

Intermolecular C–O Coupling Using Hemicucurbituril Supported Ionic Liquid Phase Catalyst

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Abstract Hemicucurbituril supported ionic liquid phase catalyst (HmCucSILP) has been synthesized by anchoring multilayer of ionic liquid ([Bmim]Cl) containing Pd(OAc)₂ and X-phos on the surface of hemicucurbit[6]uril. The HmCucSILP was effectively employed in intermolecular C–O coupling of aryl halides with sodium alkoxides for the synthesis of alkyl aryl ethers.

Graphical Abstract



Keywords Hemicucurbituril · Intermolecular C–O coupling · Alkyl aryl ethers · X-Phos · Reusability

1 Introduction

The contemporary concept of supported ionic liquid phase (SILP) catalysis involving the use of covalently anchored film of ionic liquid (IL) on a high area porous material to catalyze variety of organic and inorganic reactions is evolving

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at a fast pace since the last decade [1-3]. Much of the interest in SILP catalysts stems from their superior performance over traditional ionic liquids (ILs) that enables their application in fixed-bed technology [4]. The use of these advanced materials is particularly advantageous because of unique benefits such as ease of separation of catalyst simply by filtration, as well as facilitating significant advances in selectivity and recycling reproducibility [5]. The scrutiny of the recent literature reveals an explosion of interest in the development of novel SILP catalysts for achieving efficient organic transformations [6–11]. The SILP catalysts are usually prepared by depositing ILs on the surface of high area support material either by covalent bonding or impregnation method. The most common supports used for synthesis of SILP catalysts are silica or polymer based materials [12–16]. In addition, carbon nanotubes, [17] active carbon cloth, [18] chitosan, [19] magnetic nanoparticles [20] etc. have also been occasionally employed as supports. In expanding the catalytic properties of SILPs, it is highly desirable to search new support materials for their synthesis since the performance of SILP catalysts is strongly dependent upon the choice of support material. The scrutiny of a suitable support is often governed by the process conditions at which a SILP catalyst has to operate. Nevertheless, the key features of a support material are to possess insolubility in common solvents and chemical inertness. With this regard, we sought to explore compatibility of hemicucurbiturils [21] as a support for the synthesis of SILP catalyst. Hemicucurbiturils are macrocycles consisting of alternating methylene and N-substituted ethylene urea units that closely resemble a family of cucurbiturils [22] with a mimic chemistry. These macrocycles can be constructed in two sizes viz; hemicucurbit[6]uril and hemicucurbit[12]uril. Recent developments in the chemistry of hemicucurbiturils reveal that their cavities are particularly useful for the applications in supramolecular chemistry

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as hosts for guests like uranyl and transition metal cations and certain anions [23, 24]. The contemporary studies have unveiled the catalytic potential of these cavitands [25]. We envisioned that their insolubility in most solvents and chemical inertness are extremely well-suitable to serve as a robust support material for synthesis of SILPs.

Alkyl aryl ethers are important structural motifs found in large number of pharmaceuticals, agrochemicals, natural products, fine chemicals and functional materials [26]. In addition, many of their derivatives are deliberately utilized in skin protecting products as UV absorbers [27]. Due to intriguing structural features and diverse properties, the synthesis of these privileged scaffolds has received considerable attention in recent years. The metal-free access to these compounds is achieved by Williamson ether synthesis, [28] Mitsunobu reactions, [29] Nucleophilic aromatic substitution [30] and reactions via benzyne intermediates [31, 32]. In addition, approaches involving stoichiometric use of diaryliodonium salts [33] and hypervalent iodine compounds [34, 35] have also been employed for their synthesis. The synthesis of alkyl aryl ethers received a decisive impetus as different research groups reported on intermolecular C-O cross-coupling chemistry employing transition metal catalysis [36-41]. Amongst these, Pd mediated intermolecular C–O bond formation process by cross coupling of aryl halides and alkoxides is most attractive method due to high functional group tolerance especially with the application to unactivated aryl halide substrates, compatibility with common and ecobenign solvents, and easy binding ability to the variety of ligands. Various elegant catalytic protocols have been reported for the synthesis of alkyl aryl ethers using this procedure [42–44]. Although impressive progress has been made in the Pd catalyzed intermolecular C-O bond formation process for the synthesis of alkyl aryl ethers, there is a still scope for improvement especially towards development of environmentally benign protocol using highly efficient and reusable catalyst.

