

NJC

Accepted Manuscript



This article can be cited before page numbers have been issued, to do this please use: P. Rani and R. Srivastava, *New J. Chem.*, 2016, DOI: 10.1039/C6NJ01711H.



This is an *Accepted Manuscript*, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this *Accepted Manuscript* with the edited and formatted *Advance Article* as soon as it is available.

You can find more information about *Accepted Manuscripts* in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this *Accepted Manuscript* or any consequences arising from the use of any information it contains.

Highly efficient and recyclable copper based ionic liquid catalysts for amide synthesis

Poonam Rani and Rajendra Srivastava*

Department of Chemistry, Indian Institute of Technology Ropar, Rupnagar-140001, India

Abstract

A series of Cu based ionic liquids were synthesized by the reaction of 1-butyl-3-methylimidazolium salts and copper (II) salts. These ionic liquids were investigated as catalyst in the synthesis of amides (primary, secondary and tertiary amides). For the easy separation and recycling, Cu based ionic liquids were functionalized on nanocrystalline silicalite. Materials were characterized by powder X-ray diffraction, nitrogen adsorption, scanning and transmission electron microscope, thermo gravimetric analysis, nuclear magnetic resonance, Fourier transform infrared and UV-visible spectroscopy. Cu based ionic liquids functionalized on nanocrystalline silicalite were found to be efficient and recyclable catalysts in the amides synthesis. Catalysts were found to be stable and show negligible loss in the activity even after five cycles.

Keywords: Ionic liquid, copper, silicalite, heterogeneous catalyst, amides.

*Corresponding author: E-mail: rajendra@iitrpr.ac.in, Phone: +91-1881-242175; Fax: +91-1881-223395

1. Introduction

Ionic liquids (ILs) are organic salts in which the constituent ions are poorly coordinated, which results in their wide range of melting points varies from room temperature to 300 degree Celsius (or even more). Initially ILs were developed to replace the conventional organic solvents in chemical reactions.¹⁻⁶ ILs attracted significant attention due to their favorable physico-chemical properties. Physico-chemical properties of ILs can be finely tuned by varying the cations and anions. Therefore, it is possible to synthesize wide range of ILs for the required applications.⁷⁻⁹ ILs have been widely investigated in the inter-disciplinary research areas such as electrochemistry,^{10,11} organometallics,¹² biological uses,¹³ analytical chemistry,¹⁴ polymer,¹⁵ catalysis,¹⁶⁻²² material synthesis,²³ etc. We are interested to explore the possibilities to use ILs as catalyst and structure directing agents for the preparation of catalytic materials of industrial importance.²⁴⁻²⁶

ILs based acid catalysts were designed and investigated in several industrially important reactions by our research group.²⁴⁻²⁶ We are interested to develop metal based ILs catalysts. Most of the metal based catalysis are performed in homogeneous medium and shared some common drawbacks such as difficulty in catalyst/product separation and recyclability of the catalyst. This problem can be solved when metals becomes the integral part of recyclable system (such as heterogeneous catalysts). Since ILs can be easily separated from the reaction, therefore various metals containing ILs can be a good substitute to the homogenous catalyst systems. To make the process even more user friendly, efforts were made to prepare metal containing ILs supported on mesoporous materials.²⁷⁻²⁹

Transition metals and their complexes have been used as active catalysts in many organic transformations. Especially, ruthenium, palladium, platinum, gold and iridium are the frequently used transition metals in catalysis. However, to make the catalytic system cost effective, copper (Cu) has been used instead of the above said metals with comparable efficiency. Redox chemistry of Cu is very interesting and display excellent catalytic activity ranging from oxidation, reduction, coupling (C-C, C-N, C-O, and C-S) reactions, amidation etc. to produce wide range of fine and pharmaceutically important compounds.³⁰⁻³² Cu based catalytic systems are also employed in the bulk chemical synthesis such as methanol synthesis using synthesis gas.^{33,34} Having fascinated by the Cu chemistry, we have recently shown the application of Cu based

metal organic framework in coupling reactions.³⁵ We have also reported the catalytic reduction of nitroaromatics using Cu-exchange Nano-ZSM-5 catalyst.³⁶

In this study, Cu based ILs (Scheme 1) were prepared and investigated in the synthesis of primary, secondary and tertiary amides. To achieve the highly recyclable Cu based ILs catalysts, ILs were supported on high surface area nanocrystalline silicalite.

