VERSITA

Chemical Papers 65 (5) 707–713 (2011)
DOI: 10.2478/s11696-011-0052-z

ORIGINAL PAPER

Silicon-based thiourea-mediated and microwave-assisted thio-Michael addition under solvent-free reaction conditions

[a]Kamalakannan Prabakaran, [a]Machindra Gund, [b]Tae Kyu Kim, [b]Euh Duck Jeong, [b]Chae Young Oh, [a,b]Fazlur-Rahman Nawaz Khan*, [b]Jong Sung Jin*

[a] *Organic & Medicinal Chemistry Research Laboratory, Organic Chemistry Division, School of Advanced Sciences, VIT University, Vellore, Tamil Nadu 632 014, India*

[b] *Division of High Technology Materials Research, Busan Centre, Korea Basic Science Institute, Busan 618 230, Republic of Korea*

Received 4 February 2011; Revised 28 March 2011; Accepted 29 March 2011

Silicon-based thiourea (SiliaBond® Thiourea) (Si-THU), a heterogeneous catalyst, has been applied to the highly selective C—S bond formation via Michael addition of thiols to α,β-unsaturated carbonyl compounds under solvent-free conditions at 55–60 °C. The thio-Michael addition products were obtained in an excellent yield under optimised conditions. This methodology involving a metal-free as well as a metal scavenger catalyst has been found to be an alternative method for the thio-Michael addition reaction.

Keywords: SiliaBond® Thiourea, solvent-free Michael reaction, thioethers

Introduction

Organosulphur compounds such as thioethers are versatile intermediates for synthetic transformations (Kondo & Mitsudo, 2000) to biologically active compounds and are recognised as stimulants of the central nervous system (Jacobson, 2009). Several procedures for the synthesis of thioethers are known in the literature, including: alkylation of thiols (Salvatore et al., 2005), thiohydrolysis of imidothiolates (Sudalai et al., 2000), oxidative sulphuration of benzyl halides (Kanagasabapathy et al., 2001), transesterification of dithioesters with thiols (Thang et al., 1999), thio-Michael addition reaction (Barahman & Pershang, 2006), exchange reaction of bis(thiocarbonyl) disulphides with azo compounds (Perrier & Tokolpuckdee, 2005), and condensation of thiols and alcohols (Falck et al., 1999). However, all of these methods suffer from a nucleophilic regiocontrol problem, they require either a very high temperature or the presence of specific structures on the heterocyclic ring. Similarly, none of these methods combines good yield with high selectivity. In the present article, an efficient catalytic system is demonstrated which offers quantitative yield, purity, and also selectivity.

The thio-Michael addition reactions have emerged as one of the most powerful tools for the C—S bond formation (Amini et al., 2006). In recent years, several modifications have been made including various catalysts, solvent-free conditions, etc. (Wight & Davis, 2002; Barahman & Pershang, 2006). Many catalysts were used in thio-Michael reactions including ionic liquids, amino acids, alumina, iodine, $InBr_3$, $HClO_4$—SiO_2 montmorillonite clays, and silica nanoparticles (Ranu & Dey, 2004; Kumar & Akanksha, 2007; Firouzabadi et al., 2006; Chu et al., 2005; Bandini et al., 2002; Khatik et al., 2007; Banerjee et al., 2010). However, these catalysts have been shown to have drawbacks viz. some ionic liquids liberate HF during recycling and also the disposability of these liquids limits their application. Moreover, some catalysts showed longer reaction times and high reaction temperatures,

*Corresponding author, e-mail: jsjin@kbsi.re.kr; nawaz_f@yahoo.co.in

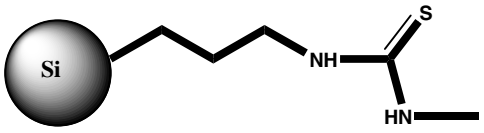

Fig. 1. SiliaBond® Thiourea.

were expensive, provided moderate yields, and required expensive metal precursors. Here we report on the multi-purpose catalyst SiliaBond® Thiourea (Si-THU) (Fig. 1) in the solvent-free microwave assisted thio-Michael reaction.

In order to overcome the drawbacks noted above, in the present study of thio-Michael addition reaction, a great deal of effort has been directed towards successful exploration of an efficient catalytic system with high selectivity in the synthesis of thioethers (Figs. 2 and 3, Tables 1–5) in good yields. The use of a solvent-free reaction in combination with heterogeneous and reusable catalysts represents one of the more powerful green chemical technology procedures. Si-THU is widely used industrially as a metals scavenger catalyst, catalyst support and reagent (Robinson & Snyder, 1955).