As part of our program aimed at exploiting the applications of SILP catalysis in synthesis of bioactive molecules, [45] we report herein the preparation of hemicucurbituril supported ionic liquid phase catalyst (acronymed as HmCucSILP) for the synthesis of alkyl aryl ethers using intermolecular C–O cross-coupling between aryl halides and sodium alkoxides.

2 Experimental Section

All reactions were carried out under air atmosphere in dried glasswares. Infrared spectra were measured with a Perkin-Elmer one FT-IR spectrophotometer. The samples were examined as KBr discs $\sim 5\%$ (w/w). Raman spectroscopy was done by using Bruker FT-Raman (MultiRAM) spectrometer. ¹H NMR and ¹³C NMR spectra were recorded on a Bruker AC (300 MHz for ¹H NMR and 75 MHz for ¹³C NMR) spectrometer using CDCl₃ as solvent and tetramethylsilane (TMS) as an internal standard. Chemical shifts are expressed in δ parts per million (ppm) values and coupling constants are expressed in hertz (Hz). Mass spectra were recorded on a Shimadzu QP2010 GCMS. The materials were analyzed by SEM using a JEOL model JSM with 5 and 20 kV accelerating voltage. Elemental analyses were performed on EURO EA3000 vectro model. Melting points were determined on MEL-TEMP capillary melting point apparatus and are uncorrected. Hemicucurbituril and [Bmim]Cl were synthesized following the literature procedure [22, 46]. The X-phos (Sigma-Aldrich) and all other chemicals (Spectrochem) were used as received.

2.1 Preparation of HmCucSILP

A mixture of Pd(OAc)₂ (224 mg), X-phos (476 mg), [Bmim] Cl (1 gm) and hemicucurbituril (5 gm) in methanol (25 mL) was stirred at room temperature. After 24 h, solvent was removed under rotary evaporator to get desired HmCuc-SILP catalyst. FT-IR (KBr, thin film): v = 3283, 2944, 1665, 1484, 1443, 1402, 1371, 1286, 1213, 1131, 1011, 929, 851, 793 cm⁻¹; FT-Raman (KBr): v = 3055, 3005, 2906, 1613, 1429, 1268, 1183, 1030, 1003, 835, 679, 641 cm⁻¹; elemental analysis observed: %C 17.57, %O 11.92, %N 16.26, %P 0.14, %Pd 0.13; loading: 0.006 mmol g⁻¹ matrix.

2.2 General Procedure for the Synthesis of Alkyl Aryl Ethers

A mixture of aryl halide (1 mmol) and sodium alkoxide (3.0 mmol) was refluxed in the presence of 200 mg of HmCucSILP catalyst in toluene (5 mL) for an appropriate time as indicated in Table 2. After completion of the reaction, the reaction mixture was filtered and solvent was evaporated in vacuo to give the crude product, which was purified by column chromatography over silica gel using hexane/EtOAc as the eluent.

2.3 Spectral Data of Representative Compounds

2.3.1 Methoxybenzene (Table 2, entry 1)

Clear liquid, bp 156 °C; FT-IR (neat): v=2916, 2875, 1640, 1568, 1420, 1402, 1317, 1298, 1108, 1068, 1012, 980, 785 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): δ 7.20–7.28 (m, 2H), 6.65–6.69 (m, 3H), 3.66 (s, 3H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 162.1, 128.8, 120.7, 114.2, 54.8 ppm;

mass (EI) m/z: 108 [M]⁺; Anal. Calcd. for C₇H₈O: %C 77.74, %H 7.47, observed: %C 77.46, %H 7.22.