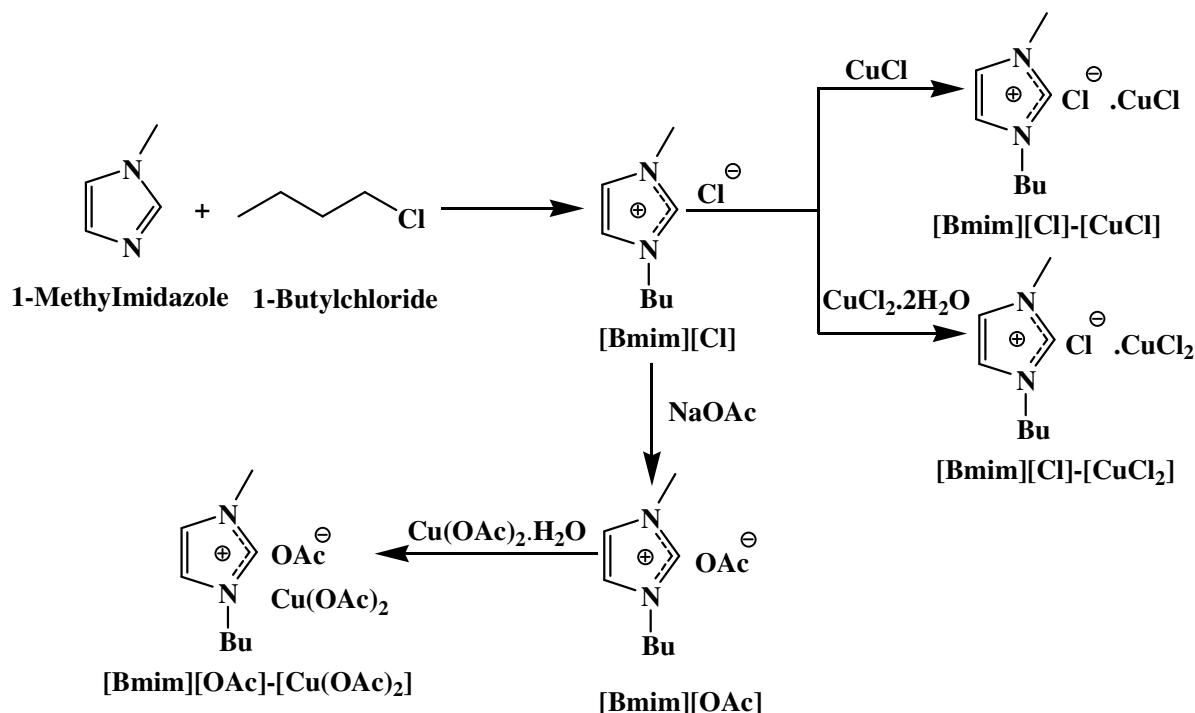
2. Experimental Section

2.1. Chemicals

All chemicals used in the study were of AR grade and used as received without further purification. Copper(II) chloride ($\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$), copper acetate ($\text{Cu}(\text{OAc})_2 \cdot \text{H}_2\text{O}$), sodium acetate (NaOAc), sodium chloride (NaCl), sulphuric acid (H_2SO_4), calcium carbonate (CaCO_3) and hydroxylamine hydrochloride ($\text{HONH}_2 \cdot \text{HCl}$) were purchased from Loba Chemie, Mumbai, India. 2-Pyrrolidone, tripotassium phosphate (K_3PO_4), tert-butyl hydroperoxide (TBHP) (70 % aqueous solution), tetraethylorthosilicate (TEOS, 98%), n-propyltriethoxysilane, 3-chloropropyltriethoxysilane, benzaldehyde derivatives, and tetrapropylammonium hydroxide (TPAOH, 1 M aq. solution) were obtained from Sigma-Aldrich, India. 1-Methylimidazole, benzaldehyde, sodium carbonate (Na_2CO_3), and iodobenzene were purchased from Spectrochem Pvt. Ltd., Mumbai, India. Dimethyl formamide (DMF) and cuprous chloride (CuCl) were obtained from SD Fine Chem. Ltd., Mumbai. 1-Chlorobutane was purchased from Alfa Aesar, India. Organic solvents used in this study were obtained from Merck India Pvt. Ltd.

2.2. Catalyst preparation

Reaction steps adopted for the preparation of Cu based ILs catalysts are shown in Scheme 1. Changes in the color observed during the synthesis of ILs are presented in Scheme S1 (Supporting information).



Scheme 1. Schematic representation for the synthesis of Cu based ILs.

2.2.1. Synthesis of [Bmim][Cl]-[CuCl] and [Bmim][Cl]-[CuCl₂]

1-butyl-3-methylimidazolium chloride ([Bmim][Cl]) was prepared by following the reported procedure.³⁷ In a typical synthesis, equivalent amounts of 1-methylimidazole and 1-chlorobutane were magnetically stirred at 343 K for 48 h.

[Bmim][Cl] was reacted with equivalent amount of cuprous chloride in neat condition. The reaction mixture was magnetically stirred at 353 K for 12 h to obtain [Bmim][Cl]-[CuCl]. [Bmim][Cl]-[CuCl₂] was prepared by the reaction of equivalent amounts of cupric chloride and [Bmim][Cl] at 353 K for 12 h.

2.2.2. Synthesis of [Bmim][OAc]-[Cu(OAc)₂]

For the synthesis of [Bmim][OAc]-[Cu(OAc)₂], first 1-butyl-3-methylimidazolium acetate ([Bmim][OAc]) was prepared by following the reported procedure.³⁸ [Bmim][Cl] (2.61 g, 15 mmol) and NaOAc (1.39 g, 17 mmol) were dissolved in ethanol (15 mL) at ambient condition and the reaction mixture was stirred at 313 K for 12 h. After the reaction, NaCl was precipitated, which was removed by filtration. Reaction mixture was evaporated under reduced pressure to

remove the ethanol. Reaction mixture was kept in refrigerator at 273 K for 24 h to precipitate remaining amount of NaOAc and NaCl. Finally, the precipitate was removed by filtration to obtain the [Bmim][OAc].

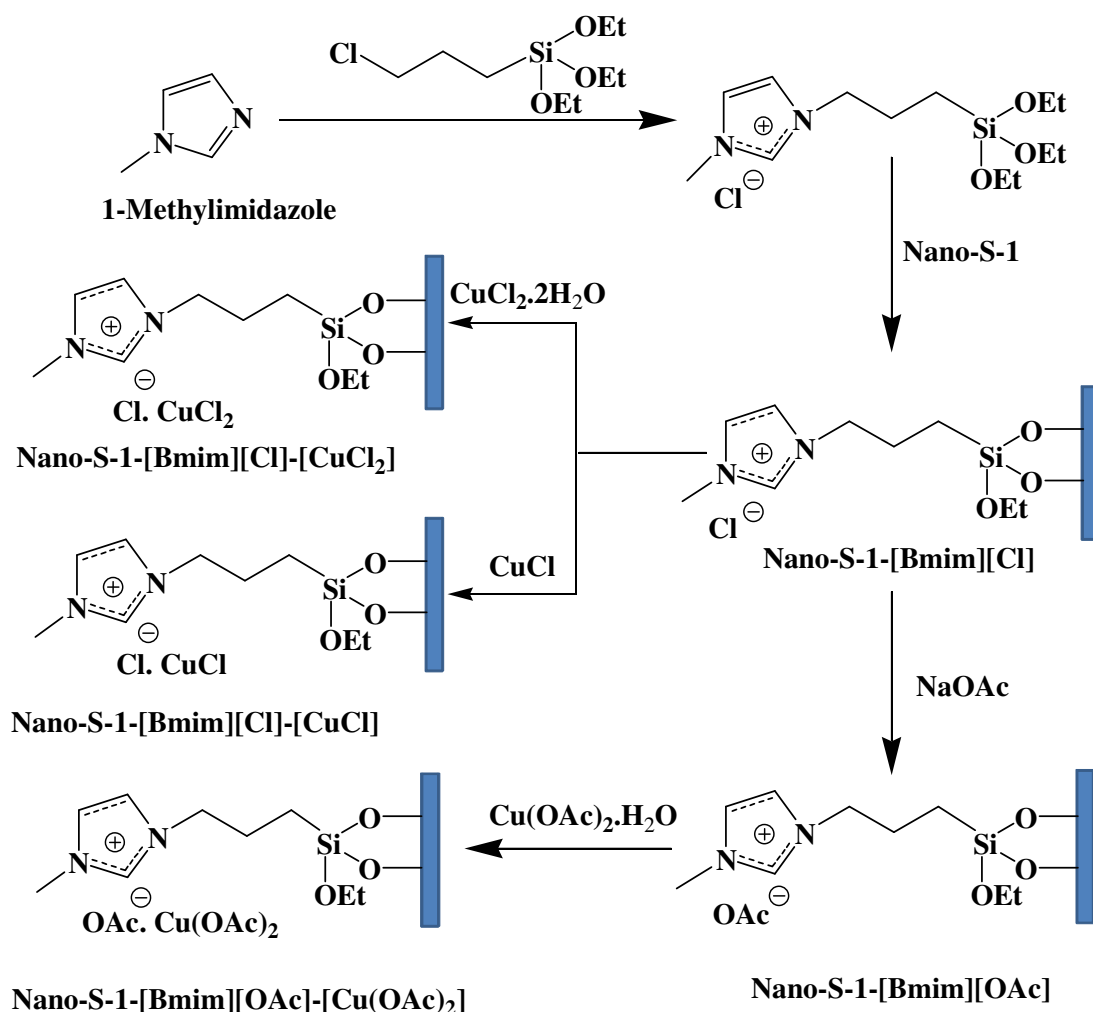
[Bmim][OAc] was reacted with equivalent amount of copper acetate in neat condition. The reaction mixture was stirred at 303 K for 12 h to get [Bmim][OAc]-[Cu(OAc)₂].³⁹

