Organic &
Biomolecular
Chemistry

Cite this: *Org. Biomol. Chem.*, 2011, **9**, 5978

www.rsc.org/obc

PAPER

Recyclable heterogeneous copper oxide on alumina catalyzed coupling of phenols and alcohols with aryl halides under ligand-free conditions†

Kokkirala Swapna, Sabbavarapu Narayana Murthy, Mocharla Tarani Jyothi and Yadavalli Venkata Durga Nageswar*

Received 16th March 2011, Accepted 28th April 2011
DOI: 10.1039/c1ob05411b

An efficient alumina-supported CuO-catalyzed *O*-arylation of phenols and aliphatic alcohols with various aryl as well as heteroaryl halides under ligand-free conditions are reported. This protocol provides a variety of diaryl ether and bis-diaryl ether motifs by reacting different aryl/aliphatic halides with differently substituted phenols and saturated alcohols in the presence of a catalytic amount of CuO on alumina and KOH as a base at moderate temperature under nitrogen atmosphere. The described methodology is simple, straightforward and efficient to afford the cross-coupled products in high yields under ligand-free conditions. The explored catalyst is inexpensive, air-stable and recyclable up to three cycles.

Introduction

Diaryl ethers constitute a very importanxt class of organic compounds that are finding widespread applications in numerous fields such as life sciences, chemical, pharmaceutical and polymer industries.[1] The formation of diaryl ether linkage is a challenging task to synthetic chemists because of its presence in many biologically active natural products,[2] cyclopeptides and weedicides,[3] such as the anti-tumor bouvardin, anti-HIV chloropeptins and other medicinally active compounds (Fig. 1). The Ullmann reaction is one of the most traditional methods for the synthesis of diaryl ethers, which typically requires high reaction temperatures and the use of a more than stoichiometric amount of copper catalyst. There has been a tremendous volume of work towards the development of highly efficient reaction parameters for the synthesis of diaryl ethers using the classical Ullmann protocol.[4] Inter- and intramolecular S_NAr reactions,[5] arene metal complexes, thallium-promoted oxidative coupling, Pt-promoted coupling, phenolic addition to cyclohexene oxides and Pummerer type rearrangements are some other methodologies towards establishing C–O coupling processes. In recent times, several protocols have been reported for diaryl ether linkage formation[6] using Pd and Cu, of which Pd-based reagents have shown greater interest.

Buchwald[7] and coworkers described the synthesis of diaryl ethers by coupling of aryl halides with alcohols/phenols in the presence of palladium and tunable ligands.[8] Hartwig[9] also developed air-stable, sterically hindered ferrocenyl dialkyl phosphines for palladium-catalyzed C–O bond forming cross-couplings.[10] However, these reactions were carried out using expensive palladium salts[11] as catalysts involving electron rich and sterically bulky aryl dialkyl phosphines as ligands, which in turn are prepared by tedious multi-step processes, and the high oxophilicity associated with these phosphine ligands limits the applicability of these processes.[12] Towards the commercialization of these protocols, the use of copper salts[13] as an alternative to palladium catalysts in the Ullmann reaction has gained significance. In spite of the

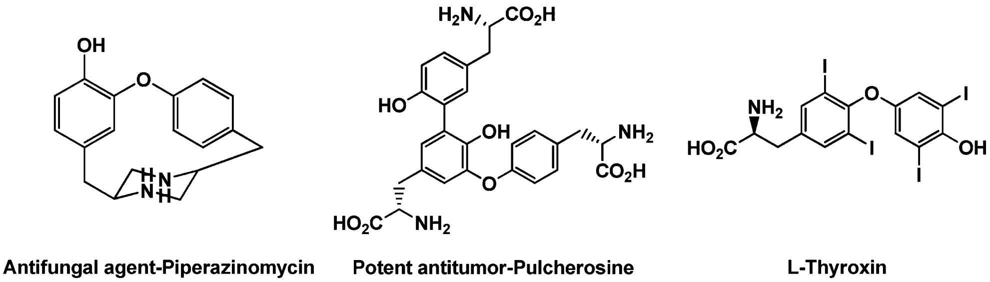


Fig. 1 Some of the biologically active molecules with diaryl ether linkage.

Organic Chemistry Division-I, Indian Institute of Chemical Technology, Hyderabad 500607, India. E-mail: dryvdnageswar@gmail.com; Fax: +91-40-27160512; Tel: +91-40-27191654

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c1ob05411b

popularity of these catalytic systems, these protocols suffer from harsh reaction conditions, higher temperatures (>200 °C), longer reaction times, use of highly polar toxic solvents and problems involving waste disposal arising from the use of excess catalyst.[14]

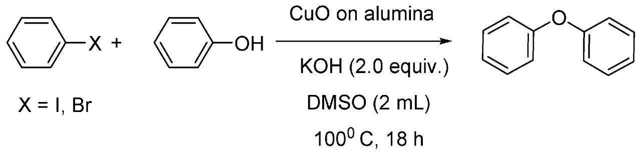
Meanwhile, efforts were directed to investigate and explore the most efficient Cu/ligand systems which can work at milder reaction conditions, for a broad substrate base with functional group tolerance.[15] During this process of exploration it was found that ethylene glycol diacetate,[16] neocuproine,[17] tripod ligands,[18] 1-naphthoic acid,[19] 2,2,6,6-tetramethylheptane-3,5-dione,[20] β-ketoester[21] were successfully introduced as ligands to enhance the reaction rate in the presence of a reduced amount of copper, with a larger substrate scope. It was explained that these additives increased the efficacy of the catalyst by increasing the solubility of the copper salts while preventing their aggregation.[22] However, although these reactions were carried out by using additives, higher reaction temperatures (120–220 °C) and high loading (stoichiometric amount) of ligand are the reaction constraints. Dewei Ma and coworkers reported that *N*,*N*-dimethyl glycine promoted the Ullmann coupling reaction of phenols with aryl halides at 90 °C.[23] Taillefer[24] *et al.* described a general and mild Ullmann-type synthesis of diaryl ethers by reacting aryl halides with phenols in the presence of Cu(I), Chxn-py-Al as a ligand and MS (3A) affording the cross-coupled product in good yields. Wu *et al.* reported the synthesis of diaryl ethers through the copper-catalyzed arylation of phenols with aryl halides under microwave irradiation.[25] Various transition metals such as Cu,[26] Fe,[27] and Cu/Fe[28] have been employed in combination with different ligands for C–O cross-coupling reactions. However, these aforementioned protocols suffer from one or more drawbacks, such as use of various well designed ligands, lack of catalyst recyclability and high cost of ligands *etc*. Hence, the development of ligand-free, air-resistant, inexpensive, recyclable catalytic systems for the formation of the ether linkage is highly desirable. Hu and coworkers have demonstrated a highly efficient C–O cross-coupling process involving the reaction of inactivated halides with various oxygen nucleophiles using heterogeneous RANEY® Ni–Al alloy copper(I) salts under ligand-free conditions to afford the corresponding coupled products in good yields.[29] Gupta *et al.* reported Zn-catalyzed Williamson's ether synthesis in the absence of base under microwave irradiation.[30] van Koten *et al.* developed ligand-free copper(I)-catalyzed *O*-arylation of aryl halides with phenols under conventional heating conditions.[31] Sekar[32a] and coworkers described an efficient BINAM–Cu(II)-catalyzed Ullmann-type synthesis of diaryl ethers from aryl halides with phenols under mild conditions in excellent yields.[32b] However, the above reactions are homogeneous, wherein catalyst recovery is the major drawback, as well as the problems of product contamination and lack of catalyst recyclability.