2.3.2 Ethoxybenzene (Table 2, entry 5)

Clear liquid, bp 169 °C; FT-IR (neat): v = 2984, 1601, 1476, 1496, 1390, 1301, 1242, 1173, 1115, 1079, 1046, 921, 883, 796 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): δ 7.42–7.48 (m, 2H), 7.05–7.14 (m, 3H), 4.13 (q, J = 6 Hz, 2H), 1.54–1.59 (d, 3H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 159.1, 129.5, 120.6, 114.5, 63.3, 14.9 ppm; mass (EI) m/z: 122 [M]⁺; Anal. Calcd. for C₈H₁₀O: %C 78.66, %H 8.24, observed: %C 78.41, %H 8.22.

2.3.3 Isopropoxybenzene (Table 2, entry 9)

Clear brown liquid, bp 176 °C; FTIR (neat): v = 2965, 1602, 1465, 1352, 1290, 1179, 1135, 1069, 1019, 945, 876, 769, 745 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): δ 6.91–6.97 (m, 2H), 6.71–6.73 (m, 3H), 4.39–4.45 (m, 1H), 1.37 (d, 6H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 158.2, 128.7, 119.6, 115.2, 73.2, 22.7 ppm; mass (EI) m/z: 136 [M]⁺; Anal. Calcd. for C₉H₁₂O: %C 79.47, %H 8.65, observed %C 79.14, %H 8.15.

2.3.4 4-Methoxyaniline (Table 2, entry 19)

Dark brown solid, mp 154 °C; FT-IR (KBr, thin film): v=3316, 3256, 1593, 1540, 1440, 1352, 1235, 1210, 1150,1035, 981, 893, 695 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): δ 6.71 (d, *J*=8.1 Hz, 2H), 6.52 (d, *J*=8.2 Hz, 2H), 3.32 (s, 2H), 3.92 (s, 3H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 151.5, 140.1, 117.2, 115.5, 55.0 ppm; mass (EI) m/z: 123[M]⁺; Anal. Calcd. for C₇H₉NO: %C 79.47, %H 8.65, %N 11.15, observed %C 79.14, %H 8.15, %N 11.03.

2.3.5 4-Ethoxyaniline (Table 2, entry 23)

Dark brown liquid, bp 251 °C; FT-IR (neat): v = 3430, 2979,1626, 1507, 1479, 1395, 1328, 1294, 1227, 1173, 1114, 1044, 921, 819 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): δ 6.78 (d, J = 7.9 Hz, 2H), 6.67 (d, J = 7.9 Hz, 2H), 3.97 (q, 2H), 3.36 (s, 2H), 1.40 (t, 3H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 152.0, 140.0, 116.4, 115.6, 64.0, 15.0 ppm; mass (EI) m/z: 137 [M]⁺; Anal. Calcd. for C₈H₁₁NO: %C 69.97, %H 8.01, %N 10.11 observed %C 70.02, %H 7.96 %N 9.96.

2.3.6 4-Isopropoxyaniline (Table 2, entry 27)

Yellow liquid, bp 93 °C; FT-IR (neat): υ =3354, 2976, 1625, 1505, 1383, 1335, 1290, 1224, 1180, 1112, 1009, 951, 821 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): δ 6.76 (d, *J*=8.7 Hz, 2H), 6.62 (d, *J*=8.7 Hz, 2H), 4.33–4.45 (m, 1H),

3.40 (s, 2H), 1.37 (d, 6H) ppm; 13 C NMR (CDCl₃, 75 MHz): δ 150.7, 140.2, 117.8, 116.4, 71.0, 22.2 ppm; mass (EI) m/z: 151 [M]⁺; Anal. Calcd. for C₉H₁₃NO: %C 71.48, %H 8.56, %N 9.13, observed %C 70.96, %H 8.65 %N 9.09.

