produits d'addition de Michael avec d'excellents rendements (82 % à 94 %), à la température ambiante; il peut être recyclé facilement et réutilisé jusqu'à cinq fois sans perte significative de son activité catalytique.

Mots-clés : liquide ionique, catalyseur sur un support, organocatalyseur, addition de Michael, cétones α,β-insaturées.

[Traduit par la Rédaction]

Introduction

Organocatalyses have emerged as new and powerful tools in organic synthesis.[1–4] Lower cost, operational simplicity, easy availability, efficiency, and less toxicity make organocatalysts attractive alternatives to organometallic catalysts in organic synthesis. The major problems associated with most homogeneous organocatalyst systems are high organocatalyst loadings to afford efficient synthesis, long and tedious preparation steps, and separation and recycling of these catalysts. To overcome these difficulties catalysts have been immobilized on various solid supports. However, reaction rates are lower with solid-supported reagents and require longer validation times.

Ionic liquids (ILs) are fascinating materials for chemists as they offer new chemical and physical properties such as high thermal stability, very low to negligible vapor pressure, good solvating ability, a noncoordinating nature, and ease of recyclability.[5–10] In recent years, functionalized ionic liquids (FILs) synthesized with properties for specific desired chemical tasks have attracted the attention of chemists.[11,12] Several ILs functionalized with catalytically active groups have been developed and used effectively as recyclable organocatalysts for various organic transformations.[13–22] Imidazolium ILs functionalized with basic organic molecules such as proline[23–25] and pyrrolidine[26–32] have been extensively studied for Michael additions. FILs not only overcome the problems of lower reaction rate and longer validation reaction time but also provide reagents with tuneable properties and "green" credentials.

1,5,7-Triazabicyclo[4,4.0]dec-5-ene (TBD) is a versatile bicyclic guanidine with nucleophilic and basic properties that render this compound an extremely useful catalyst for many organic transformations.[33–37] Several methods have been reported for the preparation of heterogeneous basic catalysts in which TBD is covalently attached with polymer support or silica.[38–40] The solid-supported TBDs have efficiently promoted some fundamental base-catalyzed organic transformations such as the Nef reaction,[41] alkylation,[42] 1,2-epoxide ring opening,[43] aldol-type condensation,[43] Knoevenagel condensation,[43,44] Michael addition,[44] synthesis of thioureas,[45] aryl ether synthesis,[46] synthesis of benzofuran[47] and thiazoles,[48] and transesterification of soybean oil.[49] However, heterogeneous TBD usually suffers from the disadvantage of being only slightly recyclable, requires a compatible solvent for swelling, and has prolonged reaction times. In continuation of our effort to develop IL-based catalysts,[50] herein, we report the synthesis of a novel IL-functionalized TBD (IL–TBD)

Received 10 July 2011. Accepted 30 November 2011. Published at www.nrcresearchpress.com/cjc on 14 February 2012.

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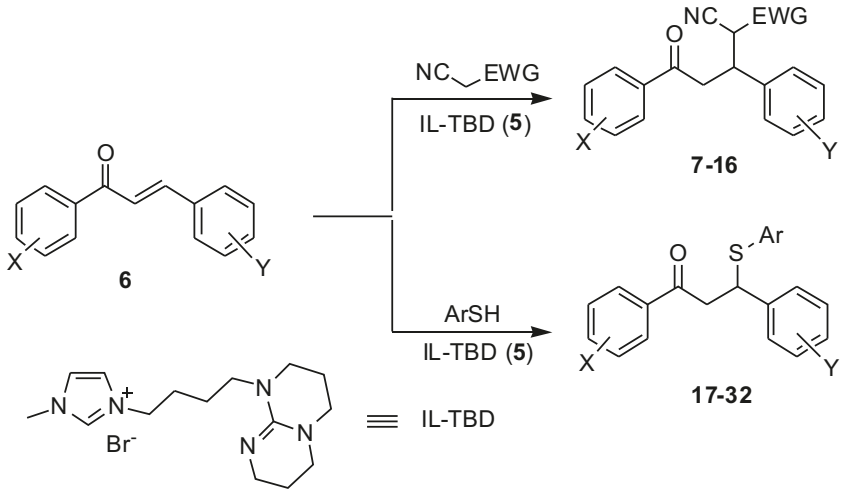
Scheme 1. Michael addition of active methylene compounds and thiophenols to chalcones. EWG, electron-withdrawing group.



and its use as an organocatalyst for the Michael addition of active methylene compounds and thiophenols to chalcones (Scheme 1).

Results and discussion

Synthesis of IL–TBD was achieved following the reaction sequences shown in Scheme 2. Initially, the reaction of 1-methylimidazole (**1**) with 1-bromo-4-chlorobutane (**2**) at room temperature afforded (4′-chlorobutyl)-3-methylimidazolium bromide (**3**). Subsequent reaction of **3** with 1.5 equiv of TBD (**4**) at 100 °C for 6 h gave IL–TBD **5** with bromide as the anion. The excess TBD was removed by washing with dichloromethane, and the IL–TBD was purified by column chromatography on silica gel. The structure of **5** was confirmed by ^{1}H NMR, ^{13}C NMR, and high-resolution mass spectrometry. The ^{1}H NMR spectrum showed multiplets in the range of 3.24 to 3.04, representing the methylene protons of TBD adjacent to nitrogens. In ^{13}C NMR, six carbons appeared in the aliphatic region in addition to methyl and methylene carbons of the IL, which corresponds to the methylene carbon of TBD. In HRMS peaks appeared at 356.1260 $[M]^+$, 358.1257 $[M + 2]^+$, and 276.1889 $[M - Br]^+$, which confirmed the structure of **5**.