The heterogeneous catalysts are attractive both from economic and industrial points of view as compared to homogeneous catalysts. Moreover, in the realm of cross-coupling reactions, metal-anchored heterogeneous supported reagents gained prominence in the recent past, in view of their advantages like improved efficacy due to the presence of numerous stable active sites, easy product purification and reusability of the catalyst. Lei Wang *et al.* demonstrated that immobilization of copper in organic–inorganic hybrid materials worked out as highly efficient and reusable catalysts for the Ullmann diaryl etherification.[33] Kantam *et al.* also developed Cu/Al–hydrotalcite as an efficient catalytic system for the diaryl ether synthesis from aryl halide and phenol in the presence of DMF.[34] Furthermore, the nanoscale catalysts are more advantageous as more active surface area is available to bind the substrates selectively and enhance the reaction efficacy.[35] Very recently, CuO[36] and CuI[37] in the form of nanoparticles were employed as recyclable catalysts for C–O cross-coupling reaction under ligand-free conditions. However, a literature survey reveals that copper-catalyzed *O*-arylation of aryl halides with oxygen nucleophiles has only a few reports with recovery of the catalyst. To develop a simple, efficient, and reusable catalytic system for the cross-coupling of aryl halides with phenols under ligand-free conditions, the role of CuO on alumina as a recyclable catalyst was investigated in the synthesis of diaryl as well as aryl/alkyl ethers.

Results and discussion

As a part of our continuous research interest in the field of cross-coupling reactions utilizing heterogeneous catalysts,[38] we describe herein for the first time the use of inexpensive, air-stable and efficient CuO on alumina as a recyclable catalyst, for the synthesis of diaryl ether derivatives from the corresponding aryl halides and phenols under ligand-free conditions.

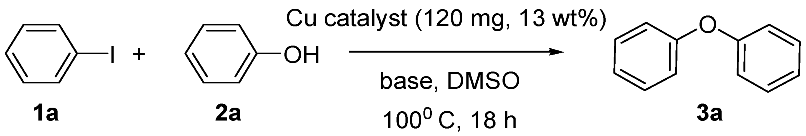
In our initial study towards the development of this methodology, we have studied the reaction of phenol (1.0 mmol) with iodobenzene (1.0 mmol) in the presence of CuO on alumina (120 mg, 13 wt%) catalyst and KOH as a base in DMSO (2 mL) at 100 °C under nitrogen atmosphere (Scheme 1). The reaction afforded the corresponding cross-coupled product **3a** in 98% yield (entry 3, Table 1). No product formation was observed at room temperature even after prolonged reaction time (entry 1, Table 1), while the reaction afforded a lower yield of product at 80 °C (entry 2, Table 1). The efficacy of different copper sources, such as $CuSO_4$, Cu $(OAc)_2$, $CuCl_2$, CuI and CuO on alumina was examined (entries 3–7, Table 1). Amongst these, CuO on alumina was found to be efficient for *O*-arylation of phenols with different aryl halides. The influence of different bases such as K_2CO_3, K_3PO_4 and KOH on the C–O cross-coupling was observed (entries 8–9, Table 1). Of the bases tested, KOH provided the *O*-arylated ethers in highest yield. Different solvents such as 1,4-dioxane, toluene, water, acetonitrile and DMF were screened for their efficacy compared to DMSO (entries 10–14, Table 1). The optimum reaction conditions for the C–O cross-coupling reaction was observed to be **1a** (1 mmol), **2a** (1 mmol), (120 mg, 13 wt%) of copper catalyst, KOH (2.0 equiv.) and DMSO (2 mL) as solvent under nitrogen atmosphere, and the optimization results are summarized in Table 1.



Scheme 1 Heterogeneous CuO on alumina catalyzed C–O cross-coupling.

After having optimized the reaction parameters, C–O cross-coupling reactions were carried out with a wide range of commercially available aryl iodides/aryl bromides and alkyl iodides/alkyl bromides with phenol under identical reaction conditions. All the

Table 1 Optimisation studies of heterogeneous copper-catalyzed *O*-arylation[a]



Entry	Copper source	Base (equiv.)	Temp.	Solvent	Yield (%)[b]
1	CuO	KOH	rt	DMSO	—
2	CuO	KOH	80 °C	DMSO	55
3	CuO	KOH	100 °C	DMSO	98
4	$CuSO_4$	KOH	100 °C	DMSO	40
5	$Cu(OAc)_2$	KOH	100 °C	DMSO	42
6	$CuCl_2$	KOH	100 °C	DMSO	45
7	CuI	KOH	100 °C	DMSO	50
8	CuO	K_2CO_3	100 °C	DMSO	51
9	CuO	K_3PO_4	100 °C	DMSO	58
10	CuO	KOH	100 °C	1,4-dioxane	45
11	CuO	KOH	100 °C	toluene	59
12	CuO	KOH	100 °C	water	—
13	CuO	KOH	100 °C	acetonitrile	50
14	CuO	KOH	100 °C	DMF	80

[a] Reaction conditions: **1a** (1 mmmol), **2a** (1 mmol), Cu source (120 mg, 13 wt%), base (2.0 equiv.), DMSO (2 mL), 100 °C, 18 h. [b] Isolated yield.

reactions were very clean, and the corresponding cross-coupled products were obtained in good to excellent yields (Table 2). To examine the scope of this reaction under optimized reaction conditions, phenol was subjected to the *O*-arylation process with various aryl iodides bearing electron withdrawing as well as electron donating groups. The presence of electron donating groups such as methyl and methoxy groups on the aryl iodide part at the *para* position decreased the yield (entries 2, 4 and 5, Table 2), compared to electron withdrawing groups (entries 7–9, Table 2). Iodobenzene with an electron donating group at the *meta* position and iodobenzene with a heteroatom in the aromatic nucleus also provided the corresponding product in good yields (entries 3, 6 and 15, Table 2). Moreover, sterically demanding *ortho*-substituted aryl iodide did not hamper the reaction and afforded the corresponding product in moderate yield (entry 14, Table 2). A slight decrease in the product yield was observed in the case of alkyl iodides with increasing carbon chain length (entries 16–21, Table 2). In general, aryl bromides were less reactive than aryl iodides and provided moderate yields (entries 22–29, Table 2).

As an extension of this work under the current optimized reaction conditions, various substituted phenols/alcohols were treated with iodobenzene and the results are summarized in Table 3. Various electronic and steric factors from the substituents played a crucial role in governing the product yield. The presence of electron donating groups at the *para* and *meta* positions on phenols increased the yield (entries 1–5, Table 3), where as in the case of electron withdrawing groups at the *para* position the yield decreased (entries 6–8, Table 3). As the carbon chain length of the alcohol used in the *O*-arylation process increased, a slight decrease in the product yield was observed (entries 11–14, Table 3).