2.2.3. Synthesis of nanocrystalline silicalite-1

6.26 g of TPAOH (1 M aq. Solution), 0.4 g PrTES, and 6.24 g of deionised water was mixed and stirred for 15 minutes at ambient temperature, until a clear solution was formed. 4.92 g of TEOS was added to the clear solution and the reaction mixture was stirred for 6 h. The molar composition of the synthesis gel was 92.5 TEOS/7.5 PrTES/25 TPAOH/2500 H₂O. Gel was transferred to a Teflon-lined stainless steel autoclave, and hydrothermally treated at 443 K for 3 days under static conditions. The product was then washed with deionised water and dried at 373 K for 10 h. Material was calcined at 823 K for 6 h in air to obtain nanocrystalline silicalite-1 (hereafter represented as Nano-S-1).

2.2.4. Synthesis of Nano-S-1 supported Cu based ionic liquids

Reaction steps adopted for the preparation of supported ILs catalysts are shown in Scheme 2. Equivalent amount of N-methyl imidazole was reacted with 3-chloropropyltriethoxy silane by following the reported procedure.²⁹ Resulted compound was reacted with Nano-S-1 (pre-activated) by following the reported procedure.²⁹ The resulted compound was converted to Nano-S-1-[Bmim][Cl]-[CuCl], Nano-S-1-[Bmim][Cl]-[CuCl₂] and Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂] by following the procedure discussed above in the Section 2.2.1 and 2.2.2. Materials were subjected to elemental analysis to determine the amount of ILs in the sample. Furthermore, atomic absorption spectroscopy (AAS) analysis was performed to determine the Cu content in the sample (Table S1).



Scheme 2. Schematic representations for the synthesis of Nano-S-1 grafted Cu based ILs.

2.3. Catalyst characterization

X-ray diffraction (XRD) patterns were recorded in the 2θ range of $5\text{--}60^\circ$ with a scan speed of $2^\circ/\text{min}$ on a PANalytical X'PERT PRO diffractometer, using Cu K α radiation ($\lambda=0.1542\text{ nm}$, 40 kV, 40 mA) and a proportional counter detector. Nitrogen adsorption measurements were performed at 77 K by Quantachrome Instruments, Autosorb-IQ volumetric adsorption analyzer. Sample was out-gassed at 473 K for 3 h in the degas port of the adsorption apparatus. The specific surface area was calculated from the adsorption data points obtained at P/P_0 between 0.05–0.3 using the Brunauer-Emmett-Teller (BET) equation. The pore diameter was estimated using the Barret–Joyner–Halenda (BJH) method. Scanning electron microscopy

(SEM) measurements were carried out on a JEOL JSM-6610LV, Japan to investigate the morphology of the materials. The nanostructure was investigated using TEM on a JEM-2100, JEOL-Japan at an accelerating voltage of 200 kV. Fourier transform infrared (FTIR) spectra were recorded on a Bruker spectrophotometer in the region 400–4000 cm^{-1} (spectral resolution = 4 cm^{-1} ; number of scans = 100). Diffused reflectance UV-visible (DR UV-visible) spectra were recorded on Shimadzu UV-2600 spectrophotometer. BaSO_4 was used as reference material. Thermo gravimetric analysis (TGA) was performed in the range of 298–873 K on a TGA/DSC 1 STAR^c SYSTEM from Mettler Toledo, Switzerland, with temperature increments of 10 K/min in N_2 atmosphere. ^1H , ^{13}C , COSY and HETCOR NMR spectra were recorded on Jeol AM-400 MHz NMR.

2.4. Procedure for catalytic reactions

2.4.1. Synthesis of primary amide

A mixture of aromatic aldehyde (1.0 mmol), hydroxylamine hydrochloride (0.07 g, 1 mmol), sodium carbonate (0.12 g, 1.1 mmol), ILs (2 mol %) and water (3 mL) was stirred at 383 K for 2 days in Teflon-lined stainless steel autoclave. After the reaction, autoclave was cooled to ambient temperature and diluted with ethyl acetate. Organic portion was extracted and analyzed by using gas chromatography (GC) (Yonglin 6100; BP-5; 30 m \times 0.25 mm \times 0.25 μm). Reactant conversion and product selectivity were obtained using GC. Product was confirmed using GC–MS (Schimadzu GCMS-QP 2010 Ultra; Rtx-5 Sil Ms; 30 m \times 0.25 mm \times 0.25 μm). Product was also confirmed by the authentic sample obtained from Aldrich (based on the retention time of the authentic sample in the GC analysis).