Experimental

The Si-THU required for the present investigation was obtained from SiliCycle Inc. (USA) and used after oven-drying. The required chemicals for the study were obtained from Aldrich (India) and are used without further purification. All reactions were carried out in resealable tubes, in a high-purity nitrogen atmosphere. The progress of the reactions was monitored by flexible TLC plates of silica gel 60 (Thomas Scien-

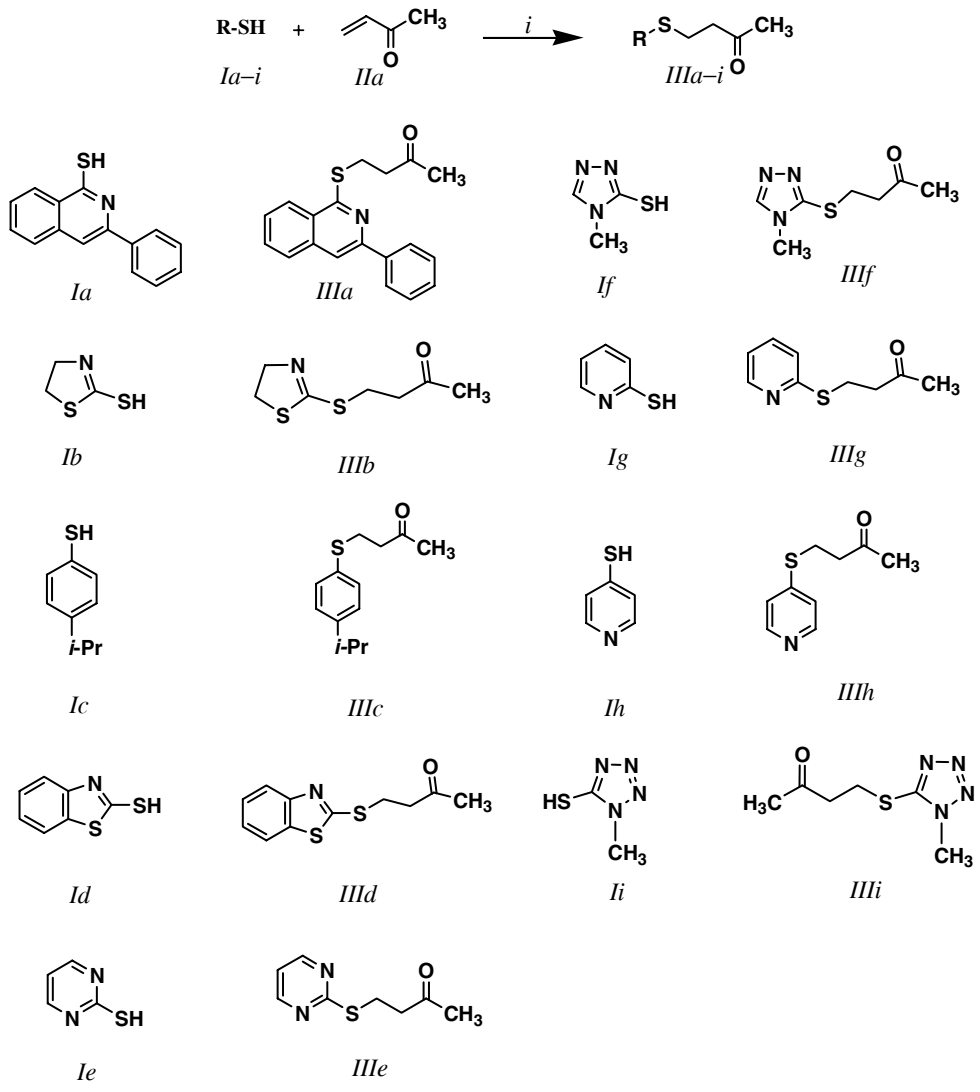

Fig. 2. Synthesis of thio-Michael products *III* from thiols, *I* using methylvinyl ketone, *IIa*. *i*) Si-THU (30 mass %), microwave (300 W), 60 °C, 15 min.