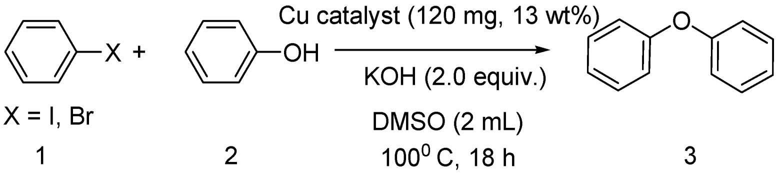
Investigations on the reusability of the copper catalyst were examined and the results are summarized in Table 4. The catalyst was centrifuged from the reaction mixture after completion of the reaction and washed with ethyl acetate and acetone and then dried, and used directly for further catalytic reactions. No significant loss of catalyst activity was observed even after three cycles. Next, the leaching of copper from the heterogeneous catalyst was checked. After separation, the filtrate was checked by SEM, XRD and FT-IR techniques and it was found that there was no change in the nature of the catalyst before and after the reaction. It was also observed from the spectral studies that the powder X-ray diffraction analysis[39] exhibited identical diffraction peaks for fresh and reused catalyst, and these were comparable with those reported in the literature (Fig. 2). The SEM analysis showed that the catalyst before and after the reaction had identical shape and size (Fig. 3). In addition, the FT-IR analysis[40] showed significant bands in the range of 490–520 cm^{-1}, which corresponds to the Cu–O bond, which indicated the presence of CuO in both fresh and reused catalyst (Fig. 4). From the obtained spectral evidence and comparison with that reported in the literature, it was evident that the catalyst was efficiently used up to three cycles without loss of catalytic activity.

The possible mechanism for *O*-arylation is represented in Scheme 2. The reaction is assumed to occur *via* oxidative addition followed by reductive elimination. Initially, the ArX oxidatively adds on to the heterogeneous copper catalyst and forms a complex **I** followed by replacement of X with the nucleophile in the presence of base forming complex **II**, which upon reductive elimination affords the desired *O*-arylated product.

Conclusions

In conclusion, an inexpensive recyclable catalytic system was developed for the efficient carbon–oxygen atom coupling leading to the formation of a C–O bond from a variety of phenols and aryl halides under ligand-free conditions. Further investigations on other useful applications of this catalyst are in progress. To the best of our knowledge, this is the first novel Cu on alumina catalyzed *O*-arylation protocol, which is of potential industrial significance because of its simplicity in operation, high yields, environmental and economical advantages, using a commercially available, economically viable, air-stable and recyclable heterogeneous catalyst to afford aryl/alkyl and aryl/aryl ethers.

Table 2 Reaction of aryl halides with phenol using heterogeneous copper as catalyst[a]



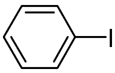
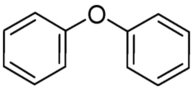
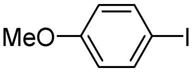
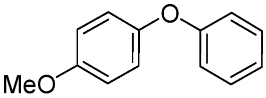
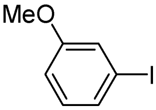
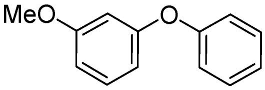
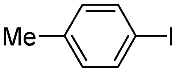
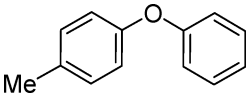
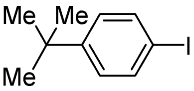
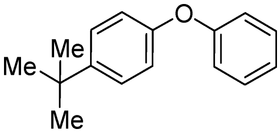
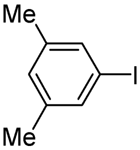
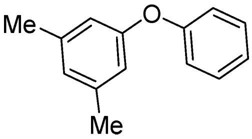
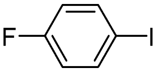
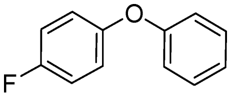
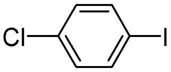
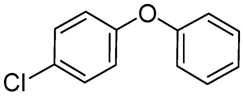
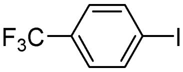
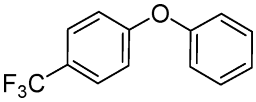
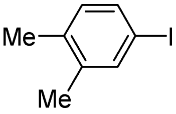
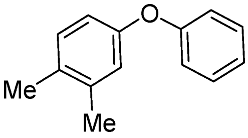
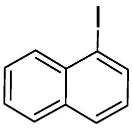
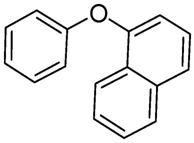
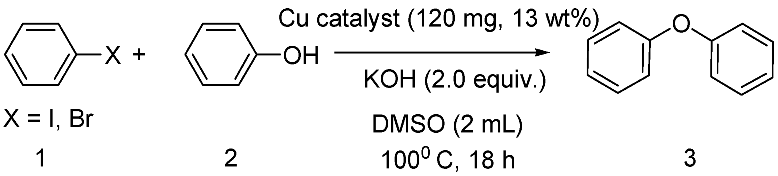
Entry	Aryl halide	Product		Yield (%)[b]
1			**3a**	98
2			**3b**	81
3			**3c**	86
4			**3d**	80
5			**3e**	79
6			**3f**	80
7			**3g**	89
8			**3h**	88
9			**3i**	85
10			**3j**	80
11			**3k**	75

Table 2 *(Contd.)*



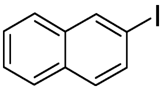
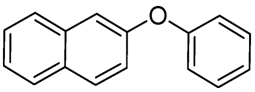
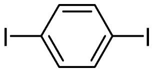
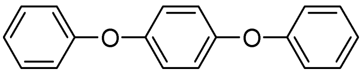
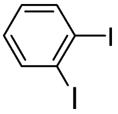
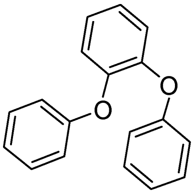
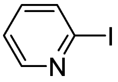
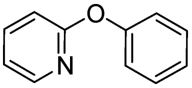
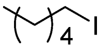
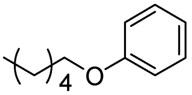
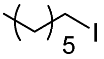
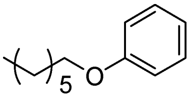
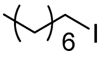
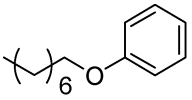
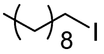
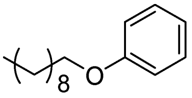
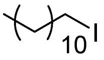
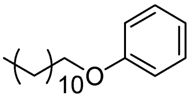
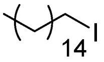
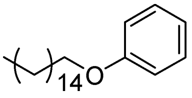
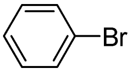
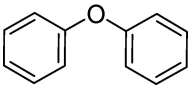
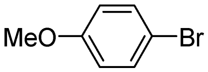
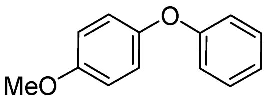
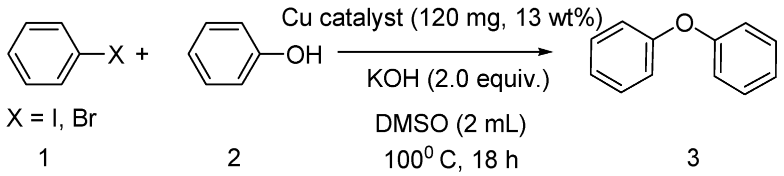
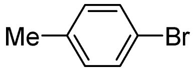
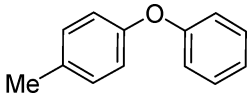
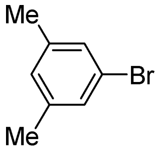
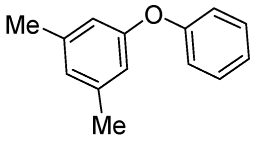
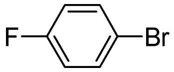
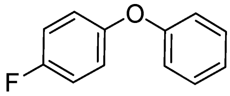
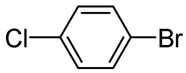
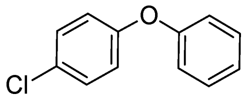
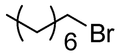
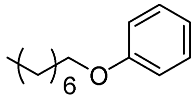
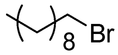
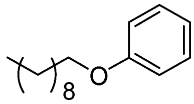
Entry	Aryl halide	Product		Yield (%)[b]
12			**3l**	85
13			**3m**	88
14			**3n**	72
15			**3o**	86
16			**3p**	89
17			**3q**	86
18			**3r**	81
19			**3s**	80
20			**3t**	75
21			**3u**	70
22			**3a**	80
23			**3b**	70