A mixture of benzaldehyde (1.0 mmol), hydroxylamine hydrochloride (0.10 g, 1 mmol), sodium carbonate (0.12 g, 1.1 mmol), solid catalyst (2 mol % with respect to ILs) and water (3 mL) was stirred at 383 K for 2 days in Teflon-lined stainless steel autoclave. After the reaction, autoclave was cooled to ambient temperature and catalyst was separated by centrifugation. Reaction mixture was diluted with ethyl acetate. Organic portion was extracted and analyzed by GC. Recovered catalyst was washed thoroughly with ethyl acetate, dried at 353 K for 10 h, and then reused in next cycle.

2.4.2. Synthesis of secondary amide

To a mixture of ILs (5.0 mol %), glycine ethyl ester hydrochloride (0.16 g, 1.2 mmol), calcium carbonate (0.11 g, 1.1 mmol) and acetonitrile (0.2 mL); benzaldehyde (0.10 g, 1 mmol) and TBHP (0.15 g, 1.1 mmol) were added and stirred at ambient temperature for 5 min under nitrogen atmosphere. Temperature of the reaction mixture was raised to 333 K and the reaction mixture was stirred for 6 h under nitrogen atmosphere. After the reaction, reaction mixture was diluted with diethyl ether and water. Organic portion was extracted and analyzed by GC-MS.

2.4.3. Synthesis of tertiary amide

To a mixture of ILs (5.0 mol %), secondary amide/secondary amine (1.2 mmol), and K_3PO_4 (0.63 g, 3.0 mmol); iodobenzene (0.20 g, 1.0 mmol) and dimethyl formamide (2.0 mL) were added at ambient temperature under nitrogen atmosphere. Temperature of the reaction mixture was raised to 383 K and the reaction mixture was stirred for 24 h under nitrogen atmosphere. After the reaction, solvent was evaporated and reaction mixture was diluted with ethyl acetate and water. Organic portion was extracted and analyzed by GC-MS.

3. Results and discussion

3.1. Physico-chemical characterization

Synthesis procedure followed for the preparation of Cu based ILs catalysts is presented in Scheme 1. ILs and their precursor were characterized by NMR. In this study, in-depth NMR investigation is made for [Bmim][OAc]-[Cu(OAc)₂] and its precursor compound. Brief description of NMR investigation along with NMR spectra is provided in Supporting information section (Fig. S1, S2). FT-IR spectra of [Bmim][Cl]-[CuCl], [Bmim][Cl]-[CuCl₂], [Bmim][OAc]-[Cu(OAc)₂] and their precursors are shown in Fig. S3. TGA analysis provides evidence for the formation of addition complex with Cu salts (Fig. S4). The decomposition temperatures for [Bmim][Cl] and [Bmim][OAc] were found to be 475 K and 496 K, respectively. Upon addition of Cu salt, the decomposition temperature of Cu based ILs was shifted. The decomposition temperatures for [Bmim][Cl]-[CuCl], [Bmim][Cl]-[CuCl₂] and [Bmim][OAc]-[Cu(OAc)₂] were found to be 534 K, 600 K, and 509 K, respectively.

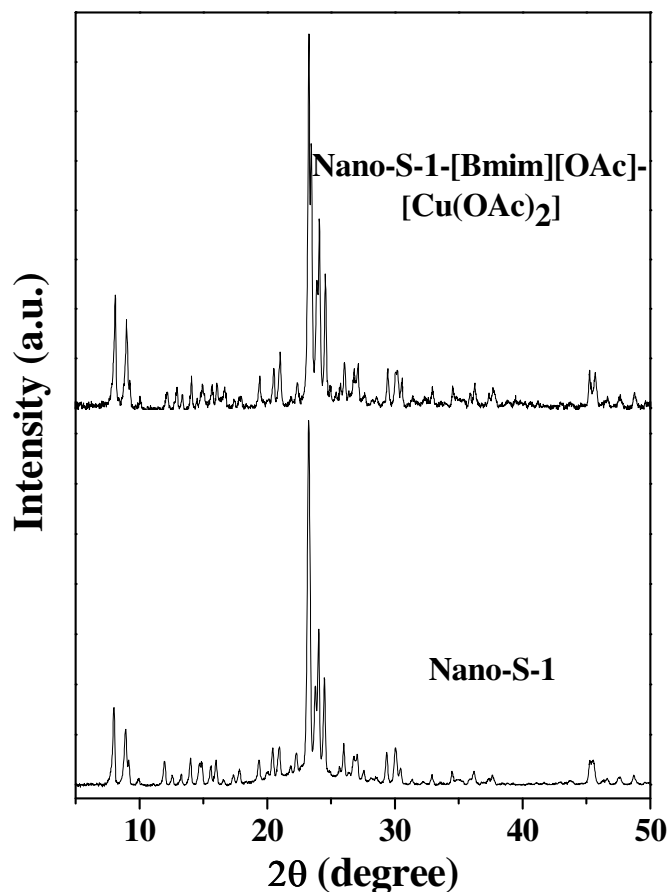


Fig. 1: XRD patterns of Nano-S-1 and Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂].

In this study nanocrystalline silicalite (Nano-S-1) was chosen as support material to functionalize the ILs. Synthesis procedure followed for the preparation of Cu based ILs supported on Nano-S-1 is shown in Scheme 2. Nano-S-1 exhibited XRD pattern similar to the XRD pattern of silicalite-1 reported in literature (Fig. 1).⁴⁰ XRD pattern of Nano-S-1 corresponds to MFI framework structure of silicalite-1. The N₂-adsorption isotherm of Nano-S-1 exhibited a type-IV isotherm similar to mesoporous materials (Fig. S5). A sharp increase in the volume of N₂ adsorption in the region 0.4 < P/Po < 0.9 is characteristic of the capillary condensation within the intercrystalline mesopore void spaces. The mesopores for Nano-S-1 showed a pore size distribution in the range of 2–10 nm. Total surface area, external surface area,