The catalytic activity of IL–TBD as an organocatalyst was evaluated for the Michael addition of malononitrile to chalcones. The reaction conditions were optimized by taking the reaction of 3-(2-fluorophenyl)-1-(4-methoxyphenyl)prop-2-en-1-one with malononitrile to give **7** as model reaction (Table 1). Loading studies using different concentrations of catalyst showed the requirement of 50 mol % of IL–TBD to catalyze the reaction to maximum yields (Table 1, entries 1–4). The yield of Michael addition product was higher under solvent-free conditions (87%; Table 1, entry 3) as compared with the reaction in different organic solvents (58%–85%; Table 1, entries 5–9). The aqueous medium served as a poor system for this reaction giving no product over the period under similar reaction conditions (Table 1, entry 11). This may be due to the insolubility of both chalcone and the catalyst in water. The product yield was low (17%–20%) when the reaction was performed in ILs ([bmim]Br, [bmim]BF_4, and [bmim]PF_6) as solvents. The low yield in these ILs may

Scheme 2. Synthesis of ionic-liquid-supported 1,5,7-triazabicyclo [4.4.0]dec-5-ene (TBD) (IL–TBD).

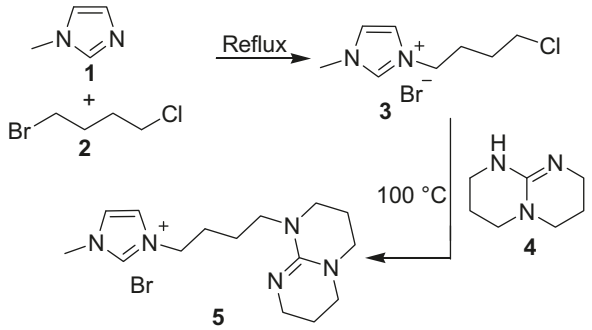


Table 1. Optimization of reaction conditions for Michael addition.

Entry	Catalyst (mol %)	Solvent	Time (h)	Yield (%)[a,b]
1	10	—	24	60
2	30	—	12	75
3	50	—	4	87
4	60	—	4	86
5	50	CH_3CN	4	85
6	50	CH_3OH	4	80
7	50	DMF	8	72
8	50	Ethanol	8	70
9	50	DCM	8	58
10	50	Toluene	36	70
11	50	H_2O	36	—[c]
12	50	[bmim]Br	12	18
13	50	[bmim]PF_6	12	17 (10)[d]
14	50	[bmim]BF_4	12	20

[a]Reaction conditions: chalcone (1 mmol), malononitrile (1 mmol), catalyst **5** (10–50 mol %), at room temperature.
[b]Isolated yield.
[c]No product formation was observed.
[d]Yield without catalyst.

probably be due to the slight acidic nature of the IL and the poor solubility of the reactant at room temperature in [bmim]Br. The role of IL–TBD as catalyst is confirmed by the fact that no product was formed in the absence of this catalyst. The reaction seems to proceed with a general base-catalyzed pathway. A plausible mechanism is shown in Scheme 3.

Furthermore, the catalyst was evaluated for its general application in Michael addition reactions by performing the reaction with different chalcones having electron-releasing and electron-withdrawing groups on either side as Michael acceptors and malononitrile and ethyl cyanoacetate as Michael donors (Table 2). It was observed that chalcones with both electron-withdrawing and electron-releasing groups resulted in high yields of Michael products. The presence of electron-withdrawing or electron-releasing groups had a negligible effect on the yield of the product. Malononitrile was found to be a better donor (Table 2, entries 1 and 8) when compared with ethyl cyanoacetate (Table 2, entries 9 and 10). The structure of the synthesized compound was confirmed by ^{1}H NMR and ^{13}C NMR.

The catalytic scope of the IL–TBD was also assessed for the thia-Michael addition to chalcones. As expected, thia-Michael addition of thiophenols to chalcones was extraordinarily fast with thiols in the presence of IL–TBD (10 mol %) and gave high yields with short reaction times (3–5 min) at room temperature (Table 3). Although the reaction also proceeded in [bmim][PF_6] alone to give **7** in 10% yield, the yield of product was greater (87%) and it required a shorter reaction time in the presence of a catalytic amount of IL–TBD under solvent-free conditions.

Finally, the recyclability of catalyst **5** was investigated in the model reaction. Addition of malononitrile to chalcone (3-(2-fluorophenyl)-1-(4-methoxyphenyl)prop-2-en-1-one) afforded **7**. After extracting **7**, the recovered **5** was again used for the model reaction and it was found that catalyst **5** can be efficiently reused for up to five cycles without much loss in the yield of **7** (Fig. 1).