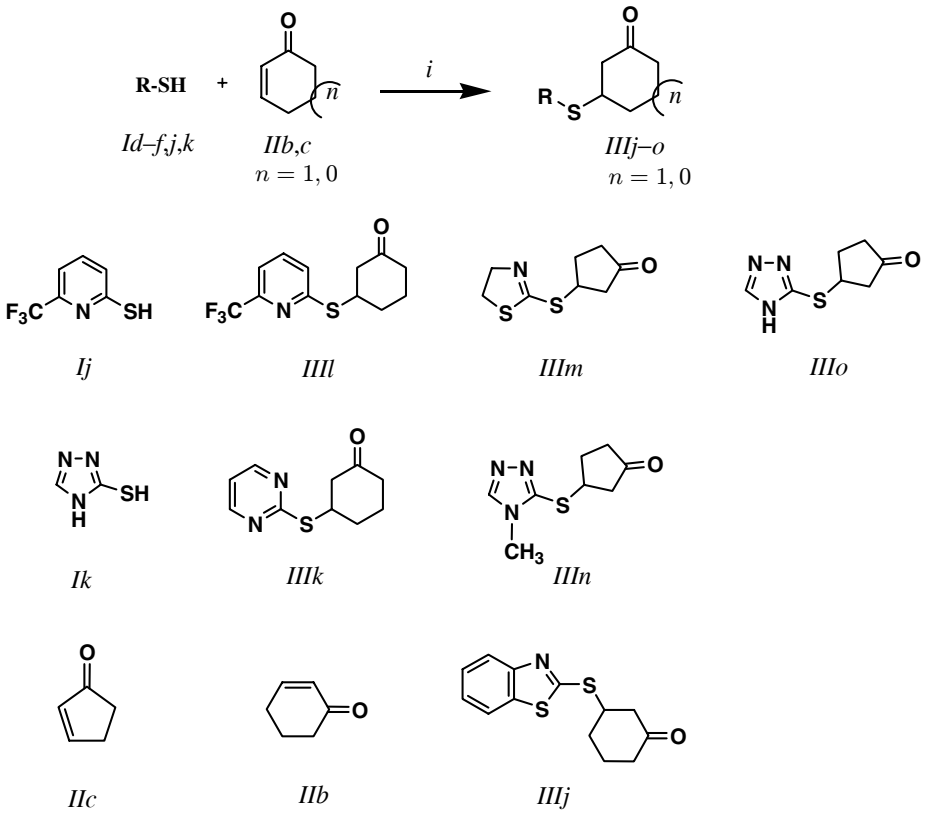

Fig. 3. Synthesis of thio-Michael products, *III* from thiols, *I* using cycloalk-2-en-ones, *IIb*, *IIc*. *i*) Si-THU (30 mass %), microwave (300 W), 60 °C, 15 min.

tific, India). Melting points were measured on Elchem Microprocessor (BVN instruments, India) based DT apparatus in open capillary tubes. ^{1}H NMR and ^{13}C NMR spectra of compounds in $CDCl_3$ were obtained using a Bruker Spectrospin Avance DPX400 Ultrashield 400 MHz spectrometer (India) and chemical shifts were reported in δ relative to tetramethylsilane (TMS) as an internal standard. IR spectra were obtained on a Nucon Infrared spectrophotometer (KBr disc) (India). LC–MS analyses were performed with LCMS-Agilent-1100 series (India). Ion Trap Mass spectra were recorded on ABI QSTAR XL ESI-TOF Mass spectrometer (Sciex Model) (India) operating at 70 eV using fast atom bombardment technique.

Table 1. Effect of catalyst on the thio-Michael reaction[a] of *Ia* and *IIa*

Entry	Catalyst	Yield (%)
1	L-proline	NR
2	L-proline ester	NR
3	L-glutamic acid	NR
4	Silica gel (60–120 mesh)	60
5	Aluminium oxide (neutral)	50
6	Aluminium oxide (basic)	70
7	Si-THU	89
8	Si-Thiol	73

a) Catalyst (50 mass, %), microwave (300 W), 60 °C, 15 min. NR – no reaction.

General procedure of synthesis of thio ethers using various enones (IIIa–IIIo)

Thiol, *I* (1.0 eq) and α,β-unsaturated carbonyl compound, *II* (1.2 eq) Si-THU (30 mass %) were mixed and microwave-irradiated at 60 °C (300 W) for 15 min. After completion of the reaction, dichloromethane (10 mL) was added to the mixture and the mixture was filtered to remove Si-THU. The mixture was washed with an aqueous solution of NaOH (10 %, 10 mL) and extracted twice with dichloromethane (2 × 10 mL). The organic layer was separated and dried over anhydrous Na_2SO_4 and filtered. The filtrate was evaporated under vacuum on a rotary evaporator to afford the desired product. The compounds were purified by column chromatography using neutral alumina eluted with petroleum ether/EtOAc ($\varphi_r = 9:1$). The products *III* obtained were characterised by ^{1}H-NMR, ^{13}C-NMR, LC-MS, and FTIR spectral techniques.

Results and discussion

As part of our ongoing interest in the use of heterogeneous catalysts (Prabakaran & Khan, 2010; Khan et al., 2009a, 2009b, 2010), we have studied thiol-Michael

Table 2. Optimisation of Si-THU catalyst concentration in the thio-Michael reaction[a] of *Ie*, *IIa*, and *Id*, *IIb*

Entry	Ketone	Catalyst	Time	Yield	Product
		mass %	min	%	
1	*IIa*	none	120	40	*IIId*
2	*IIa*	10	45	62	*IIId*
3	*IIa*	20	25	73	*IIId*
4	*IIa*	30	15	87	*IIId*
5	*IIa*	40	15	88	*IIId*
6	*IIa*	50	15	89	*IIId*
7	*IIb*	10	60	45	*IIIj*
8	*IIb*	20	30	69	*IIIj*
9	*IIb*	30	15	84	*IIIj*
10	*IIb*	40	15	83	*IIIj*

a) Microwave (300 W), 60 °C, 15 min.