2.3.7 4-Methoxybenzaldehyde (Table 2, entry 10)

Dark brown liquid, bp 250 °C; FT-IR (neat): $v = 2940, 2910, 2850, 2710, 1710, 1625, 1595, 1535, 1480, 1412, 1390, 1275, 1177, 1101, 1030, 825, 780 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): <math>\delta$ 9.91 (s, 1H), 7.83 (d, *J*=8.8 Hz, 2H), 7.04 (d, *J*=8.9 Hz, 2H), 3.77 (s, 3H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 190.5, 164.5, 131.09, 129.84, 114.64, 55.14 ppm; mass (EI) m/z: 136[M]⁺; Anal. Calcd. for C₈H₈O₂: %C 70.47, %H 5.46, observed %C 70.12, %H 5.22.

2.3.8 4-Ethoxybenzaldehyde (Table 2, entry 14)

Dark brown liquid, bp 252 °C; FT-IR (neat): $\upsilon = 2985, 2889, 2827, 1682, 1598, 1576, 1509, 1476, 1425, 1396, 1312, 1251, 1214, 1156, 1114, 1038, 921, 828, 781 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): <math>\delta$ 9.89 (s, 1H), 7.87 (d, *J*=8.8 Hz, 2H), 7.02 (d, *J*=8.8 Hz, 2H), 4.18 (q, 2H), 1.47 (t, *J*=12 Hz, 3H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 190.85, 164.07, 132.01, 129.78, 114.72, 6.92, 14.63 ppm; mass (EI) m/z: 150 [M]⁺; Anal. Calcd. for C₉H₁₀O₂ %C 71.77, %H 6.59, observed %C 71.42, %H 6.46.

2.3.9 4-Isopropoxybenzaldehyde (Table 2, entry 18)

Dark yellow liquid, bp 111 °C; FT-IR (neat): $v = 2981, 2939, 2733, 1688, 1597, 1574, 1507, 1467, 1428, 1386, 1310, 1253, 1216, 1157, 1102, 1007, 947, 866 cm⁻¹; ¹H NMR (CDCl₃, 300 MHz): <math>\delta$ 9.85 (s, 1H), 7.82 (d, J = 7.5 Hz, 2H), 6.96 (d, J = 7.5 Hz, 2H), 4.63–4.69 (m, 1H), 1.37 (d, 6H) ppm; ¹³C NMR (CDCl₃, 75 MHz): δ 190.8, 163.1, 132.04, 129.4, 115.5, 70.2, 21.8 ppm; mass (EI) m/z: 164 [M]⁺; Anal. Calcd. for C₁₀H₁₂O₂: %C 72.97, %H 7.27, observed %C 72.62, %H 7.16.

3 Results and Discussion

Amongst the various approaches used for the synthesis of SILP catalysts, the impregnation method is the most attractive since it is simple and no further treatment of the support is needed. In the SILP catalysts prepared by this method, the IL containing catalytic system is deposited on the support as a multilayer which acts as an immobilizing medium for the catalyst. The van der Waals forces are strong enough to hold the entire system sufficiently stringent in the catalytic process. These interesting properties prompted us to synthesize HmCucSILP by using impregnation method. In the preparation of HmCucSILP, a mixture of hemicucurbit[6] uril, ionic liquid (1-butyl-3-methylimidazolium chloride, [Bmim]Cl), ligand (X-phos) and catalyst [Pd(OAc)₂] was stirred in methanol at ambient temperature for 24 h. The removal of solvent under vacuo afforded desired HmCuc-SILP in the form of dry powder that was used without any further treatment for further studies.