Table 2 *(Contd.)*



Entry	Aryl halide	Product		Yield (%)[b]
24			**3d**	68
25			**3f**	70
26			**3g**	76
27			**3h**	75
28			**3r**	72
29			**3s**	68

[a] Reaction conditions: aryl halide (1 mmol), phenol (1 mmol), Cu source (120 mg, 13 wt%), KOH (2.0 equiv.), DMSO (2 mL), 100 °C, 18 h. [b] Isolated yield.

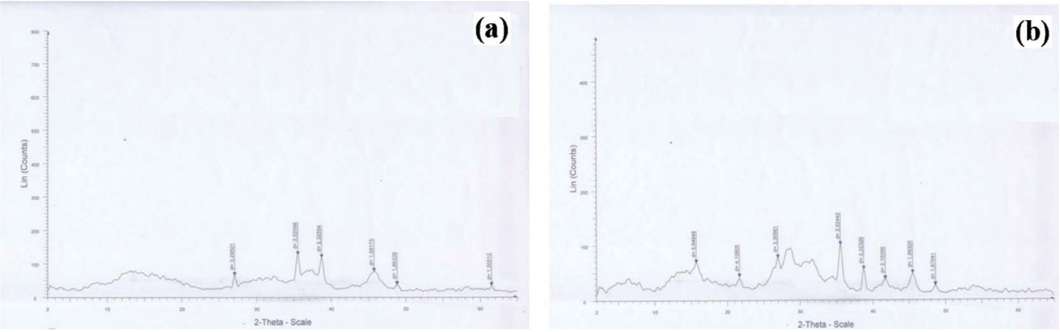


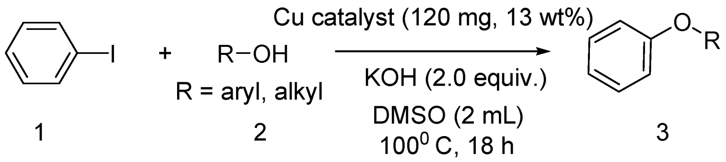
Fig. 2 XRD spectra of heterogeneous CuO on alumina catalyst (a) before and (b) after the third cycle.

Experimental section

General methods

Aryl halides (99%), CuO on alumina (99.9%) were purchased from Sigma Aldrich and used without purification. All experiments were carried out under nitrogen atmosphere. Column chromatography was carried out with 60–120 sized mesh silica gel using hexane as eluent. Analytical TLC was performed with Merck silica gel 60 F_{254} plates, and the products were visualized by UV detection. ^{1}H NMR and ^{13}C NMR (Avance 300, Innova 400 MHz and Brucker Gemini 200 MHz) spectra were recorded in $CDCl_3$ using TMS as internal standard. Chemical shifts (δ) are reported in ppm, and spin–spin coupling constants (J) are in Hz. Melting points were determined

Table 3 Reaction of aryl iodide with various phenols/alcohols using heterogeneous copper as catalyst[a]



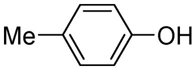
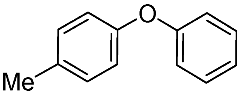
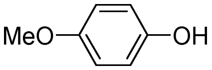
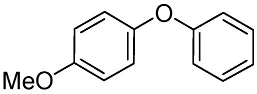
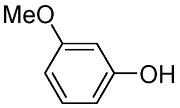
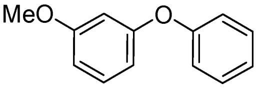
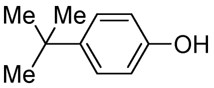
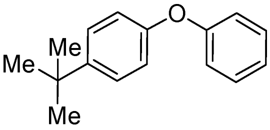
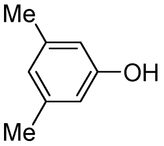
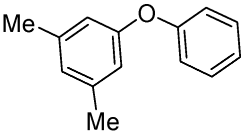
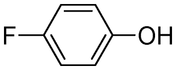
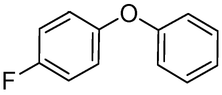
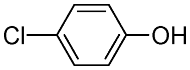
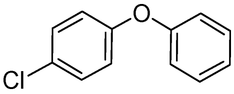
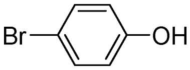
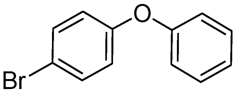
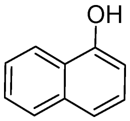
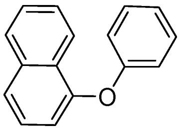
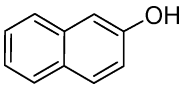
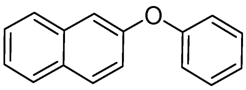
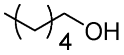
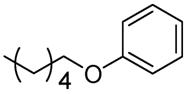
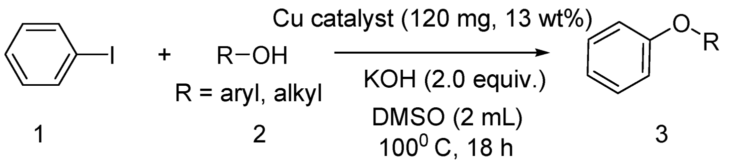
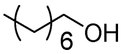
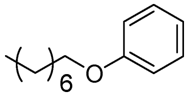
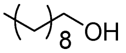
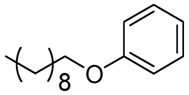
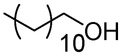
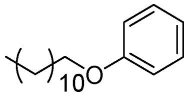
Entry	Phenols/Alcohols	Product		Yield (%)[b]
1			**3d**	88
2			**3b**	89
3			**3c**	89
4			**3e**	80
5			**3f**	79
6			**3g**	75
7			**3h**	70
8			**3v**	70
9			**3k**	69
10			**3l**	75
11			**3p**	82

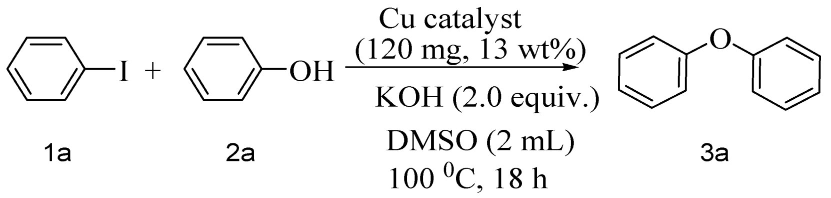
Table 3 *(Contd.)*



Entry	Phenols/Alcohols	Product		Yield (%)[b]
12			**3r**	80
13			**3s**	78
14			**3t**	75

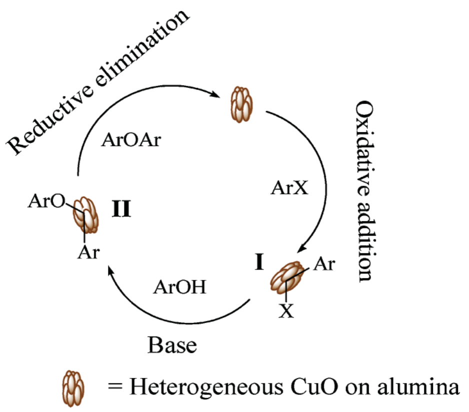
[a] Reaction conditions: iodobenzene (1 mmol), phenol/alcohol (1 mmol), Cu source (120 mg, 13 wt%), KOH (2.0 equiv.), DMSO (2 mL), 100 °C, 18 h.
[b] Isolated yield.