Conclusion

We have described the synthesis of a novel IL–TBD and its ability to act as an active organocatalyst in the Michael addition of active methylene compounds and thiophenols to chalcones under solvent-free conditions. The IL–TBD afforded Michael addition products in excellent yields (82%–94%) at room temperature, and it was easily recycled and reused at least five times without significant loss of catalytic activity. This is the first example of an IL–TBD and its use in organic synthesis. The present study shows that high catalytic efficacy can be achieved by functionalizing ILs with organocatalysts under greener reaction conditions.

Experimental section

General

1-Methylimidazole, 1-bromo-4-chlorobutane, and TBD were purchased from Sigma-Aldrich, India. All other reagents and solvents were purchased from S. D. Fine, India, and used without further purification unless otherwise specified. Column chromatography was carried out over silica gel (60–120 mesh, S. D. Fine, India). NMR spectra were recorded on Brucker Heaven Avance 11 400 and Varian (500 MHz) spectrometers using $CDCl_3$ and DMSO-d_6 as solvents, and the chemical shifts are expressed in ppm. Mass spectra were recorded on a QSTAR ELITE LX/MS/MS mass spectrometer from Applied Biosystems. The purity of the products was determined on silica-coated aluminum plates (Merck).

Synthesis of 1-methyl-3-(4′-TBD-butyl)imidazolium bromide (IL–TBD) (5)

1-Bromo-4-chlorobutane (**2**, 2.09 g, 12 mmol) was added dropwise to 1-methylimidazole (**1**, 1.0 g, 12 mmol) at room temperature, and the reaction mixture was stirred for 4 h. The mixture turned viscous over this time. After completion of the reaction as indicated by thin-layer chromatography (TLC), the reaction mixture was extracted with ethyl acetate (3 × 10 mL) to remove unreacted starting materials. The trapped ethyl acetate was removed on a rotatory evaporator under reduced pressure to obtain the product **3** in 2.7 g (89% yield). IL **3** (2.7 g, 10.7 mmol) was added to TBD (**4**, 3.71 g 17.7 mmol) and the mixture was heated at 100 °C for 6 h. After completion of the reaction, the reaction mixture was cooled to room temperature and washed with DCM (5 × 15 mL) to remove unreacted TBD and TBD salt. The resulting IL was dried under reduced pressure to form a thick light yellow liquid, which was purified by column chromatography on silica gel to give **5**. Viscous liquid. Yield: 3.48 g (92%). ^{1}HNMR (500 MHz, DMSO-d_6) δ: 9.30 (s, 1H), 7.73 (s, 1H), 7.62 (s, 1H), 4.06 (t, J = 6.8 Hz, 2H), 3.69 (s, 3H), 3.24–3.19 (m, 2H), 3.13–3.04 (m, 6H), 3.00 (s, 2H), 1.74–1.56 (m, 6H), 1.32–1.23 (m, 2H). ^{13}C NMR (126 MHz, DMSO-d_6) δ: 150.2, 137.0, 123.9, 122.7, 48.9, 48.7, 47.7, 47.2, 46.1, 38.5, 36.2, 26.5, 23.6, 20.9, 20.7. HRMS calcd for $C_{15}H_{26}N_5Br$: 356.14; found: 356.1260 $[M]^+$, 358.1257 $[M + 2]^+$, 276.1889 $[M - Br]^+$.

General procedure for the Michael addition of active methylene compounds and thiophenols to chalcones

Malononitrile / ethyl 2-cyanoacetate / thiophenol (1.0 mmol) was added to a solution of chalcone (1.0 mmol) and **5** (0.5 mmol or 0.1 mmol for thiophenols). The reaction mixture was stirred vigorously until reaction completions (see Tables 2 and 3 for reaction times). The progress of the reaction was monitored by TLC. After completion of the reaction, the product was extracted from the catalyst by ethyl acetate (2 × 5 mL), leaving the IL–TBD catalyst in the flask. The ethyl acetate layer was evaporated and washed with diethyl ether to afford the pure product.

2-(1-(2-Fluorophenyl)-3-(4-methoxyphenyl)-3-oxopropyl) malononitrile (7)

^{1}H NMR (400 MHz, DMSO) δ: 7.87 (d, J = 7.4 Hz, 2H), 7.68–6.68 (m, 6H), 5.32 (d, J = 6.3 Hz, 1H), 4.58–4.19 (m, 1H), 3.80 (s, 3H), 3.71–3.57 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 194.81, 163.96, 161.93, 159.54, 130.92, 129.29, 125.24, 116.17, 116.00, 114.39, 113.63, 113.44, 56.00, 39.98, 33.72, 28.92. HRMS calcd for $C_{19}H_{15}FN_2O_2$: 322.1118; found: 323.1016 $[M]^+$.

Scheme 3. Plausible mechanism for the catalytic activity of ionic-liquid-supported 1,5,7-triazabicyclo[4.4.0]dec-5-ene (IL–TBD).