Table 3. Reusability of Si-THU catalyst and its efficiency

Entry	Number of cycles	Yield (%)
1	1	89
2	2	86
3	3	83
4	4	78
5	5	72

Table 4. Michael reaction[a] of thiols *I* and methylvinyl ketone *IIa*

Entry	Thiol	Product	Yield[b] (%)
1	*Ia*	*IIIa*	89
2	*Ib*	*IIIb*	76
3	*Ic*	*IIIc*	86
4	*Id*	*IIId*	78
5	*Ie*	*IIIe*	87
6	*If*	*IIIf*	78
7	*Ig*	*IIIg*	75
8	*Ih*	*IIIh*	77
9	*Ii*	*IIIi*	75

a) Si-THU (30 mass %), microwave (300 W), 60 °C, 15 min; *b*) isolated yield.

Table 5. Michael reaction[a] of thiols *I* and cycloalk-2-en-ones

Entry	Thiol	Ketone	Product	Yield[b] (%)
1	*Id*	*IIb*	*IIIj*	84
2	*Ie*	*IIb*	*IIIk*	79
3	*Ij*	*IIb*	*IIIl*	82
4	*Ib*	*IIc*	*IIIm*	90
5	*If*	*IIc*	*IIIn*	82
6	*Ik*	*IIc*	*IIIo*	84

a) Si-THU (30 mass %), microwave (300 W), 60 °C, 15 min; *b*) isolated yield.

reaction in the synthesis of thioethers using Si-THU as a multi-purpose, heterogeneous and reusable catalyst under solvent-free conditions. The thio-Michael reaction was carried out simply by mixing thiols *I*, enones *II*, and the heterogeneous catalyst Si-THU (30 mass %) in the absence of solvent followed by irradiation in a microwave device set at 300 W for 15 min at 60 °C. The reaction afforded the desired Michael products *III* in good yields (Figs. 2 and 3, Tables 1–5).

Optimisation of reaction conditions was carried out by choosing thio-Michael reaction of *Ia* with *IIa* as a model reaction (Fig. 2, Tables 1 and 4). Optimisation of the reaction conditions included the examination of different heterogeneous catalysts as shown in Table 1 (Entries 1–8). The Si-THU catalyst was found to be superior to the other catalysts tested affording the desired product in good yield (Table 1, entry 7). Other catalysts such as aluminium oxide (basic) and SiliaBond® Thiol (Si-Thiol) produced moderate yields (Table 1, entries 6 and 8) whereas amino acid type catalysts, L-proline, L-proline ester, L-glutamic acid (Table 1, entries 1–3) etc. did not participate in the reaction at all and the remaining catalysts were found to be least effective.

The influence of the amount of catalyst was also investigated, using the reactions of *Ie* and *IIa*, *Id* and *IIb* (Table 2). The result indicated that without catalyst the reaction was longer with lower yields (Table 2, entry 1). An increase in the amount of catalyst increased the yield and the reaction time decreased substantially (Table 2, entries 2–10). The optimum amount of catalyst in the reaction was found to be 30 mass %. The reusability of the catalyst was investigated (Table 3) by examining successive runs of the reactions using the recycled catalyst, i.e., catalyst recovered by filtration from the reaction mixture, washed with ethyl acetate, and dried. Then it was utilised in the second run of the reaction. The result showed that the efficiency of the catalyst remained unaltered up to three cycles with higher product yields (Table 3, entries 1–3) and a further two cycles gave moderate yields (Table 3, entries 4 and 5). Under the optimised conditions, various thio-Michael products were synthesised and the results are reported in Tables 4 and 5. The Michael products, *IIIa*–*IIIo* obtained were of high yield (75–90 %) and purity. The purified products were characterised by different spectral techniques including ^{1}H NMR, ^{13}C NMR, IR, and MS techniques (Table 6).