The confinement of [Bmim]Cl, Pd(OAc)₂ and XPhos in hemicucurbituril matrix was investigated by FT-IR and FT-Raman spectroscopy. The FT-IR spectrum of HmCucSILP displayed characteristic vibrational bands of



Fig. 1 SEM of HmCucSILP catalyst

hemicucurbituril ring at 3283, 1664 cm⁻¹ and the [Bmim]Cl bands at 2944 cm⁻¹ (aliphatic C–H stretch) and 1484 cm⁻¹ (in-plane C–C and C–N stretching vibrations of imidazolium ring). In addition, the characteristic peak of Pd(OAc)₂ at 1443 cm⁻¹ (C–H bending vibration of C–O–O and CH₃ in Pd(OAc)₂) and X-phos at 793 cm⁻¹ (weak bending vibration indicate the presence of P–C bond) confirmed the confinement of ionic liquid along with catalyst and ligand without any obvious changes in the structures. The FT-Raman spectrum of HmCucSILP showed vibrational bands of imidazolium ring at 3055, 2906, 1268, and 1183 cm⁻¹ and characteristics C=O stretching mode at 1613 cm⁻¹. The wagging vibrational bands at 641 and 1030 cm⁻¹ for O–C–O bond of Pd(OAc)₂ and Ar–P bond of X-phos confirmed the formation of HmCucSILP.

The amount of $Pd(OAc)_2$ and X-phos in HmCucSILP catalyst was quantified by mapping palladium and phosphorus using energy dispersive X-ray (EDX) analysis. The analysis revealed presence of 0.13% of Pd and 0.14% of P in the HmCucSILP catalyst confirming almost 1:1 metal to ligand stoichiometry.

The size and morphology of the HmCucSILP catalyst was studied by scanning electron microscopy (SEM). A typical SEM image is presented in Fig. 1. The SEM image showed that HmCucSILP catalyst particles are spherical in shape.



Fig. 2 TGA curve of HmCucSILP catalyst

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Table 1Optimization of reac-
tion conditions in intermolecu-
lar C–O cross coupling reaction
between diverse aryl halides
with sodium ethoxide

	+ CH ₃ CH	20Na HmCucSILP Solvent, Reflux]	
Entry	Solvent	Catalyst (mg)	Time (h)	Temp (°C)	Yield ^a (%)
1	Methanol	100 (0.0006 mmol)	25	Reflux	30
2	Ethanol	100 (0.0006 mmol)	28	Reflux	20
3	Isopropanol	100 (0.0006 mmol)	23	Reflux	30
4	1,4-Dioxane	100 (0.0006 mmol)	48	Reflux	Trace
5	Toluene	100 (0.0006 mmol)	12	Reflux	60
6	Toluene	150 (0.0009 mmol)	10	Reflux	71
7	Toluene	200 (0.0012 mmol)	9	Reflux	83
8	Toluene	300 (0.0018 mmol)	8	Reflux	85
9	DMSO	100 (0.0006 mmol)	24	Reflux	40
10	THF	100 (0.0006 mmol)	28	Reflux	15
11	Water	100 (0.0006 mmol)	30	Reflux	-
12	DMF	100 (0.0006 mmol)	35	Reflux	42
13 ^b	Hemicucurbituril	-	30	Reflux	_
14	[Bmim]Cl	Pd-X phos (1:1) 2.5 (0.012 mmol)–5.71 (0.012 mmol)	24	Reflux	30
15 ^b	Pd-X phos (1:1)	2.5 (0.012 mmol)–5.71 (0.012 mmol)	28	Reflux	40
16 ^b	Hemicucurbituril- Pd-X phos (1:1)	Hemicucurbituril 100 mg and Pd-X phos 2.5 (0.012 mmol)–5.71 (0.012 mmol)	25	Reflux	56