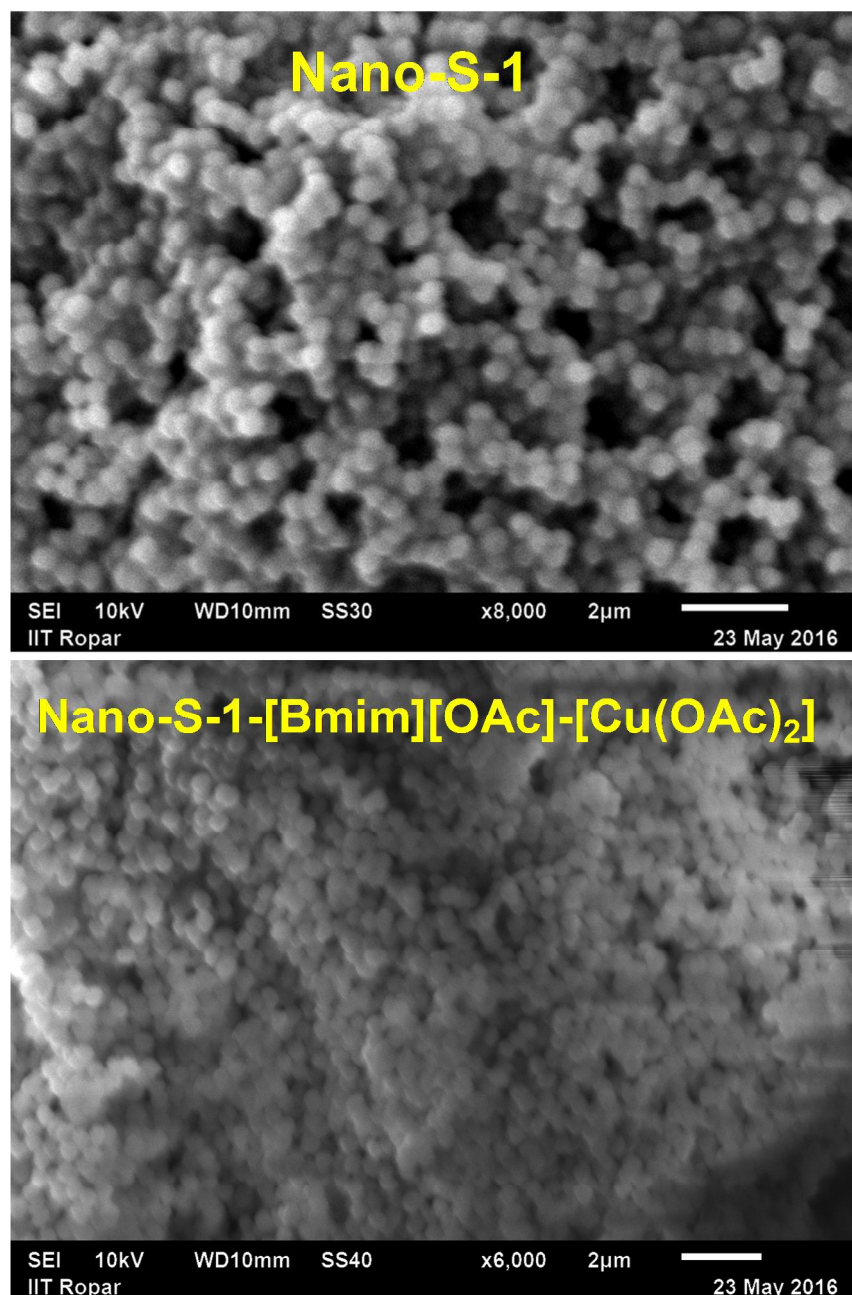


Fig. 2: SEM images of Nano-S-1 and Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂].

and total pore volume of Nano-S-1 were found to be 498 m²/g, 245 m²/g, and 0.57 cm³/g, respectively. SEM image shows that Nano-S-1 exhibits spheroid morphology with particle size in the range of 300-500 nm (Fig. 2). TEM image clearly shows that these particles are built with small zeolite nanocrystals of the order of 15-20 nm (Fig. S6). Nano-S-1 was prepared in the presence of PrTES as additive. Nano-S-1 was obtained by the addition of PrTES to the synthesis

composition of conventional silicalite. PrTES contains three hydrolyzable moieties and one hydrophobic propyl group. The hydrophobic propyl group is unfavorable for the formation of extended tetrahedral SiO₂ linkages. Consequently, the zeolite growth is significantly retarded at the organic and inorganic interfaces, resulting in the formation of nanocrystalline zeolites. Mesopores are created in Nano-S-1 because of the crystal packing of these nano size zeolite particles. Large external surface area and surface silanol groups are important for the surface functionalization. Furthermore, Nano-S-1 do not contain any Al in the framework, therefore the catalytic activity demonstrated in this study is only due to Cu based ILs functionalized on the surface of Nano-S-1.

XRD patterns of Nano-S-1-[Bmim][Cl]-[CuCl], Nano-S-1-[Bmim][Cl]-[CuCl₂] and Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂] were found to be similar to Nano-S-1, which confirms that the functionalization of ILs did not disturb the framework structure of the material (Fig. 1). Upon surface functionalization, surface area and pore volume of the material were reduced. For example, the total surface area, external surface area, and total pore volume of Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂] were found to be 394 m²/g, 150 m²/g, and 0.44 cm³/g, respectively. DR-UV visible study provides further information about the incorporation of metal salts in the ILs structure (Fig. S7). TGA analysis was performed for Nano-S-1 supported Cu based ILs samples (Fig. S4). The decomposition temperatures for Nano-S-1-[Bmim][Cl] and Nano-S-1-[Bmim][OAc] were found to be 494 K and 556 K, respectively. Upon addition of Cu salt, the decomposition temperature was shifted. The decomposition temperatures for Nano-S-1-[Bmim][Cl]-[CuCl], Nano-S-1-[Bmim][Cl]-[CuCl₂] and Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂] were found to be 558 K, 560 K, and 598 K, respectively. The amount of the ILs anchored on Nano-S-1 was calculated by elemental analysis and TGA analysis. The amounts of [Bmim][Cl]-[CuCl], [Bmim][Cl]-[CuCl₂] and [Bmim][OAc]-[Cu(OAc)₂] anchored on Nano-S-1 are found to be 0.55 mmol/g, 0.56 mmol/g, and 0.49 mmol/g by TGA, which are consistent with the elemental analysis of these materials (Table S1). Incorporation of Cu based ILs on the external surface of Nano-S-1 was also confirmed by the EDX spectrum obtained from the SEM investigation. Morphology of Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂] is similar to the morphology of Nano-S-1 (Fig. 2). EDX analysis clearly shows that Cu is not present in the parent Nano-S-1 but it is present in the EDX spectrum of Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂] along with other constituent elements of Nano-S-1 (Fig. 3).