Table 4 Recyclability of heterogeneous copper oxide catalyst[a]



Cycle	Product isolated yield (%)	Catalyst recovery (%)
Native	98	94
1	91	92
2	85	89
3	83	81

[a] Reaction conditions: **1a** (1 mmol), **2a** (1 mmol), Cu source (120 mg, 13 wt%), KOH (2.0 equiv.), DMSO (2 mL), 100 °C, 18 h.



Scheme 2 Plausible mechanistic pathway for CuO on alumina catalyzed C–O cross-coupling.

on a Fischer–Johns melting point apparatus. IR and MS were recorded on a Thermo Nicolet Nexus 670 FT-IR spectrometer and Finnegan MAT 1020 mass spectrometer operating at 70 eV.

Representative experimental procedure for the synthesis of diaryl ether by using CuO on alumina as a catalyst. To a stirred solution of iodobenzene (**1a**) (1.0 mmol) and phenol (**2a**) (1.0 mmol) in dry DMSO (2.0 ml) were added CuO on alumina catalyst (13%, 120 mg) and KOH (2.0 equiv.), and the reaction mixture was heated at 100 °C under nitrogen atmosphere for 18 h. The progress of the reaction was monitored by TLC. After completion of the reaction, the reaction mixture was extracted with ethyl acetate (3 × 10 ml). The combined organic layers were dried with anhydrous Na_2SO_4. The solvent was evaporated under vacuum to give the crude product, which was purified by column chromatography with hexane as eluent to yield the expected product **3a** (166 mg, 98%) as yellowish oil. The purity of the product was confirmed by ^{1}H, ^{13}C and mass and IR spectroscopies.

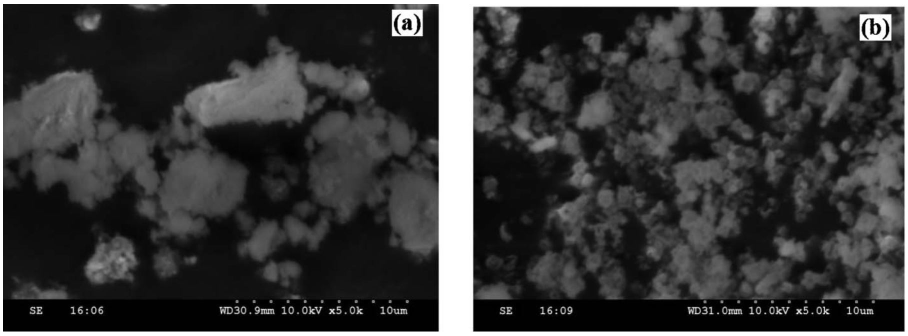


Fig. 3 SEM of heterogeneous CuO on alumina catalyst (a) before and (b) after the third cycle.

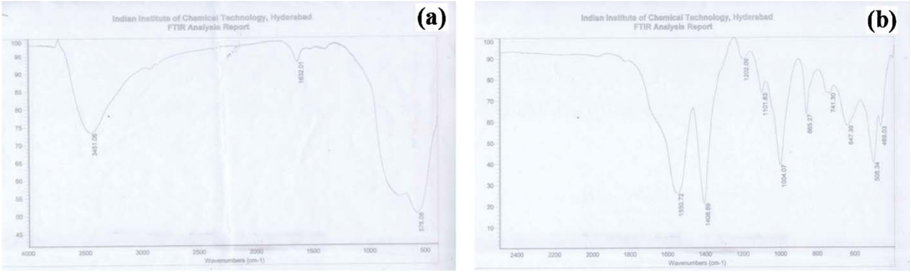


Fig. 4 FT-IR spectra of heterogeneous CuO on alumina catalyst (a) before and (b) after the third cycle.

Representative procedure for recycling. After extraction of the organic compounds with ethyl acetate, the recovered heterogeneous catalyst was placed in a 25 mL round-bottomed flask with a condenser. Phenol (**2a**) (1.0 mmol), KOH (2.0 equiv.) and iodobenzene (**1a**) (1 mmol) were added under nitrogen, followed by addition of dry DMSO (2.0 mL). The reaction mixture was heated in an oil bath at 100 °C and stirred at this temperature for 18 h. After completion of the reaction (monitored by TLC), the heterogeneous mixture was then cooled to room temperature and treated with ethyl acetate (2 mL). The aqueous layer was separated and extracted with ethyl acetate (3 × 5 mL). The combined organic layers were dried with anhydrous Na_2SO_4 and concentrated under reduced pressure to yield the product, which was purified by column chromatography using silica gel (ethyl acetate/hexane) to obtain the pure product **3a** (154 mg, 91%) as a yellow oil. All the products were characterized by ^{1}H and ^{13}C NMR, and MS analysis, and compared with the literature values. The same procedure was extended for further cycles.

Spectroscopic data

Oxydibenzene[24] (3a)

98%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.34–7.24 (4H, m), 7.09–6.94 (6H, m). ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.3, 129.7, 123.1, 118.9. IR: 3443, 2922, 1637, 1479, 1232, 752 cm^{-1}. EI-MS: 170.

1-Methoxy-4-phenoxybenzene[41] (3b)

81%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.37–7.12 (5H, m), 6.91–6.80 (2H, m), 6.76–6.67 (2H, m), 3.78 (3H, s). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.4, 155.7, 150.1, 129.7, 122.4, 121.1, 118.0, 116.3, 114.9, 55.2. IR: 3443, 2960, 1590, 1362, 1172, 753, 694 cm^{-1}. EI-MS: 200.

3-Methoxy-4-phenoxybenzene[32b] (3c)

86%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.34–7.24 (2H, m), 7.20–7.12 (1H, m), 7.09–6.95 (3H, m), 6.62–6.50 (3H, m), 3.76 (3H, s). ^{13}C NMR (75 MHz, $CDCl_3$): δ 160.9, 158.5, 157.1, 130.1, 129.6, 123.2, 119.0, 110.9, 108.9, 104.8. IR: 3443, 2958, 1596, 1362, 1170, 849, 753, 694 cm^{-1}. EI-MS: 200.

1-Methyl-4-phenoxybenzene[18] (3d)

80%, yellowish oil, ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30–7.23 (2H, m), 7.18–6.83 (5H, m), 6.80–6.74 (2H, m), 2.32 (3H, s). ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.7, 154.6, 132.7, 130.1, 129.5, 122.9, 119.5, 118.2, 20.6. IR: 3440, 2930, 1591, 1298, 1169, 760, 698 cm^{-1}. EI-MS: 184.

1-*Tert*-butyl-4-phenoxybenzene[24] (3e)

79%, white solid, m.p. 52–53 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.33–7.24 (4H, m), 7.06–6.85 (5H, m), 1.32 (9H, s). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.1, 154.1, 145.2, 129.1, 126.4, 123.2, 118.4, 34.1, 31.3. IR: 3448, 2959, 2926, 1591, 1498, 1364, 874, 754, 692 cm^{-1}. EI-MS: 226.