Conclusions

In the present study, the formation of C—S bond via Michael addition of thiols to α,β-unsaturated ketones under solvent-free, microwave-assisted conditions was successfully carried out using Si-THU as an efficient catalyst. The yields and purity of the products were high and the optimisation procedure of the reaction was very simple and not time-consuming. We

Table 6. Spectral data of newly prepared compounds

Compound	Spectral data
IIIa	IR, $\tilde{\nu}$/cm^{-1}: 3409, 3056, 2922, 2852, 1711, 1588, 1553, 1492, 1450, 1437, 1402, 1355, 1307, 1264, 1151, 988, 848, 782, 763, 690, 651, 569 ^{1}H NMR ($CDCl_3$), δ: 8.17–8.15 (d, J = 8.5 Hz, 3H), 7.84–7.82 (d, J = 5.8 Hz, 2H), 7.70–7.65 (t, J = 6.9 Hz, 1H), 7.56–7.49 (m, 3H), 7.44–7.42 (t, J = 6.0 Hz, 1H), 3.73–3.69 (t, J = 6.8 Hz, 2H), 3.11–3.08 (t, J = 6.8 Hz, 2H), 2.18 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 207.2, 158.5, 149.3, 139.2, 136.4, 130.6, 128.7, 128.5, 128.3, 127.7, 127.5, 126.8, 126.5, 124.8, 124.4, 112.8, 43.5, 30.1, 23.5 MS, m/z: 308.2 (M^+ + 1)
IIIb	IR, $\tilde{\nu}$/cm^{-1}: 3474, 3408, 2991, 2938, 1706, 1487, 1422, 1362, 1312, 1289, 1224, 1154, 1033, 989, 897, 739, 538 ^{1}H NMR ($CDCl_3$), δ: 4.22–4.18 (t, J = 7.8 Hz, 2H), 3.95–3.91 (t, J = 6.1 Hz, 2H), 3.28–3.24 (t, J = 8.0 Hz, 2H), 3.00–2.97 (t, J = 6.1 Hz, 2H), 2.19 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 206.9, 196.8, 58.5, 44.0, 40.6, 30.0, 27.9 MS, m/z: 190.0 (M^+ + 1)
IIIc	IR, $\tilde{\nu}$/cm^{-1}: 3411, 3070, 3017, 2959, 2929, 2870, 1713, 1495, 1407, 1359, 1155, 1096, 1050, 1013, 826, 540 ^{1}H NMR ($CDCl_3$), δ: 7.30–7.27 (t, J = 8.1 Hz, 2H), 7.17–7.15 (d, J = 8.2 Hz, 2H), 3.12–3.08 (t, J = 7.4 Hz, 2H), 2.92–2.85 (q, 1H), 2.77–2.73 (t, J = 7.3 Hz, 2H), 2.15 (s, 3H), 1.25–1.23 (d, J = 6.9 Hz, 6H) ^{13}C NMR ($CDCl_3$), δ: 206.7, 147.5, 132.1, 130.3, 127.1, 43.2, 33.6, 30.0, 28.1, 23.8 MS, m/z: 223.20 (M^+ + 1)
IIId	IR, $\tilde{\nu}$/cm^{-1}: 3468, 3060, 2922, 1709, 1456, 1425, 1358, 1236, 1157, 1071, 993, 754, 724, 665 ^{1}H NMR ($CDCl_3$), δ: 7.87–7.85 (d, J = 7.6 Hz, 1H), 7.77–7.75 (d, J = 8.0 Hz, 1H), 7.44–7.40 (t, J = 7.4 Hz, 1H), 7.32–7.28 (t, J = 8.0 Hz, 1H), 3.57–3.53 (t, J = 6.7 Hz, 2H), 3.09–3.06 (t, J = 6.7 Hz, 2H), 2.2 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 206.3, 166.5, 153.0, 135.2, 126.0, 124.2, 121.4, 121.0, 43.2, 29.9, 26.8 MS, m/z: 238.0 (M^+ + 1)
IIIe	IR, $\tilde{\nu}$/cm^{-1}: 3392, 3039, 2903, 1707, 1562, 1548, 1405, 1378, 1342, 1188, 1156, 954, 899, 809, 739, 627, 575 ^{1}H NMR ($CDCl_3$), δ: 8.50–8.49 (d, J = 4.8 Hz, 2H), 6.97–6.95 (t, J = 4.8 Hz, 1H), 3.34–3.30 (t, J = 6.8 Hz, 2H), 2.95–2.92 (t, J = 7.2 Hz, 2H), 2.17(s, 3H) ^{13}C NMR ($CDCl_3$), δ: 206.8, 172.1, 157.2, 116.4, 43.3, 30.0, 24.6 MS, m/z: 183.4 (M^+ + 1)