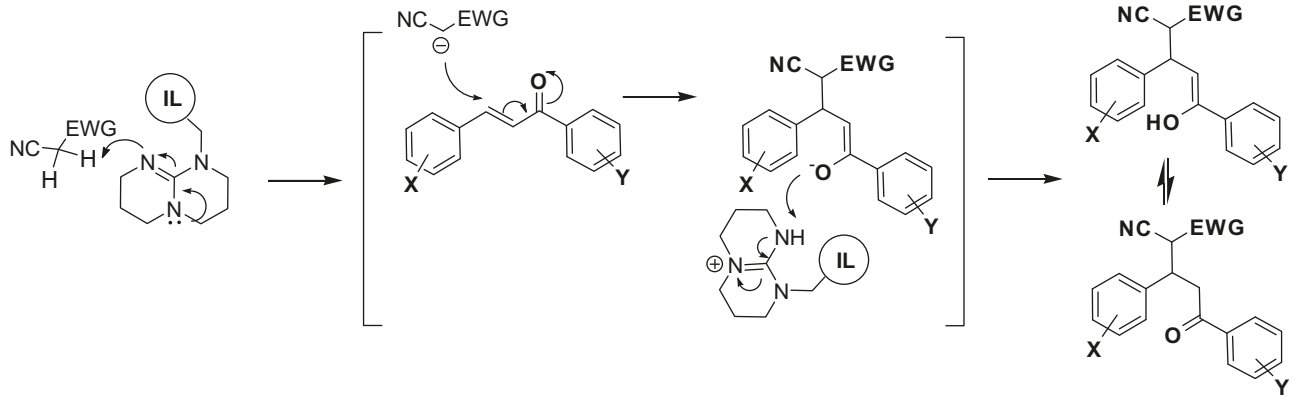


Table 2. Michael addition of active methylene compounds to chalcones catalyzed by **5**.

Product	X	Y	EWG	Time (h)	Yield (%)[a,b]
7	4-OCH_3	2-F	CN	4	87
8	4-Cl	2-F	CN	1.5	90
9	4-Cl	3-NO_2	CN	2	87
10	4-Cl	4-NO_2	CN	2	87
11	4-Cl	H	CN	2	92
12	4-OCH_3	4-NO_2	CN	4	86
13	4-OCH_3	4-OCH_3	CN	3	86
14	H	4-OCH_3	CN	3	85
15	4-Cl	H	CO_2Et	3	87
16	4-OCH_3	2-F	CO_2Et	6	82

Note: EWG, electron-withdrawing group.
[a]All the compounds showed satisfactory ^{1}H NMR and ^{13}C NMR.
[b]Isolated yield.

Table 3. Michael addition of thiophenols to chalcones catalyzed by **5**.

Product	X	Y	Ar	Time (min)	Yield (%)[a,b]
17	4-Cl	2-F	Ph	2	93
18	4-OCH_3	2-F	Ph	2	92
19	H	4-Cl	Ph	2	91
20	4-CH_3	H	Ph	2	92
21	4-OCH_3	3-NO_2	Ph	5	90
22	4-OCH_3	4-NO_2	Ph	5	92
23	4-CH_3	4-Cl	Ph	3	92
24	4-Cl	4-OCH_3	Ph	2	94
25	4-CH_3	4-OCH_3	Ph	2	93
26	4-OCH_3	4-OCH_3	Ph	2	92
27	4-Cl	H	Ph	4	92
28	4-NO_2	H	Ph	5	90
29	4-OCH_3	H	Ph	2	93
30	4-CH_3	3-NO_2	Ph	5	92
31	H	3-NO_2	Ph	5	91
32	4-Cl	H	4-CH_3OPh	4	90

[a]All the compounds showed satisfactory ^{1}H NMR and ^{13}C NMR.
[b]Isolated yield.

2-(3-(4-Chlorophenyl)-1-(2-fluorophenyl)-3-oxopropyl) malononitrile (8)

^{1}H NMR (500 MHz, DMSO) δ: 7.98 (d, J = 7.28 Hz, 2H), 7.60–7.58 (m, 3H), 7.40–7.35 (m, 1H), 7.26–7.20 (m, 2H), 5.25 (d, J = 6.5 Hz, 1H), 4.36–4.32 (m, 1H), 3.90 (dd, J = 18.3, 8.65 Hz, 1H), 3.69 (dd, J = 18.3, 5.4 Hz, 1H). ^{13}C NMR (126 MHz, DMSO) δ: 195.66, 139.03, 135.00, 130.76, 130.70, 130.45, 129.33, 125.25, 116.16, 115.98, 113.55, 113.35, 40.48, 33.60, 28.85. HRMS calcd for $C_{18}H_{12}ClFN_2O$: 326.0622; found: 327.0006 $[M]^+$.

2-(3-(4-Chlorophenyl)-1-(3-nitrophenyl)-3-oxopropyl) malononitrile (9)

^{1}H NMR (400 MHz, DMSO) δ: 8.00 (d, J = 6.8 Hz, 2H), 7.65–7.61 (m, 3H), 7.42–7.38 (m, 1H), 7.26 (d, J = 6.68 Hz, 2H), 5.26 (d, J = 6.5 Hz, 1H), 4.41–4.32 (m, 1H), 3.95–3.89 (m, 1H), 3.73–3.68 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 195.73, 139.09, 135.01, 130.84, 130.74, 130.54, 129.37, 125.29, 116.23, 115.98, 113.66, 113.43, 40.93, 33.52, 28.93. HRMS calcd for $C_{18}H_{12}ClN_3O_3$: 353.0567; found: 375.0487 $[M - H + Na]^+$.