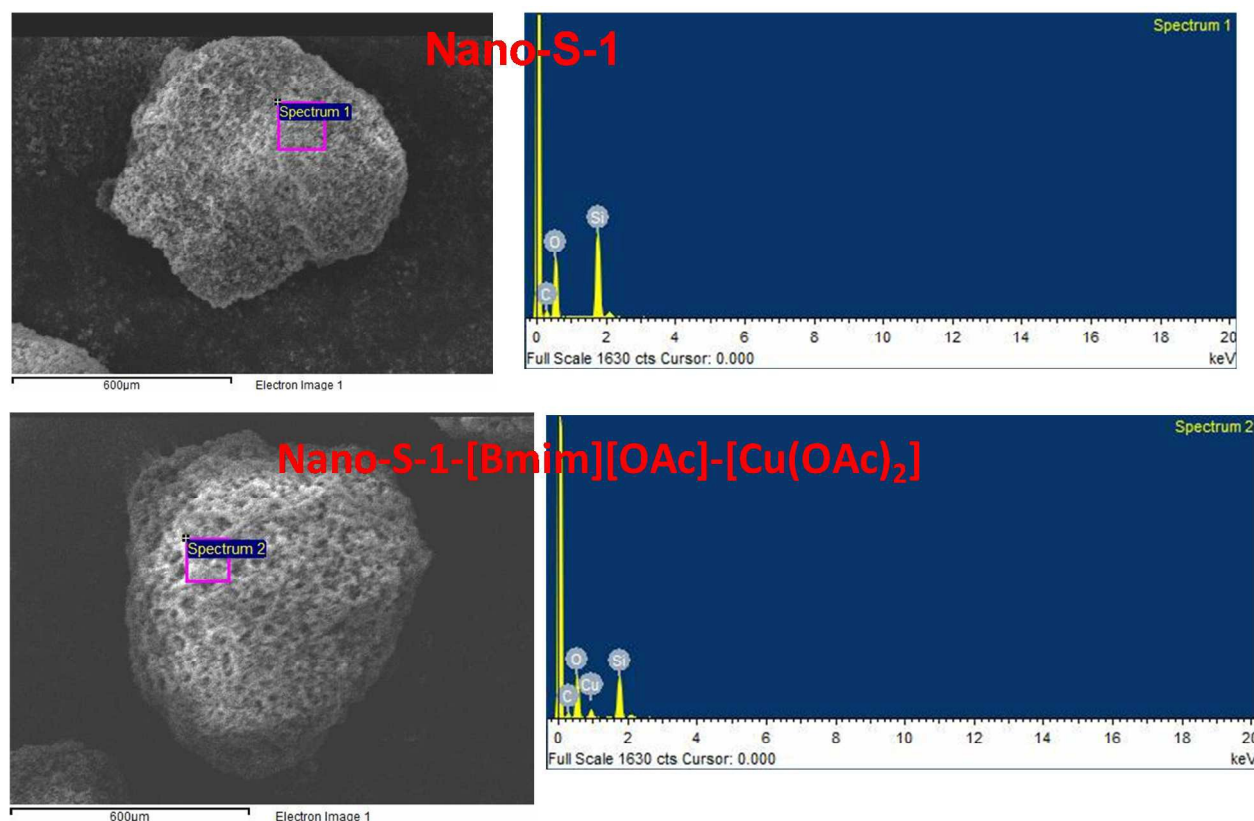
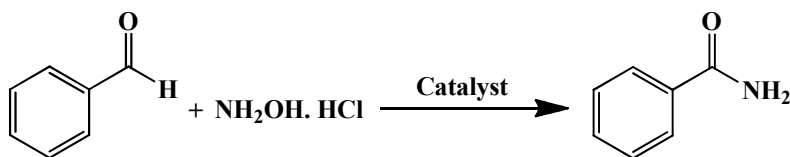


Fig. 3: EDX spectra (right panel) obtained from the SEM images (Left panel) of Nano-S-1 and Nano-S-1-[Bmim][OAc]-[Cu(OAc)₂].

3.2. Catalytic activity

Recent literature suggests that efforts are being made for the synthesis of amides using a variety of catalysts.⁴¹⁻⁴⁹ Cu based ILs prepared in this study was investigated in the synthesis of wide range of aromatic amides. In-depth investigation was made for the synthesis of primary amide with Cu based ILs and supported ILs catalysts. First, reaction condition was optimized with benzaldehyde as a reactant and [Bmim][OAc]-[Cu(OAc)₂] as a catalyst (Table 1). Influence of the base was investigated. Among the base investigated in this study, Cs₂CO₃ exhibited the highest activity. However, the activities of Na₂CO₃ and K₂CO₃ were also found to be very good. Considering the economy of the process, Na₂CO₃ was chosen as suitable base for further

optimization. Reactions were performed to investigate the influence of solvent in the production of benzamide from benzaldehyde. Among the solvent investigated, H₂O was found to be ideally suited for this reaction. It was found that high selectivity of benzamide was obtained when the reaction was performed at 383 K. Reaction also took place at low temperature (353 K), however, it lead to the formation of oxime as side product. Having optimized the reaction condition, several Cu based ILs were investigated in this reaction. All Cu based catalysts investigated in this study were found to be active and produced benzamide as selective product. The order of catalytic activity was found to be [Bmim][OAc]-[Cu(OAc)₂] > [Bmim][Cl]-[CuCl₂] ≈ [Bmim][Cl]-[CuCl]. Having found the best catalyst and optimized reaction condition, it was important to investigate the reusability of catalyst system. After the reaction, two separate phases were obtained. Aqueous phase containing [Bmim][OAc]-[Cu(OAc)₂] and base were easily separated from the organic portion containing products and un-reacted benzaldehyde. Aqueous portion was extracted several times with ethyl acetate to separate the product/reactant. Water fraction was evaporated under reduced pressure and then diluted with CH₂Cl₂. CH₂Cl₂ fraction was collected and evaporated to recover the [Bmim][OAc]-[Cu(OAc)₂]. During this process approximately 8 wt % of ILs was lost; therefore it was not possible to recover 100% ILs by this process. However, recovered ILs was found to be reusable. Catalytic activity data demonstrated that only a negligible decrease in the catalytic activity was observed after first cycle.