IIIf	IR, $\tilde{\nu}$/cm^{-1}: 3480, 3129, 3057, 2944, 1707, 1544, 1419, 1352, 1221, 1197, 1166, 1108, 1058, 998, 849, 778, 744, 674, 632, 575 ^{1}H NMR ($CDCl_3$), δ: 7.74 (s, 1H), 4.46–4.42 (t, J = 8.0 Hz, 2H), 3.57 (s, 3H), 3.04–3.00 (t, J = 6.8 Hz, 2H), 2.20 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 205.3, 166.4, 139.3, 44.4, 40.9, 32.6, 30.0 MS, m/z: 186.4 (M^+ + 1)
IIIg	IR, $\tilde{\nu}$/cm^{-1}: 3411, 3045, 2994, 2934, 1709, 1577, 1555, 1453, 1413, 1358, 1281, 1152, 1122, 1043, 1009, 985, 757, 719, 617, 575 ^{1}H NMR ($CDCl_3$), δ: 8.42–8.40 (d, J = 5.2 Hz, 1H), 7.48–7.44 (td, J = 7.6 Hz, J = 1.6 Hz, 1H), 7.16–7.14 (d, J = 8.0 Hz, 1H), 6.99–6.95 (t, J = 4.8 Hz, 1H), 3.38–3.35 (t, J = 6.8 Hz, 2H), 2.93–2.90 (t, J = 6.8 Hz, 2H), 2.17 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 207.1, 158.5, 149.4, 135.8, 122.3, 119.3, 43.7, 30.0, 23.6 MS, m/z: 182.4 (M^+ + 1)
IIIh	IR, $\tilde{\nu}$/cm^{-1}: 3385, 3035, 2898, 2832, 1708, 1622, 1574, 1538, 1478, 1407, 1359, 1216, 1161, 1108, 1027, 984, 803, 705, 575 ^{1}H NMR ($CDCl_3$), δ: 8.40–8.38 (dd, J = 6.2 Hz, J = 1.60 Hz, 2H), 7.11–7.09 (dd, J = 6.2 Hz, J = 1.60 Hz, 2H), 3.22–3.18 (t, J = 7.1 Hz, 2H), 2.86–2.83 (t, J = 7.1 Hz, 2H), 2.19 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 205.7, 149.3, 124.8, 120.6, 42.1, 30.0, 24.1 MS, m/z: 182.4 (M^+ + 1)
IIIi	IR, $\tilde{\nu}$/cm^{-1}: 3585, 3000, 2948, 2901, 2774, 1712, 1453, 1410, 1355, 1310, 1167, 1105, 1004, 925, 851, 786, 740, 680, 575, 531 ^{1}H NMR ($CDCl_3$), δ: 4.54–4.51 (t, J = 7.0 Hz, 2H), 3.89 (s, 3H), 3.15–3.12 (t, J = 7.08 Hz, 2H), 2.22 (s, 3H) ^{13}C NMR ($CDCl_3$), δ: 204.3, 164.1, 43.1, 40.2, 34.6, 29.9 MS, m/z: 187.0 (M^+ + 1)
IIIj	IR, $\tilde{\nu}$/cm^{-1}: 3071, 2957, 1696, 1583, 1459, 1403, 1346, 1302, 1250, 1217, 1124, 1052, 998, 886, 731, 629, 573 ^{1}H NMR ($CDCl_3$), δ: 7.59–7.57 (d, J = 7.8 Hz, 1H), 7.52–7.50 (d, J = 7.4 Hz, 1H), 7.42–7.38 (t, J = 7.2 Hz, 1H), 7.33–7.29 (dt, J = 7.8 Hz, J = 0.8 Hz, 1H), 3.24–3.17 (t, J = 14.0 Hz, 1H), 2.75–1.98 (m, 8H) ^{13}C NMR ($CDCl_3$), δ: 206.6, 139.7, 126.4, 124.5, 121.8, 113.0, 55.4, 42.9, 40.6, 26.9, 26.0, 22.0 MS, m/z: 264.4 (M^+ + 1)
IIIk	IR, $\tilde{\nu}$/cm^{-1}: 3406, 3114, 3032, 2940, 2865, 1706, 1561, 1545, 1446, 1421, 1375, 1313, 1187, 1060, 969, 802, 772, 748, 626 ^{1}H NMR ($CDCl_3$), δ: 8.51–8.50 (d, J = 4.8 Hz, 2H), 6.99–6.97 (t, J = 4.8 Hz, 1H), 4.22–4.12 (m, 1H), 2.97–1.86 (m, 8H) ^{13}C NMR ($CDCl_3$), δ: 208.6, 171.3, 157.3, 116.7, 47.4, 42.5, 40.9, 30.8, 24.4 MS, m/z: 208.4 (M^+ + 1)