1,3-Dimethyl-5-phenoxybenzene[24] (3f)

80%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.31–7.19 (2H, m), 7.06–6.90 (2H, m), 6.85–6.76 (2H, m), 6.70–6.57 (2H, m), 2.27 (6H, s). ^{13}C NMR (75 MHz, $CDCl_3$): δ 158.3, 157.1, 139.4, 132.0, 129.6, 127.6, 124.9, 122.8, 121.9, 120.1, 118.7, 116.8, 21.3. IR: 3440, 2859, 2490, 1638,1480, 1240 cm^{-1}. EI-MS: 198.

1-Fluoro-4-phenoxybenzene[27] (3g)

89%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.58 (1H, d, *J* 8.9), 7.36–7.20 (2H, m), 7.13–6.89 (4H, m), 6.77–6.64 (2H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 160.4, 157.7, 152.9, 138.6, 129.7, 123.1, 120.5, 120.4, 118.3, 116.4, 116.1. IR: 3445, 2925, 2854, 1591, 1485, 1213, 841, 757, 690 cm^{-1}. EI-MS: 188.

1-Chloro-4-phenoxybenzene[27] (3h)

88%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.35–7.22 (4H, m), 7.12–7.03 (1H, m), 7.01–6.89 (4H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.9, 156.1, 129.8, 129.7, 123.6, 129.1, 119.0. IR: 3447, 2924, 2853, 1583, 1482, 1089, 833, 753,691 cm^{-1}. EI-MS: 204.65.

1-Phenoxy-4-(trifluoromethyl)benzene[13g] (3i)

85%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.55 (2H, d, *J* 8.5), 7.45–7.30 (2H, m), 7.22–7.10 (3H, m), 7.02 (2H, d, *J*, 8.5). ^{13}C NMR (75 MHz, $CDCl_3$): δ 160.5, 155.7, 130.2, 130.0, 127.0, 124.4, 124.1, 119.9, 119.4, 117.8. IR: 3440, 2925, 2850, 1596, 1480, 1220, 841, 760 cm^{-1}. EI-MS: 238.

1,2-Dimethyl-4-phenoxybenzene[27] (3j)

80%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.34–7.22 (2H, m), 7.11–6.94 (4H, m), 6.90–6.73 (2H, m), 2.22 (6H, s). ^{13}C NMR (75 MHz, $CDCl_3$): δ 158.0, 154.1, 138.2, 131.0, 130.1, 129.5, 123.1, 120.4, 118.2, 117.0. IR: 3444, 2924, 2859, 1479, 1232, 10230 cm^{-1}. EI-MS: 198.

1-Phenoxynaphthalene[39] (3k)

75%, colorless oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.17 (1H, d, *J* 7.9), 7.82 (1H, d, *J* 7.9), 7.56 (1H, d, *J* 7.6), 7.50–7.42 (2H, m), 7.36–7.22 (3H, m), 7.09–6.89 (4H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.9, 153.1, 135.0, 129.7, 128.1, 127.7, 126.5, 125.9, 125.7, 123.3, 123.1, 122.2, 118.9, 118.6, 113.4. IR: 3440, 2925, 1599, 1480, 1235, 1152, 1039 cm^{-1}. EI-MS: 220.

2-Phenoxynaphthalene[27] (3l)

85%, white solid, m.p. 47–48 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.85–7.62 (3H, m), 7.45–7.18 (6H, m), 7.13–6.95 (3H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.1, 155.0, 134.3, 129.7, 129.6, 127.6, 127.1, 126.4, 124.6, 123.3, 119.9, 119.0, 118.8, 114.1. IR: 3440, 2920, 1591, 1496, 1243, 1159, 1040 cm^{-1}. EI-MS: 220.

1,4-Diphenoxybenzene[26f] (3m)

88%, colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.32–7.23 (4H, m), 7.06–7.01 (2H, m), 6.99–6.92 (8H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.8, 152.7, 129.7, 122.9, 120.4, 118.3. IR: 3395, 2960, 2329, 1596, 1238, 1050, 850 cm^{-1}. EI-MS: 262.

1,2-Diphenoxybenzene[41] (3n)

72%, white solid, m.p. 89–90 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.94 (1H, d, *J* 7.5), 7.85 (1H, d, *J* 7.5), 7.56 (1H, d, *J* 8.1), 7.49–7.39 (2H, m), 7.36–7.17 (6H, m), 7.12–6.89 (3H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.8, 148.5, 129.7, 125.1, 122.9, 121.8, 118.5. IR: 3400, 3100, 2958, 1240, 1029 cm^{-1}. EI-MS: 262.

2-Phenoxypyridine[13g] (3o)

86%, colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.56–7.44 (4H, m), 7.34–7.17 (5H, m). ^{13}C NMR (75 MHz, $CDCl_3$): δ 162.6, 154.0, 148.1, 139.5, 129.8, 124.9, 121.2, 119.1, 111.3. IR: 3359, 3050, 2960, 1360, 1285, 1172, 840, 752, 680 cm^{-1}. EI-MS: 171.

Hexyloxybenzene (3p)

89%, yellowish oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.28–7.15 (2H, m), 6.91–6.78 (3H, m), 3.92 (2H, d, *J* 6.9), 1.77 (2H, d, *J* 6.9, *J* 7.9), 1.51–1.23 (6H, m), 0.92 (3H, d, *J* 6.9). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.1, 129.3, 120.4, 114.4, 67.7, 31.6, 29.3, 25.7, 22.6, 14.1. IR: 3444, 2930, 2862, 1596, 1496, 1386, 1244, 1146 cm^{-1}. Found: C, 79.74; H, 10.19; $C_{12}H_{18}O$, requires C, 80.96; H, 10.19%. EI-MS: 178.

Heptyloxybenzene (3q)

86%, yellowish oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.25–7.17 (2H, m), 6.89–6.80 (3H, m), 3.92 (2H, d, *J* 6.6), 1.77 (2H, d, *J* 6.6, *J* 7.9), 1.51–1.24 (8H, m), 0.90 (3H, d, *J* 6.8). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.0, 129.3, 120.4, 114.4, 67.7, 31.8, 29.3, 29.1, 26.0, 22.6, 14.1. IR: 3444, 2927, 2859, 1598, 1495, 1243, 1170 cm^{-1}. Found: C, 81.29; H, 10.46; $C_{13}H_{20}O$, requires C, 81.31; H, 10.47%. EI-MS: 192.

Octyloxybenzene (3r)

81%, yellowish oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25–7.16 (2H, m), 6.90–6.79 (3H, m), 3.92 (2H, d, *J* 6.6), 1.77 (2H, d, *J* 6.6, *J* 7.9), 1.51–1.23 (10H, m), 0.92 (3H, d, *J* 6.6). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.0, 129.2, 120.3, 114.4, 67.6, 31.9, 29.5, 29.4, 29.3, 26.2, 22.7, 14.1. IR: 3440, 2921, 1597, 1491, 1240, 1159 cm^{-1}. Found: C, 81.54; H, 11.00; $C_{14}H_{22}O$, requires C, 81.62; H, 10.74%. EI-MS: 206.