2-(3-(4-Chlorophenyl)-1-(4-nitrophenyl)-3-oxopropyl) malononitrile (10)

^{1}H NMR (400 MHz, DMSO) δ: 8.26 (d, J = 7.27 Hz, 2H), 8.01 (d, J = 7.3 Hz, 2H), 7.82 (d, J = 7.3 Hz, 2H), 7.61 (d, J = 7.3 Hz, 2H), 5.32 (d, J = 6.3 Hz, 1H), 4.32–4.26 (m, 1H), 4.06–3.96 (m, 1H), 3.81–3.69 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 195.68, 147.86, 145.87, 139.15, 134.99, 130.57, 130.36, 129.39, 124.17, 113.60, 113.36, 40.47, 40.16, 29.30. HRMS calcd for $C_{18}H_{12}ClN_3O_3$: 353.0567; found: 375.0484 $[M - H + Na]^+$.

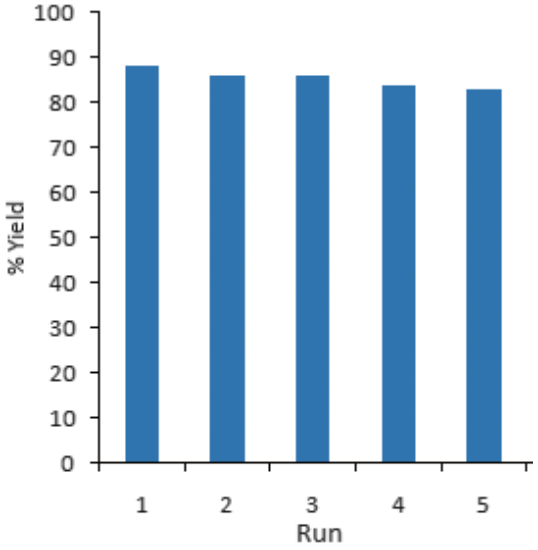
2-(3-(4-Chlorophenyl)-3-oxo-1-phenylpropyl)malononitrile (11)

^{1}H NMR (400 MHz, DMSO) δ: 8.02–7.98 (m, 2H), 7.64–7.54 (m, 3H), 7.53–7.41 (m, 2H), 7.39–7.35 (m, 2H), 5.25–5.20 (m, 1H), 4.07–4.03 (m, 1H), 3.88–3.84 (m, 1H), 3.68–3.64 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 196.02, 139.07, 138.20, 135.18, 130.54, 129.37, 129.11, 128.74, 113.93, 113.65, 40.67, 40.50, 29.77. HRMS calcd for $C_{18}H_{13}ClN_2O$: 308.0716; found: 309.0701 $[M]^+$.

2-(3-(4-Methoxyphenyl)-1-(4-nitrophenyl)-3-oxopropyl) malononitrile (12)

^{1}H NMR (400 MHz, DMSO) δ: 8.22 (d, J = 7.12 Hz, 2H), 7.84 (d, J = 6.9 Hz, 2H), 7.43 (d, J = 6.9 Hz, 2H), 6.89 (d,

Fig. 1. Recycling of ionic-liquid-supported 1,5,7-triazabicyclo[4.4.0] dec-5-ene (IL–TBD) for the Michael addition reaction.



J = 7.1 Hz, 2H), 5.23 (d, J = 6.5 Hz, 1H), 4.43–4.36 (m, 1H), 4.01–3.96 (m, 1H), 3.83–3.72 (m, 1H), 3.78 (s, 3H). ^{13}C NMR (101 MHz, DMSO) δ: 195.78, 144.87, 143.97, 139.25, 135.69, 130.64, 130.23, 128.59, 128.23, 114.64, 113.86, 55.53, 40.87, 41.26, 29.45. HRMS calcd for $C_{19}H_{15}N_3O_4$: 349.1063; found: 371.0978 $[M - H + Na]^+$.

2-(1,3-Bis(4-methoxyphenyl)-3-oxopropyl)malononitrile (13)

^{1}H NMR (400 MHz, DMSO) δ: 8.01–7.96 (m, 2H), 7.45–7.37 (m, 2H), 7.04–7.02 (m, 2H), 7.01–6.98 (m, 2H), 5.21 (d, J = 6.5 Hz, 1H), 4.03–3.98 (m, 1H), 3.82 (s, 3H), 3.77–3.73 (m, 1H), 3.72 (s, 3H), 3.55–3.53 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 195.22, 163.92, 159.50, 130.95, 130.12, 129.88, 129.53, 114.41, 114.11, 113.80, 56.03, 55.50, 40.34, 40.31, 29.99. HRMS calcd for $C_{20}H_{18}N_2O_3$: 334.1317; found: 335.1187 $[M]^+$.