Table 6. (continued)

Compound	Spectral data
IIIl	IR, $\tilde{\nu}$/cm^{-1}: 3060, 2945, 2870, 1710, 1595, 1555, 1472, 1377, 1320, 1220, 1165, 1110, 1072, 1007, 970, 937, 831, 791, 746 ^{1}H NMR ($CDCl_3$), δ: 8.70 (s, 1H), 7.70–7.67 (dd, J = 8.4 Hz, J = 1.8 Hz, 1H), 7.26–7.24 (d, J = 8.4 Hz, 1H), 4.35–4.29 (m, 1H), 2.91–2.87 (dd, J = 14.4 Hz, J = 4.6 Hz, 1H), 2.60–1.87 (m, 8H) ^{13}C NMR ($CDCl_3$), δ: 199.8, 162.7, 150.7, 132.8, 129.9, 122.4, 41.9, 40.9, 38.1, 30.9, 25.6, 22.7 MS, m/z: 276.0 ($M^+ + 1$)
IIIm	IR, $\tilde{\nu}$/cm^{-1}: 2935, 1735, 1694, 1471, 1425, 1301, 1223, 1131, 1038, 992, 866, 754, 674, 592 ^{1}H NMR ($CDCl_3$), δ: 5.60–5.56 (m, 1H), 4.06–3.99 (m, 2H), 3.35–3.31 (t, J = 7.6 Hz, 2H), 2.71–1.98 (m, 6H) ^{13}C NMR ($CDCl_3$), δ: 213.4, 197.6, 55.0, 51.6, 40.5, 37.7, 27.6, 26.3 MS, m/z: 202.2 ($M^+ + 1$)
IIIn	IR, $\tilde{\nu}$/cm^{-1}: 3452, 3126, 2919, 1735, 1540, 1468, 1417, 1345, 1222, 1146, 1057, 997, 895, 865, 793, 726, 639, 568, 534 ^{1}H NMR ($CDCl_3$), δ: 7.78 (s, 1H), 5.60–5.56 (t, J = 6.8 Hz, 1H), 3.60 (s, 3H), 2.68–2.29 (m, 6H) ^{13}C NMR ($CDCl_3$), δ: 214.8, 166.2, 139.5, 55.6, 42.9, 36.5, 32.5, 28.3 MS, m/z: 198.0 ($M^+ + 1$)
IIIo	IR, $\tilde{\nu}$/cm^{-1}: 3136, 3045, 2917, 1739, 1536, 1427, 1394, 1346, 1241, 1137, 1008, 983, 892, 800, 643, 563 ^{1}H NMR ($CDCl_3$), δ: 7.83 (s, 1 H), 5.65–5.61 (t, J = 6.8 Hz, 1H), 2.75–2.23 (m, 6H) ^{13}C NMR ($CDCl_3$), δ: 214.7, 165.6, 136.4, 55.3, 42.8, 36.5, 28.4 MS, m/z: 184.0 ($M^+ + 1$)

conclude that an efficient catalytic system has been demonstrated in the thio-Michael reaction which afforded selectivity as well as high yield and purity.

Acknowledgements. We gratefully acknowledge financial support from the Department of Science and Technology, Government of India (Grant No. SR/FTP/CS-99/2006). The authors are grateful to the VIT University management for their generous support and facilities. We also wish to thank the SAIF, IIT Madras, Chennai for providing the NMR and MS facility.

References

Amini, M. M., Shaabani, A., & Bazgir, A. (2006). Tangstophosphoric acid ($H_3PW_{12}O_{40}$): An efficient and eco-friendly catalyst for the one-pot synthesis of dihydropyrimidin-2(1*H*)-ones. *Catalysis Communications*, *7*, 843–847. DOI: 10.1016/j.catcom.2006.02.027.

Bandini, M., Cozzi, P. G., Giacomini, M., Melchiorre, P., Selva, S., & Umani-Ronchi, A. (2002). Sequential one-pot $InBr_3$-catalyzed 1,4- then 1,2-nucleophilic addition to enones. *Journal of Organic Chemistry*, *67*, 3700–3704. DOI: 10.1021/jo0163243.

Banerjee, S., Das, J., Alvarez, R. P., & Santra, S. (2010). Silica nanoparticles as a reusable catalyst: a straightforward route for the synthesis of thioethers, thioesters, vinyl thioethers and thio-Michael adducts under neutral reaction conditions. *New Journal of Chemistry*, *34*, 302–306. DOI: 10.1039/B9NJ00399A.

Barahman, M. B., & Pershang, S. (2006). Michael addition of thiols to α,β-unsaturated carbonyl compounds under solvent-free conditions. *ARKIVOC*, *2006*(12), 130–137.

Chu, C. M., Gao, S., Sastry, M. N. V., & Yao, C.-F. (2005). Iodine-catalyzed Michael addition of mercaptans to α,β-unsaturated ketones under solvent-free conditions. *Tetrahedron Letters*, *46*, 4971–4974. DOI: 10.1016/j.tetlet.2005.05.099.

Falck, J. R., Lai, J.-Y., Cho, S.-D., & Yu, J. (1999). Alkylthioether synthesis via imidazole mediated Mitsunobu condensation. *Tetrahedron Letters*, *40*, 2903–2906. DOI: 10.1016/S0040-4039(99)00390-1.

Firouzabadi, H., Iranpoor, N., Jafarpour, M., & Ghaderi, A. (2006). $ZrOCl_2 \cdot 8H_2O$/silica gel as a new efficient and a highly water–tolerant catalyst system for facile condensation of indoles with carbonyl compounds under solvent-free conditions. *Journal of Molecular Catalysis A: Chemical*, *253*, 249–251. DOI: 10.1016/j.molcata.2006.03.043.