Decyloxybenzene[39] (3s)

80%, yellowish oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.27–7.15 (2H, m), 6.91–6.79 (3H, m), 3.92 (2H, d, *J* 6.9), 1.77 (2H, d, *J* 6.6, *J* 7.9), 1.52–1.23 (14H, m), 0.92 (3H, d, *J* 6.9). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.0, 129.3, 120.3, 114.4, 67.7, 31.9, 29.7, 29.6, 29.3, 26.0, 22.7, 14.1. IR: 3400, 3045, 2930, 1592, 1239, 1170 cm^{-1}. EI-MS: 234.

Dodecyloxybenzene (3t)

75%, yellowish oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.17 (2H, m), 6.93–6.78 (3H, m), 3.93 (2H, d, *J* 6.9), 1.77 (2H, d, *J* 6.9, *J* 8.9), 1.50–1.22 (18H, m), 0.89 (3H, d, *J* 6.9). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.1, 129.3, 120.3, 114.4, 67.7, 31.9, 29.7, 29.6, 29.5, 29.4, 29.3, 26.0, 22.7, 14.1. IR: 3441, 2925, 2859, 1596, 1493, 1177 cm^{-1}. Found: C, 82.46; H, 11.66; $C_{18}H_{30}O$, requires C, 82.51; H, 11.54%. EI-MS: 262.

Hexadecyloxybenzene (3u)

70%, white solid, m.p. 98–99 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.28–7.18 (2H, m), 6.90–6.79 (3H, m), 3.92 (2H, d, *J* 6.9), 1.77 (2H, d, *J* 6.9, *J* 7.9), 1.49–1.22 (26H, m), 0.89 (3H, d, *J* 6.9). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.1, 129.3, 120.4, 114.4, 67.7, 31.9, 29.8, 29.7, 29.6, 29.5, 29.4, 29.3, 26.1, 22.7, 14.1. IR: 2920, 2850, 1596, 1469, 1251, 1168 cm^{-1}. Found: C, 82.08; H, 11.94; $C_{22}H_{38}O$, requires C, 83.08; H, 12.04%.EI-MS: 318.

1-Bromo-4-phenoxybenzene[42] (3v)

70%, yellowish oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.40 (1H, d, *J* 8.9), 7.33–7.23 (3H, m), 7.10–7.03 (2H, m), 6.97 (2H, d, *J* 7.9), 6.86 (1H, d, *J* 8.9). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.2, 156.5, 132.6, 129.8, 129.6, 123.6, 123.1, 120.3, 118.9, 118.8, 115.5. IR: 3445, 2926, 2853, 1592, 1485, 1213, 840, 756, 690 cm^{-1}. EI-MS: 247.

Acknowledgements

We are grateful to UGC, New Delhi for the research fellowships to KS, and CSIR, New Delhi for SNM.

Notes and references

1 (*a*) F. Theil, *Angew. Chem., Int. Ed.*, 1999, **38**, 2345; (*b*) T. H. M. Jonckers, B. U. Maes, G. L. F. Lemiere, G. Rombouts, L. Pieters, A. Haemers and R. A. Dommisse, *Synlett*, 2003, **615**; (*c*) E. Gonthier and R. Breinbauer, *Synlett*, 2003, 1049; (*d*) S. Iyer and A. Jayanthi, *Synlett*, 2003, 1125; (*e*) K. C. Nicolaou and N. C. B. Christopher, *J. Am. Chem. Soc.*, 2002, **124**, 10451; (*f*) K. C. Nicolaou, C. N. C. Boddy, S. Brase and N. Winssinger, *Angew. Chem., Int. Ed.*, 1999, **38**, 2096.

2 (*a*) D. L. Boger, M. A. Patane and J. Zhou, *J. Am. Chem. Soc.*, 1994, **116**, 8544–8556; (*b*) J. Zhu, *Synlett*, 1997, 133.

3 *The Pesticide Manual*; 10th ed.; C. Tomlin, Ed.; Crop Protection Publications: Farnham, UK, 1994.

4 (*a*) A. Afzali, H. Firouzabadi and A. K. Nejad, *Synth. Commun.*, 1983, **13**, 335; (*b*) J. Lindley, *Tetrahedron*, 1984, **40**, 1433; (*c*) J. S. Sawyer, *Tetrahedron*, 2000, **56**, 5045; (*d*) J. Hassan, M. Sevignon, C. Gozzi, E. Schulz and M. Lemaire, *Chem. Rev.*, 2002, **102**, 1359.

5 A. Kiyomori, J.-F. Marcoux and S. L. Buchwald, *Tetrahedron Lett.*, 1999, **40**, 2657.

6 (*a*) P. J. Fagan, E. Hauptman, R. Shapiro and A. Casalnuovo, *J. Am. Chem. Soc.*, 2000, **122**, 5043; (*b*) D. A. Evans, J. L. Katz and T. R. West, *Tetrahedron Lett.*, 1998, **39**, 2937; (*c*) J. S. Sawyer, E. A. Schmittling, J. A. Palkowitz and W. J. Smith, *J. Org. Chem.*, 1998, **63**, 6338; (*d*) J. F. Hartwig, *Synlett*, 1997, 329; (*e*) M. Palucki, J. P. Wolfe and S. L. Buchwald, *J. Am. Chem. Soc.*, 1996, **118**, 10333; (*f*) M. Palucki, J. P. Wolfe and S. L. Buchwald, *J. Am. Chem. Soc.*, 1997, **119**, 3395; (*g*) G. Mann and J. F. Hartwig, *J. Org. Chem.*, 1997, **67**, 5413; (*h*) G. Mann and J. F. Hartwig, *J. Am. Chem. Soc.*, 1996, **118**, 13109; (*i*) J. Lindley, *Tetrahedron*, 1984, **40**, 1433.

7 (*a*) S. Kuwabe, K. E. Torraca and S. L. Buchwald, *J. Am. Chem. Soc.*, 2001, **123**, 12202; (*b*) K. E. Torraca, X. Huang, C. A. Parrish and S. L. Buchwald, *J. Am. Chem. Soc.*, 2001, **123**, 10770; (*c*) A. Aranyos, D. W. Old, A. Kiyomori, J. P. Wolfe, J. P. Sadighi and S. L. Buchwald, *J. Am. Chem. Soc.*, 1999, **121**, 4369.

8 A. V. Vorogushin, X. Huang and S. L. Buchwald, *J. Am. Chem. Soc.*, 2005, **127**, 8146.

9 (*a*) G. Mann and J. Hartwig, *Tetrahedron Lett.*, 1997, **38**, 8005; (*b*) G. Mann, C. Incarvito, A. L. Rheingold and J. F. Hartwig, *J. Am. Chem. Soc.*, 1999, **121**, 3224.

10 N. Kataoka, Q. Shelby, J. P. Stambuli and J. F. Hartwig, *J. Org. Chem.*, 2002, **67**, 5553.

11 (*a*) G. Mann and J. F. Hartwig, *J. Am. Chem. Soc.*, 1996, **118**, 13109; (*b*) G. Mann and J. F. Hartwig, *Tetrahedron Lett.*, 1997, **38**, 8005; (*c*) A. V. Vorogushin, X. Huang and S. L. Buchwald, *J. Am. Chem. Soc.*, 2005, **127**, 8146; (*d*) N. Kataoka, Q. Shelby, J. Stambuli and J. Hartwig, *J. Org. Chem.*, 2002, **67**, 5553; (*e*) D. Prim, J. M. Campagne, D. Joseph and B. Andrioletti, *Tetrahedron*, 2002, **58**, 2041.