2-(1-(4-Methoxyphenyl)-3-oxo-3-phenylpropyl)malononitrile (14)

^{1}H NMR (400 MHz, DMSO) δ: 7.99 (d, J = 7.3 Hz, 2H), 7.71–7.62 (m, 1H), 7.60–7.49 (m, 2H), 7.45–7.36 (m, 2H), 7.03–6.89 (m, 2H), 5.24–5.05 (m, 1H), 4.06–3.98 (m, 1H), 3.82–3.78 (m, 1H), 3.73 (s, 3H), 3.63–3.57 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 196.95, 159.51, 136.54, 134.12, 130.06, 129.89, 129.28, 128.58, 114.43, 114.08, 113.76, 55.54, 40.78, 40.58, 29.98. HRMS calcd for $C_{19}H_{16}N_2O_2$: 304.1212; found: 333.1114 $[M - H + K]^+$.

Ethyl 5-(4-chlorophenyl)-2-cyano-5-oxo-3-phenylpentanoate (15)

^{1}H NMR (400 MHz, DMSO) δ: 8.01 (d, J = 7.5 Hz, 2H), 7.59 (d, J = 7.1 Hz, 2H), 7.35–7.26 (m, 5H), 4.69–4.46 (m, 1H), 4.08–3.97 (m, 3H), 3.72–3.65 (m, 2H), 1.08 (t, J = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, DMSO) δ: 196.24, 165.75, 138.93, 135.39, 130.48, 129.39, 128.93, 128.57, 128.42, 128.20, 62.58, 44.11, 41.75, 40.86, 14.22. HRMS calcd for $C_{20}H_{18}ClNO_3$: 355.0975; found: 356.0798 $[M]^+$.

Ethyl 2-cyano-3-(2-fluorophenyl)-5-(4-methoxyphenyl)-5-oxopentanoate (16)

^{1}H NMR (400 MHz, DMSO) δ: 7.99 (d, J = 5.9, Hz, 2H), 7.62–7.58 (m, 2H), 7.53–7.45 (m, 1H), 7.35–7.30 (m, 1H), 7.18 (d, J = 6.6 Hz, 2H), 4.60 (d, J = 4.5 Hz, 1H), 4.37–4.28 (m, 1H), 4.11–4.04 (m, 2H), 3.88–3.57 (m, 2H), 1.01 (t, J = 6.7 Hz, 3H). ^{13}C NMR (101 MHz, DMSO) δ: 196.23, 165.85, 139.25, 135.49, 132.83, 130.46, 130.06, 129.50, 129.39, 125.22, 116.71, 115.94, 62.80, 43.49, 43.16, 41.60, 32.61, 14.09. HRMS calcd for $C_{21}H_{20}FNO_4$: 369.1376; found: 370.1288 $[M]^+$.

1-(4-Chlorophenyl)-3-(2-fluorophenyl)-3-(phenylthio) propan-1-one (17)

^{1}H NMR (400 MHz, DMSO) δ: 8.21–8. 13 (m, 1H), 7.97 (d, J = 6.9 Hz, 2H), 7.57–7.09 (m, 10H), 5.18–4.98 (m, 1H), 3.90–3.81 (m, 1H), 3.79–3.72 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 196.32, 138.93, 135.32, 133.89, 133.39, 132.49, 131.02, 130.48, 129.56, 129.35, 128.76, 125.43, 124.91, 116.09, 115.59, 43.36, 40.83. HRMS calcd for $C_{21}H_{16}ClFOS$: 370.0594; found: 392.0561 $[M - H + Na]^+$.

3-(2-Fluorophenyl)-1-(4-methoxyphenyl)-3-(phenylthio) propan-1-one (18)

^{1}H NMR (400 MHz, DMSO) δ: 7.95 (d, J = 6.87 Hz, 2H), 7.54–7.46 (m, 1H), 7.36–7.18 (m, 6H), 7.15–7.05 (m, 2H), 7.01 (d, J = 6.85 Hz, 2H), 5.21–5.08 (m, 1H), 3.83 (s, 3H), 3.83–3.78 (m, 1H), 3.72–3.58 (m, 1H). ^{13}C NMR (101 MHz, DMSO) δ: 195.48, 163.83, 161.33, 158.89, 134.17, 132.36, 130.92, 129.67, 129.55, 129.46, 129.04, 128.91, 128.07, 124.90, 115.82, 115.60, 114.40, 56.03, 42.87, 40.96. HRMS calcd for $C_{22}H_{19}FO_2S$: 366.1090; found: 367.1062 $[M]^+$.

3-(4-Chlorophenyl)-1-phenyl-3-(phenylthio)propan-1-one (19)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.89 (d, J = 7.3 Hz, 2H), 7.59–7.55 (m, 1H), 7.46 (d, J = 7.5, 2H), 7.38–7.16 (m, 9H), 4.94–4.90 (m, 1H), 3.67–3.55 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.50, 139.62, 136.31, 133.47, 133.24, 132.78, 128.97, 128.77, 128.49, 128.38, 127.85, 127.63, 47.41, 44.27. HRMS calcd for $C_{21}H_{17}ClOS$: 352.0689; found: 353.0597 $[M]^+$.