Table 1. Optimization of the reaction condition for the synthesis of benzamide from benzaldehyde and hydroxyl amine hydrochloride salts using Cu based ILs catalyst.

E. no.	Catalyst	Base	Solvent	Temp. (K)	Benzaldehyde conv. (%)
1	[Bmim][OAc]-[Cu(OAc) ₂]	Na ₂ CO ₃	H ₂ O	383	92
2	[Bmim][OAc]-[Cu(OAc) ₂]	K ₂ CO ₃	H ₂ O	383	93
3	[Bmim][OAc]-[Cu(OAc) ₂]	CS ₂ CO ₃	H ₂ O	383	100
4	[Bmim][OAc]-[Cu(OAc) ₂]	NaHCO ₃	H ₂ O	383	70
5	[Bmim][OAc]-[Cu(OAc) ₂]	Na ₂ CO ₃	CH ₃ OH	383	60
6	[Bmim][OAc]-[Cu(OAc) ₂]	Na ₂ CO ₃	C ₂ H ₅ OH	383	42
7	[Bmim][OAc]-[Cu(OAc) ₂]	Na ₂ CO ₃	Toluene	383	35
8	[Bmim][OAc]-[Cu(OAc) ₂]	Na ₂ CO ₃	CH ₃ CN	383	49
9	[Bmim][OAc]-[Cu(OAc) ₂] ^a	Na ₂ CO ₃	H ₂ O	353	83
10	[Bmim][OAc]-[Cu(OAc) ₂]	Na ₂ CO ₃	H ₂ O	373	88
11	[Bmim][Cl]-[CuCl]	Na ₂ CO ₃	H ₂ O	383	81
12	[Bmim][Cl]-[CuCl ₂]	Na ₂ CO ₃	H ₂ O	383	82
13	[Bmim][OAc]-[Cu(OAc) ₂] ^b	Na ₂ CO ₃	H ₂ O	383	89

Reaction condition: Benzaldehyde (1.0 mmol), hydroxylamine hydrochloride (1.0 mmol), catalyst (2.0 mol %), base (1.1 mmol), solvent (3 mL), reaction time (2 d).

^a 80 % selectivity for the benzamide and 20 % selectivity of oxime were obtained.

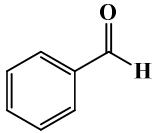
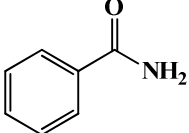
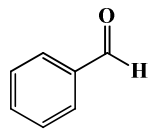
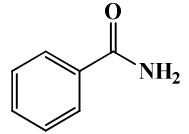
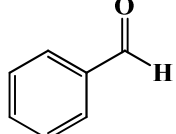
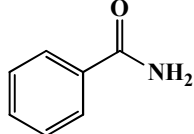
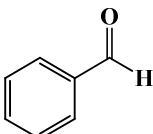
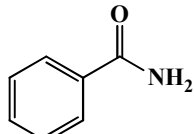
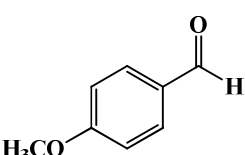
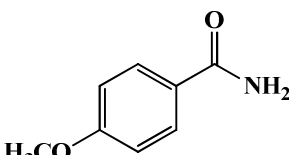
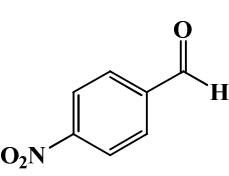
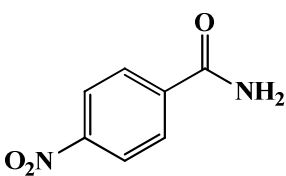
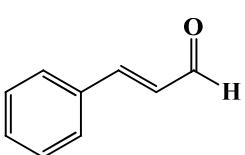
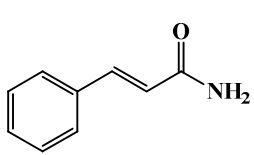
^b Data obtained after first recycle.

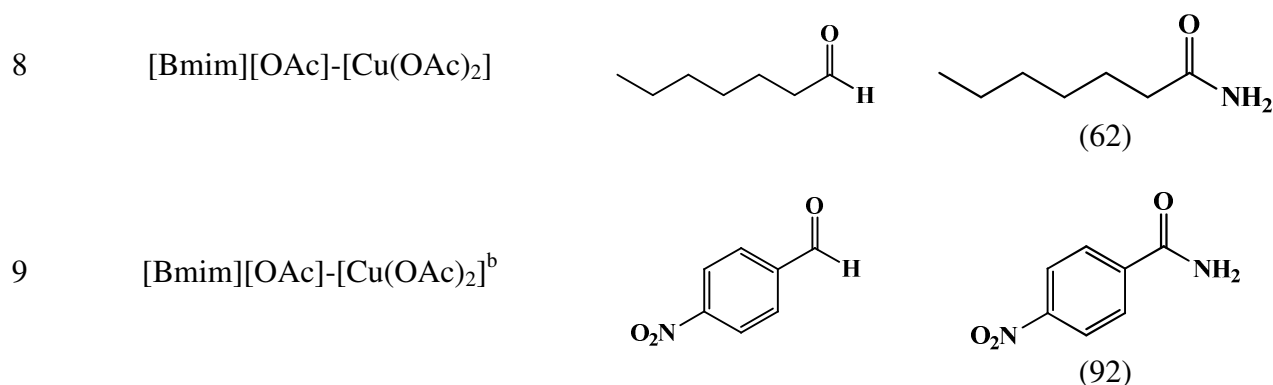
We were interested to develop recyclable and user-friendly catalyst system based on ILs for this process. To achieve this goal, ILs was functionalized on the surface of Nano-S-1. Through this study, we would like to demonstrate the functionalization ability of Nano-S-1, which is rarely reported in the literature. Functionalized ILs based heterogeneous catalysts were investigated in the synthesis of benzamide from benzaldehyde under the optimized reaction condition (Table 2). In this case also, [Bmim][OAc]-[Cu(OAc)₂] functionalized Nano-S-1 exhibited the highest activity. After the reaction, catalyst was easily centrifuged, washed with