Jacobson, K. A. (2009). Functionalized congener approach to the design of ligands for G protein-coupled receptors (GPCRs). *Bioconjugate Chemistry*, *20*, 1816–1835. DOI: 10.1021/bc9000596.

Kanagasabapathy, S., Sudalai, A., & Benicewicz, B. C. (2001). Montmorillonite K 10-catalyzed regioselective addition of thiols and thiobenzoic acids onto olefins: an efficient synthesis of dithiocarboxylic esters. *Tetrahedron Letters*, *42*, 3791–3794. DOI: 10.1016/S0040-4039(01)00570-6.

Khan, F. N., Manivel, P., Prabakaran, K., Hathwar, V. R., & Akkurt, M. (2010). 5-(4-Chlorophenyl)-3-(2-furyl)-1,2,4-triazolo[3,4-a]isoquinoline. *Acta Crystallographica E*, *66*, 1061. DOI: 10.1107/S1600536810012924.

Khan, F. N., Manivel, P., Prabakaran, K., Hathwar, V. R., & Ng, S. W. (2009a). 1-(4-Chlorophenyl)-2-phenyl-2-(3-phenyl-1-isoquinolylsulfanyl)ethanone. *Acta Crystallographica E*, *65*, 2732. DOI: 10.1107/S1600536809041282.

Khan, F. N., Manivel, P., Prabakaran, K., Hathwar, V. R., & Ng, S. W. (2009b). 2-[2-(Cyclohexylcarbonyl)phenyl]-1-phenylethanone. *Acta Crystallographica E*, *65*, 2745. DOI: 10.1107/S1600536809041270.

Khatik, G. L., Sharma, G., Kumar, R., & Chakraborti, A. K. (2007). Scope and limitations of $HClO_4$–SiO_2 as an extremely efficient, inexpensive, and reusable catalyst for chemoselective carbon–sulfur bond formation. *Tetrahedron*, *63*, 1200–1210. DOI: 10.1016/j.tet.2006.11.050.

Kondo, T., & Mitsudo, T. (2000). Metal-catalyzed carbon–sulfur bond formation. *Chemical Reviews*, *100*, 3205–3220. DOI: 10.1021/cr9902749.

Kumar, A., & Akanksha (2007). Amino acid catalyzed thio-Michael addition reactions. *Tetrahedron*, *63*, 11086–11092. DOI: 10.1016/j.tet.2007.08.033.

Robinson, J. C., Jr., & Snyder, H. R. (1955). β-phenylethylamine. *Organic Syntheses*, *Collective Volume 3*, 720.

Perrier, S., & Tokolpuckdee, P. (2005). Macromolecular design via reversible addition–fragmentation chain transfer

(RAFT)/xanthates (MADIX) polymerization. *Journal of Polymer Science Part A: Polymer Chemistry*, *43*, 5347–5393. DOI: 10.1002/pola.20986.

Prabakaran, K., & Khan, F. N. (2010). Basic alumina-catalyzed, solvent-free synthesis of diversified thioethers. *Phosphorus, Sulfur, and Silicon and the Related Elements*, *185*, 825–831. DOI: 10.1080/10426500902998131.

Ranu, B. C., & Dey, S. S. (2004). Catalysis by ionic liquid: a simple, green and efficient procedure for the Michael addition of thiols and thiophosphate to conjugated alkenes in ionic liquid, [pmIm]Br. *Tetrahedron*, *60*, 4183–4188. DOI: 10.1016/j.tet.2004.03.052.

Salvatore, R. N., Smith, R. A., Nischwitz, A. K., & Gavin, T. (2005). A mild and highly convenient chemoselective alkylation of thiols using Cs_2CO_3–TBAI. *Tetrahedron Letters*, *46*, 8931–8935. DOI: 10.1016/j.tetlet.2005.10.062.

Sudalai, A., Kanagasabapathy, S., & Benicewicz, B. C. (2000). Phosphorus pentasulfide: A mild and versatile catalyst/reagent for the preparation of dithiocarboxylic esters. *Organic Letters*, *2*, 3213 –3216. DOI: 10.1021/ol006407q.

Thang, S. H., Chong, (B.) Y. K., Mayadunne, R. T. A., Moad, G., & Rizzardo, E. (1999). A novel synthesis of functional dithioesters, dithiocarbamates, xanthates and trithiocarbonates. *Tetrahedron Lett*ers, *40*, 2435–2438. DOI: 10.1016/S0040-4039(99)00177-X.

Wight, A. P., & Davis, M. E. (2002). Design and preparation of organic–inorganic hybrid catalysts. *Chemical Reviews*, *102*, 3589–3614. DOI: 10.1021/cr010334m.