3-Phenyl-3-(phenylthio)-1-*p*-tolylpropan-1-one (20)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.79 (d, J = 7.4, 2H), 7.33–7.22 (m, 12H), 4.95 (t, J = 7.0 Hz, 1H), 3.63–3.50 (m, 2H), 2.39 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.63, 132.50, 129.09, 128.63, 128.23, 128.00, 127.60, 127.28, 127.13, 48.01, 44.27, 21.46. HRMS calcd for $C_{22}H_{20}OS$: 332.1235; found: 333.1187 $[M]^+$.

1-(4-Methoxyphenyl)-3-(3-nitrophenyl)-3-(phenylthio) propan-1-one (21)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.18 (s, 1H), 8.04 (d, J = 6.5 Hz, 1H), 7.88 (d, J = 7.5 Hz, 2H), 7.62 (d, J = 6.7 Hz, 1H), 7.48–7.35 (m, 1H), 7.31–7.23 (m, 5H), 6.93 (d, J = 7.5 Hz, 2H), 5.01 (t, J = 6.0 Hz, 1H), 3.86 (s, 3H), 3.63 (d, J = 6.8 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 194.46, 163.68, 143.64, 134.13, 133.19, 130.20, 129.14, 129.01,

128.88, 128.04, 122.42, 122.09, 113.69, 55.34, 47.64, 43.46. HRMS calcd for $C_{22}H_{19}NO_4S$: 393.1035; found: 394.0985 $[M]^+$.

1-(4-Methoxyphenyl)-3-(4-nitrophenyl)-3-(phenylthio) propan-1-one (22)

^{1}H NMR (400 MHz, DMSO) δ: 8.09 (d, J = 5.6 Hz, 2H), 7.95 (d, J = 5.2 Hz, 4H), 7.64 (d, J = 5.1 Hz, 2H), 7.31–7.19 (m 5H), 7.03 (d, J = 5.37 Hz, 2H), 5.07–4.98 (m, 1H), 3.83 (s, 3H), 3.73–3.68 (m, 2H). ^{13}C NMR (101 MHz, DMSO) δ: 195.27, 163.88, 150.24, 146.80, 133.74, 132.35, 130.99, 129.62, 128.12, 124.26, 123.79, 114.42, 47.42, 42.48. HRMS calcd for $C_{22}H_{19}NO_4S$: 393.1035; found: 394.0989 $[M]^+$.

3-(4-Chlorophenyl)-3-(phenylthio)-1-*p*-tolylpropan-1-one (23)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.79 (d, J = 8.0 Hz, 2H), 7.42–7.14 (m, 11H), 4.91 (dd, J = 6.1, 7.8 Hz, 1H), 3.69–3.46 (m, 2H), 2.41 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.11, 144.13, 139.69, 133.87, 133.53, 132.74, 129.99, 129.16, 128.97, 128.74, 128.35, 127.98, 127.57, 47.47, 44.10, 21.48. HRMS calcd for $C_{22}H_{19}ClOS$: 366.0845; found: 367.0782 $[M]^+$.

1-(4-Chlorophenyl)-3-(4-methoxyphenyl)-3-(phenylthio) propan-1-one (24)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.81 (d, J = 8.1 Hz, 2H), 7.48–7.17 (m, 9H), 6.79 (d, J = 8.1 Hz, 2H), 4.98–4.82 (m, 1H), 3.76 (s, 3H), 3.63–3.48 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.85, 158.57, 139.52, 132.65, 132.52, 129.28, 128.72, 128.69, 128.63, 127.35, 113.65, 55.01, 47.44, 44.58. HRMS calcd for $C_{22}H_{19}ClO_2S$: 382.0794; found: 383.0703 $[M]^+$.

3-(4-Methoxyphenyl)-3-(phenylthio)-1-*p*-tolylpropan-1-one (25)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.79 (d, J = 8.1 Hz, 2H), 7.33–7.22 (m, 9H), 6.79 (d, J = 8.6 Hz, 2H), 4.94 (dd, J = 5.6, 8.4 Hz, 1H), 3.76 (s, 3H), 3.65–3.49 (m, 2H), 2.40 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.61, 158.48, 143.90, 134.06, 132.94, 132.41, 129.08, 128.67, 128.64, 128.00, 127.20, 113.59, 55.00, 47.45, 44.42, 21.46. HRMS calcd for $C_{23}H_{22}O_2S$: 362.1341; found: 363.1274 $[M]^+$.

1,3-Bis(4-methoxyphenyl)-3-(phenylthio)propan-1-one (26)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.87 (d, J = 8.0 Hz, 2H), 7.32–7.13 (m, 7H), 6.90 (d, J = 7.9 Hz, 2H), 6.79 (d, J = 6.4 Hz, 2H), 4.94 (m, 1H), 3.85 (s, 3H), 3.75 (s, 3H), 3.63–3.50 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.49, 176.44, 163.37, 158.47, 132.98, 132.36, 130.19, 128.66, 127.17, 113.58, 113.52, 55.28, 55.00, 47.52, 44.16. HRMS calcd for $C_{23}H_{22}O_3S$: 378.129; found: 390.1205 $[M - H + Na]^+$.