^aIsolated yields after column chromatography

^bToluene was used as solvent

The thermal stability of HmCucSILP catalyst was studied by using TGA analysis in the temperature range of 25-1000 °C. The TGA profile is shown in Fig. 2. The initial weight loss of 5.2% observed in the thermogram can be attributed to loss of physisorbed water. The further weight loss of 14.2% could be due to collective loss of water of crystallization and any other water molecules associated with ionic liquid matrix and decomposition of X-phos. The steep weight loss (52.92%) in the range 250–350°C can be reasonably assigned to allied decomposition of hemicucurbituril and [Bmim]Cl. The last weight loss of 25.95% can be plausibly due to decomposition of carbonaceous intermediates formed during previous decomposition steps. Finally, the small residual weight of around 0.8% retained in the thermogram corresponds to the formation of non volatile metal oxide (PdO) from Pd(OAc)₂. The thermal profile is in good agreement with the individual TGA profiles of [Bmim] Cl, and Pd(OAc)₂ reported in the literature [47, 48].

Next, we turned our attention toward assessing catalytic potential of HmCucSILP catalyst. The C–O coupling between iodobenzene with sodium ethoxide was chosen as a model reaction for the optimization of reaction parameters (Table 1). Initially, the effect of various solvents on the model reaction was studied. The model reaction was performed under reflux conditions in various solvents that include nonpolar toluene and 1,4-dioxane, polar aprotic acetonitrile, THF, DMF and DMSO and polar protic methanol, ethanol, isopropanol and water. The experimental procedure for reaction was simple and straightforward. A mixture of iodobenzene (1 mmol) and sodium ethoxide (3 mmol) in solvent (5 mL) was heated to reflux in the presence of HmCucSILP (200 mg) till the completion of reaction as monitored by TLC. The reaction was sluggish in ethanol, methanol, isopropanol, DMSO and DMF as the corresponding ethoxy benzene was formed in low yield (Table 1, entries 2, 1, 3, 9, 12). The use of 1,4-dioxane, THF, and water, (Table 1, entries 4, 10, 11) gave anticipated product in trace amount. It was observed that toluene was the most effective in providing highest conversion (Table 1, entry 8). Next, the effect of catalyst loading on the model reaction



Entry	Х	–R 1	-R' 2	Product 3	Time (h)	Yield ^a (%)
1	–Cl	-H	CH ₃	3a	9	82
2	-Cl	-H	-CH ₃ CH ₂	3b	9	82
3	-Cl	-H	-CH(CH ₃) ₂	3c	10	80
4	–Br	-H	-CH ₃	3a	9	78
5	–Br	-H	-CH ₃ CH ₂	3b	9	80
6	–Br	-H	-CH(CH ₃) ₂	3c	10	75
7	-I	-H	-CH ₃	3a	8	85
8	-I	-H	-CH ₃ CH ₂	3b	9	84
9	-I	-H	-CH(CH ₃) ₂	3c	9	80
10	4-Cl	-CHO	-CH ₃	3d	10	75
11	4-Cl	-CHO	-CH ₃ CH ₂	3e	10	72
12	4-Cl	-CHO	-CH(CH ₃) ₂	3f	10	75
13	4-Br	-CHO	-CH ₃	3d	10	78
14	4-Br	-CHO	-CH ₃ CH ₂	3e	9	76
15	4-Br	-CHO	CH(CH ₃) ₂	3f	10	72
16	4-I	-CHO	-CH ₃	3d	8	78
17	4-I	-CHO	-CH ₃ CH ₂	3e	8	78
18	4-I	-CHO	CH(CH ₃) ₂	3f	8	76
19	4-Cl	$-NH_2$	-CH ₃	3g	9	75
20	4-Cl	$-NH_2$	-CH ₃ CH ₂	3h	9	77
21	4-Cl	$-NH_2$	CH(CH ₃) ₂	3i	10	71
22	4-Br	$-NH_2$	-CH ₃	3g	10	78
23	4-Br	-NH ₂	-CH ₃ CH ₂	3h	10	75
24	4-Br	$-NH_2$	CH(CH ₃) ₂	3i	9	73
25	4-I	-NH ₂	-CH ₃	3g	9	77
26	4-I	$-NH_2$	-CH ₃ CH ₂	3h	10	80
27	4-I	-NH ₂	CH(CH ₃) ₂	3i	10	74