12 (*a*) J. Hartwig, *Angew. Chem., Int. Ed.*, 1998, **37**, 2046; (*b*) Q. Shelby, N. Kataoka, G. Mann and J. Hartwig, *J. Am. Chem. Soc.*, 2000, **122**, 10718.

13 (*a*) D. Ma, Q. Cai and X. Xie, *Synlett*, 2005, 1767; (*b*) R. Ghosh and A. G. Samuelson, *New J. Chem.*, 2004, **28**, 1390; (*c*) S. M. S. Chauhan, N. Jain, A. Kumar and K. A. Srinivas, *Synth. Commun.*, 2003, **33**, 3607; (*d*) R. Hosseinzadeh, M. Tajbakhsh, M. Mohadjerani, P. Rezaei and M. Alikarami, *Synth. Commun.*, 2008, **38**, 3023; (*e*) J. Niu, H. Zhou, Z. Li, J. Xu and S. Hu, *J. Org. Chem.*, 2008, **73**, 7814; (*f*) Y. H. Liu, G. Li and L. M. Yang, *Tetrahedron Lett.*, 2009, **50**, 343; (*g*) Q. Zhang, D. Wang, X. Wang and K. Diang, *J. Org. Chem.*, 2009, **74**, 7187.

14 (*a*) Y Jin, J. Liu, Y. Yin, H. Fu, Y. Jiang and Y. Zhao, *Synlett*, 2006, 1564; (*b*) L. Liu, H. Fu, Y. Jiang and Y. Zhao, *Synlett*, 2008, 221; (*c*) N. R. Jogdand, B. B. Shingate and M. S. Shingare, *Tetrahedron Lett.*, 2009, **50**, 4019; (*d*) S. Benyahya, F. Monnier, M. W. C. Man, C. Bied, F. Ouazzani and M. Taillefer, *Green Chem.*, 2009, **11**, 1121.

15 (*a*) M. Wolter, G. Nordmann, G. E. Job and S. L. Buchwald, *Org. Lett.*, 2002, **4**, 973; (*b*) H. B. Goodbrand and N. X. Hu, *J. Org. Chem.*, 1999, **64**, 670; (*c*) Z. Lu, R. J. Twieg and S. D. Huang, *Tetrahedron Lett.*, 2003, **44**, 6289.

16 H. Weingarten, *J. Org. Chem.*, 1964, **29**, 3624.

17 R. K. Gujadhur, C. G. Bates and D. Venkataraman, *Org. Lett.*, 2001, **3**, 4315.

18 Y. J. Chen and H. H. Chen, *Org. Lett.*, 2006, **8**, 5609.

19 J. F. Marcoux, S. Doye and S. L. Buchwald, *J. Am. Chem. Soc.*, 1997, **119**, 10539.

20 E. Buck, Z. J. Song, D. Tschaen, P. G. Dormer, R. P. Volante and P. J. Reider, *Org. Lett.*, 2002, **4**, 1623.

21 X. Lv and W. Bao, *J. Org. Chem.*, 2007, **72**, 3863.

22 A. Kiyomori, J. F. Marcoux and S. L. Buchwald, *Tetrahedron Lett.*, 1999, **40**, 2657.

23 D. Ma and Q. Cai, *Org. Lett.*, 2003, **5**, 3799.

24 H. J. Cristau, P. P. Cellier, S. Hamada, J. F. Spindler and M. Taillefer, *Org. Lett.*, 2004, **6**, 913.

25 H. He and Y. J. Wu, *Tetrahedron Lett.*, 2003, **44**, 3445.

26 (*a*) R. Hosseinzadeh, M. Tajbakhsh, M. Mohadjerani and M. Alikarami, *Synlett*, 2005, 1101–1104; (*b*) W. B. An, Z. R. Sheng, W. H. Qin, J. A. Quan and Z. J. Ping, *Chin. J. Chem.*, 2006, **24**, 1062; (*c*) J. W. W. Chang, S. Chee, S. Maka, P. Buranaprasertsuk, W. Chavasiri and P. W. H. Chan, *Tetrahedron Lett.*, 2008, **49**, 2018; (*d*) L. Yuhua, L. Gang and Y. Lianming, *Chin. J. Chem.*, 2009, **27**, 423; (*e*) F. Benaskar, V. Engels, N. Patil, E. V. Rebrov, J. Meuldijk, V. Hessel, L. A. Hulshof, D. A. Jefferson, J. C. Schouten and A. E. H. Wheatley, *Tetrahedron Lett.*, 2010, **51**, 248; (*f*) D. Ma and Q. Cai, *Org. Lett.*, 2003, **5**, 3799.

27 O. Bistri, A. Correa and C. Bolm, *Angew. Chem., Int. Ed.*, 2008, **47**, 586.

28 J. Mao, G. Xie, M. Wu, J. Guo and S Ji, *Adv. Synth. Catal.*, 2008, **350**, 2477.

29 L. W. Xu, C. G. Xia, J. W. Li and X. X. Hu, *Synlett*, 2003, 2071.

30 S. Paul and M. Gupta, *Tetrahedron Lett.*, 2004, **45**, 8825.

31 E. Sperotto, J. G. de Vries, G. P. M. van Klinka and G. van Koten, *Tetrahedron Lett.*, 2007, **48**, 7366.

32 (*a*) A. B. Naidu, O. R. Raghunath, D. J. C. Prasad and G. Sekar, *Tetrahedron Lett.*, 2008, **49**, 1057–1061; (*b*) A. B. Naidu, E. A. Jaseer and G. Sekar, *J. Org. Chem.*, 2009, **74**, 3675.

33 T. Miao and L. Wang, *Tetrahedron Lett.*, 2007, **48**, 95.

34 B. Sreedhar, R. Arundhathi, M. A. Reddy and M. L. Kantam, *Synthesis*, 2009, 483.

35 (*a*) G. Pacchioni, *Surf. Rev. Lett.*, 2000, **7**, 277; (*b*) W. D. Knight, K. Clemenger, W. A. de Heer, W. A. M. Saunders, Y. Chou and M. L. Cohen, *Phys. Rev. Lett.*, 1984, **52**, 2141; (*c*) A. Kaldor, D. Cox and M. R. Zakin, *Adv. Chem. Phys.*, 1988, **70**, 211.

36 M. Kidwai, N. K. Mishra, V. Bansal, A. Kumar and S. Mozumdar, *Tetrahedron Lett.*, 2007, **48**, 8883.

37 B. Sreedhar, R. Arundhathi, P. L. Reddy and M. L. Kantam, *J. Org. Chem.*, 2009, **74**, 7951.

38 (*a*) K. Swapna, A. V. Kumar, V. P. Reddy and K. R. Rao, *J. Org. Chem.*, 2009, **74**, 7514; (*b*) K. Swapna, S. N. Murthy and Y. V. D. Nageswar, *Eur. J. Org. Chem.*, 2010, 6678.

39 S. Jammi, S. Sakthivel, L. Rout, T. Mukherjee, S. Mandal, R. Mitra, P. Saha and T. Punniamurthy, *J. Org. Chem.*, 2009, **74**, 1971.

40 A. Viswanathan and S. A. Suthanthiraraj, *J. Mater. Sci. Lett.*, 1994, **13**, 1139.

41 Z. Liu and R. C. Larock, *Org. Lett.*, 2004, **6**, 99.

42 H. Rao, Y. Jin, H. Fu, Y. Jiang and Y. Zhao, *Chem.–Eur. J.*, 2006, **12**, 3636.