1-(4-Chlorophenyl)-3-phenyl-3-(phenylthio)propan-1-one (27)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.82 (d, J = 7.6 Hz, 2H), 7.42–2.24 (m, 12H), 4.94 (t, J = 7.8 Hz, 1H), 3.66–3.52 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.69, 140.77, 139.55, 134.78, 133.86, 132.60, 129.29, 128.74, 128.71, 128.32, 127.57, 127.44, 127.28, 48.02, 44.44. HRMS calcd for $C_{21}H_{17}ClOS$: 352.0689; found: 353.0582 $[M]^+$.

1-(4-Nitrophenyl)-3-phenyl-3-(phenylthio)propan-1-one (28)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.26 (d, J = 8.80, 2H), 8.00 (d, J = 8.74 Hz, 2H), 7.37–7.17 (m, 10H), 4.90 (dd, J = 7.6, 6.0 Hz, 1H), 3.70–3.57 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.45 141.18, 139.45, 134.96, 133.98, 132.60, 129.64, 128.84, 128.61, 128.46, 127.12, 127.44, 127.28, 48.10, 44.42. HRMS calcd for $C_{21}H_{17}NO_3S$: 363.0929; found: 385.0879 $[M - H + Na]^+$.

1-(4-Methoxyphenyl)-3-phenyl-3-(phenylthio)propan-1-one (29)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.00–7.79 (m, 2H), 7.34–7.24 (m, 10H), 6.98–6.84 (m, 2H), 4.97 (m, 1H), 3.85 (s, 3H), 3.61–3.51 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.32, 163.40, 141.08, 132.45, 130.20, 129.60, 128.64, 128.24, 127.61, 127.26, 127.12, 113.54, 55.29, 48.10, 44.02. HRMS calcd for $C_{22}H_{20}O_2S$: 348.1184; found: 349.1079 $[M]^+$.

3-(3-Nitrophenyl)-3-(phenylthio)-1-*p*-tolylpropan-1-one (30)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.18 (s, 1H), 8.04 (d, J = 6.1 Hz, 1H), 7.90–7.74 (m, 2H), 7.62 (d, J = 6.3 Hz, 1H), 7.42–7.35 (m, 1H), 7.32–7.25 (m, 7H), 5.09–4.90 (m, 1H), 3.67–3.56 (m, 2H), 2.41 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.62, 147.98, 144.42, 143.59, 134.11, 133.59, 133.22, 132.65, 129.24, 129.02, 128.89, 128.07, 127.99, 122.44, 122.11, 47.58, 43.72, 21.49. HRMS calcd for $C_{22}H_{19}NO_3S$: 377.1086; found: 378.1023 $[M]^+$.

3-(3-Nitrophenyl)-1-phenyl-3-(phenylthio)propan-1-one (31)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.18 (s, 1H), 8.05 (d, J = 7.1 Hz, H), 7.91 (d, J = 7.0 Hz, 2H), 7.71–7.54 (m, 2H), 7.54–7.36 (m, 3H), 7.36–7.17 (m, 5H), 5.01 (t, J = 6.7 Hz, 1H), 3.69 (d, J = 6.7 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.00, 143.51, 136.03, 134.10, 133.46, 133.26, 129.05, 128.91, 128.58, 128.12, 127.86, 122.44, 122.15, 47.51, 43.90. HRMS calcd for $C_{21}H_{17}NO_3S$: 363.0929; found: 364.00875 $[M]^+$.

3-(4-Methoxyphenylthio)-1-(4-chlorophenyl)-3-phenylpropan-1-one (32)

^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.79 (d, J = 8.6 Hz, 2H), 7.38 (d, J = 8.6 Hz, 2H), 7.29–7.17 (m, 7H), 6.74 (d, J = 8.7 Hz, 2H), 4.70 (m, 1H), 3.75 (s, 3H), 3.53–3.57 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 195.99, 159.92, 141.19, 139.69, 136.28, 135.11, 129.50, 128.93, 128.43, 127.80, 127.35, 124.06, 123.51, 121.93, 114.41, 55.29, 49.40, 44.26. HRMS calcd for $C_{22}H_{19}ClO_2S$: 382.0794; found: 404.0703 $[M - H + Na]^+$.

General procedure for recycling the catalyst

Malononitrile (1.0 mmol) was added to the solution of 3-(2-fluorophenyl)-1-(4-methoxyphenyl)prop-2-en-1-one and

IL–TBD (**5**) (0.5 mmol). The reaction mixture was stirred vigorously until reaction completion. The product was then extracted from the catalyst by ethyl acetate (2 × 5 mL) leaving the IL–TBD catalyst in the flask. The IL–TBD was washed with diethyl ether and dried under reduced pressure. The recovered IL was again used as a catalyst for a fresh batch of chalcone and malononitrile (1.0 mmol) under the same experimental conditions. The process was repeated five times without much loss in catalytic activity.

Acknowledgement

This work was financially supported by the Council of Scientific and Industrial Research (CSIR), New Delhi (Project No. 01(2214)/08/EMR-II) and the US National Science Foundation, Grant No. CHE 0748555. M.M.K. thanks CSIR, New Delhi, for a junior research fellowship.

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