Optimal reaction conditions: 1 (1 mmol), R'ONa (3 mmol), Toluene (5 mL) and HmCucSILP (200 mg) ^aIsolated yields after column chromatography

was investigated. As shown in Table 1, the yield of ethoxybenzene increased by increasing quantity of catalyst from 100 to 200 mg (Table 1, entries 5–7). However, further increase in the amount of the catalyst did not have a significant effect on the product yield and reaction time (Table 1, entries 8).

Using the optimal reaction conditions, the generality of this protocol was studied. Firstly, a wide range of aryl halides including iodides, bromides and chlorides were studied (Table 2). In all cases, the reactions gave the corresponding products in good to excellent yields (Table 2). The reactions proceeded smoothly and equally well for electron-withdrawing as well as electron-donating substituents on aryl halides to afford the corresponding ethers in good to excellent yields (71–75% yield; Table 2, entries 10–27). In addition, the tolerance for the alkoxide reagent was also investigated. As shown in Table 2, several alkyl alkoxides such as sodium methoxide and isopropoxide underwent smooth C–O coupling with aryl halides forming the corresponding ethers in satisfactory yields.

It is noteworthy to mention that in control experiments when hemicucurbituril, [Bmim]Cl and Pd(OAc)₂-X-phos (1:1) were used as only catalysts, all the reactions were



incomplete and <60% yields were obtained (Table 1, entries 13–15). These results suggest that hemicucurbituril in combination with palladium acetate-XPhos and [Bmim] Cl exhibit synergistic effect in catalysis. The enhanced reactivity of HmCucSILP in the synthesis of alkyl aryl ethers can be attributed to the ability of hemicucurbit[6] uril to form stable host guest complex as evidenced from ¹H NMR and FT-IR spectroscopic studies. The comparison of ¹H NMR spectra of hemicucurbit[6]uril and HmCucSILP shown in Figs. 3 and 4 clearly indicates that the shapes of proton resonances of hemicucurbit[6]uril (δ 3.37 and δ 4.68) get broaden in HmCucSILP. It has been demonstrated by Xiang et al. [22, 49] that such a broadening results due to the formation of host guest inclusion complex in case of hemicucurbit[6]uril. Seen in this light, the HmCucSILP is a host–guest type complex. This has been further supported by the changes observed in the FT-IR spectra. The FT-IR absorption of carbonyl groups on hemicucurbit[6]uril exhibits split bands at 1681 and 1644 cm⁻¹ while only one band at 1644 cm⁻¹ in the FT-IR spectrum of HmCucSILP reveals the probability of formation of inclusion complex with X-phos in presence of [Bmim]Cl. We believe that the resultant inclusion complex acts as a strong ligand for stabilization of Pd(OAc)₂. The collective effect increases the catalytic activity of Pd as seen from the high yields obtained in the presence of hemicucurbituril to that in its absence. Scheme 1 Proposed mechanism for synthesis of alkyl aryl ethers



Support is removed for simplicity



Fig. 5 Reusability of HmCucSILP catalyst in synthesis of alkyl aryl ethers

The comprehensive studies involving nature of interactions responsible for existence and stabilization of inclusion complexes wherein hemicucurbiturils act as a host for better understanding of its role in organic transformations is underway in our laboratory.

A proposed mechanism for the synthesis of alkyl aryl ethers from aryl halides and sodium alkoxides using HmCucSILP catalyst is illustrated in Scheme 1. The initially formed X-phos-Pd species enters into the catalytic cycle by reacting with aryl halide to produce X-phos-Pd-Ar-X adduct via oxidative addition. In next step, transmetalation occurs subsequent to the oxidative addition in which Pd-alkoxide complex is formed from Pd-halide adduct. In the conclusive step, expected alkyl aryl ether is produced by reductive elimination process which readily occurs due to cis-interaction of Pd-arene to phosphorous center along with the regeneration of Ln-Pd active center.

In order to ascertain whether the catalyst is truly heterogeneous, we have performed a number of heterogeneity tests. Initially, leaching of Pd and phosphorous from HmCucSILP was studied by ICP-AES. Only a small amount of Pd (<1.2 ppb) as well as phosphorous (<1 ppb) was leached into the solvent indicating that most of IL along with catalyst remains tethered to the support. This indicates that IL containing catalyst is significantly embedded in the hemicucurbituril matrix thus making HmCucSILP leaching resistant for a good retrieval and reusability. Using the same amount of Pd and phosphorous as that leached out, the model reaction could not be initiated even after prolonged reaction time (36 h). The heterogeneity of HmCucSILP was also assessed by hot filtration test for the model reaction. After 50% completion of reaction (GC), the HmCuc-SILP was quickly removed by filtration and the reaction was continued with filtrate for additional 4 h. No further

increase in the product yield beyond 50% was observed (GC). This result confirmed the heterogeneous nature of the HmCucSILP.

Recovery and reusability of SILP catalysts with minimal effort is an important issue that must be addressed before endorsing it for industrial scale. The reusability of the HmCucSILP catalyst was tested for model reaction. The catalyst was easily recovered after each run simply by filtration, washed three times with toluene, dried in an oven at 110 °C for 12 h and tested in the subsequent runs. The catalyst showed unprivileged recycling performance as there was significant decrease in the product yield with the prolonged reaction time during each successive run. The decline in catalytic potential was elucidated on the basis of inflation of reactant and product molecules that might be hooked up the catalyst sites. Therefore, we attempted reusability studies after reactivation at each cycle. The reactivation involved vacuum treatment of HmCucSILP after filtering and washing with toluene, so as to remove captivated reactant and product moieties on the surface. The reactivation resulted in improved catalytic performance as the corresponding yields started at 84% and reached 55% at the third run without extended reaction time (Fig. 5). The decline in the yields of the products even after reactivation is probably due to agglomeration of support particles into larger crystallites which limits accessing of reacting molecules to the active catalytic sites. Another striking feature of HmCucSILP was its stability. The catalytic activity of HmCucSILP did not change after 1 week of air exposure at room temperature indicating its exceptional stability. The FT-IR spectrum of reused catalyst displayed the characteristic bands at 3279, 1675 cm⁻¹ (vibrational bands of hemicucurbituril ring), 2959 cm⁻¹ (aliphatic C-H stretch of [Bmim]Cl), 1479 cm⁻¹ (in-plane C–C and C–N stretching vibrations of imidazolium ring), 1456 cm⁻¹ [C-H bending vibration of C–O–O and CH₃ in Pd(OAc)₂] and 784 cm⁻¹ (P-C bond stretching vibration of X-phos) whereas EDX analysis indicated the presence of 0.12% Pd and 0.11% P revealing that the basic structure of the catalyst is retained even after the third catalytic cycle.

4 Conclusion

In conclusion, we have demonstrated a novel catalytic protocol in which supramolecular catalysis is encouraged by inducing hemicucurbituril in the field of supported ionic liquid phase catalysis. In this regards, we have engineered hemicucurbituril supported ionic liquid phase (HmCuc-SILP) catalyst by supporting metal–ligand system of Pd(OAc)₂ and X-phos with the help of ionic liquid, [Bmim] Cl. The catalyst displayed ingenious effect in intermolecular C–O cross coupling reaction between diverse aryl halides with different sodium alkoxides. The efficiency of protocol is represented by efficient C–O bond formation using electron rich aryl chlorides and bromides. In addition, this procedure displays number of significant key features such as high product yields, shorter reaction times, clean and easy work-up procedure and easy recovery and reuse of catalyst.

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