ethyl acetate, dried at 353 K for 10 h, and reused in the next cycle. Recovered catalyst was recycled at least five times with no appreciable decrease in the catalytic activity. To study the leaching phenomenon, hot filtration test was performed. The solid catalyst was removed after 6 h of reaction (Benzaldehyde conversion = 25.1 %) and the reaction was extended for 2d. No further increase in the benzaldehyde conversion (= 25.4 %) was observed after the catalyst removal. Atomic absorption (AAS) analysis only showed 0.3 ppm copper in the solution, demonstrating that essentially no Cu was leached into the solution. These studies show that $[\text{Cu}(\text{OAc})_2]$ are strongly bonded with $[\text{Bmim}][\text{OAc}]$ and Nano-S-1 and that the trace amount of copper leached into solution was unable to catalyze the reaction. These investigations confirmed the heterogeneous nature of the catalytic system under the optimized reaction condition.

Scope of this catalytic protocol was extended for the wide range of aromatic aldehyde. Aromatic aldehydes were converted to aromatic amides in good to excellent yield by this protocol. Reactivity of aromatic aldehyde varies by varying the substituent (Table 2). Electron donating substituted ($-\text{OCH}_3$) aromatic aldehyde exhibited higher product yield when compared to electron withdrawing substituted ($-\text{NO}_2$) aromatic aldehyde. Based on the results obtained one can conclude that electron donating group enhances the rate of reaction whereas electron withdrawing group retards the reaction rate. This protocol can also be applied to cinnamaldehyde and aliphatic aldehydes. In these cases product yield was comparatively low when compared to benzaldehyde. To achieve good product yield, rate of the reaction need to be enhanced. This can be achieved just by increasing the amount of catalyst. Here we have shown that product yield can be easily improved by increasing the amount of catalyst (Table 2). Mechanism of the formation of amide from aldehyde is presented in Scheme 3. Dehydration/hydration followed by rearrangement lead to form the amide. This mechanism is consistent with the literature report.⁴² Furthermore; oxime obtained at low temperature also advocates the proposed mechanism.

Table 2. Synthesis of benzamide and its derivative using Cu based ILs catalysts

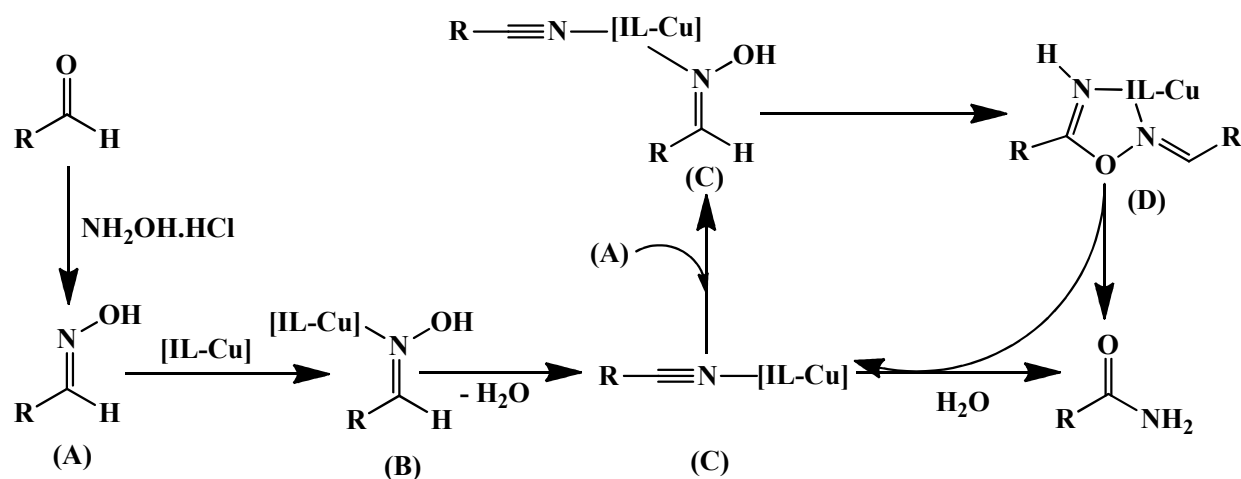
E. No.	Catalyst	Reactant	Product (Yield %)
1	Nano-S-1-[Bmim][OAc]-[Cu(OAc) ₂]		 (82)
2	Nano-S-1-[Bmim][Cl]-[CuCl ₂]		 (77)
3	Nano-S-1-[Bmim][Cl]-[CuCl]		 (66)
4	Nano-S-1-[Bmim][OAc]-[Cu(OAc) ₂] ^a		 (80)
5	[Bmim][OAc]-[Cu(OAc) ₂]		 (84)
6	[Bmim][OAc]-[Cu(OAc) ₂]		 (67)
7	[Bmim][OAc]-[Cu(OAc) ₂]		 (65)



Reaction condition: Aldehyde (1.0 mmol), hydroxylamine hydrochloride (1.0 mmol), catalyst (2.0 mol %), Na₂CO₃ (1.1 mmol), H₂O (3 mL), reaction temperature (383 K), time (2 d).

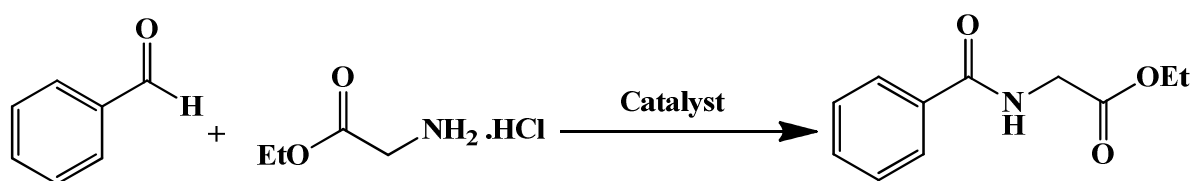
^aData obtained after fifth recycle.

^bCatalyst (3 mol %).



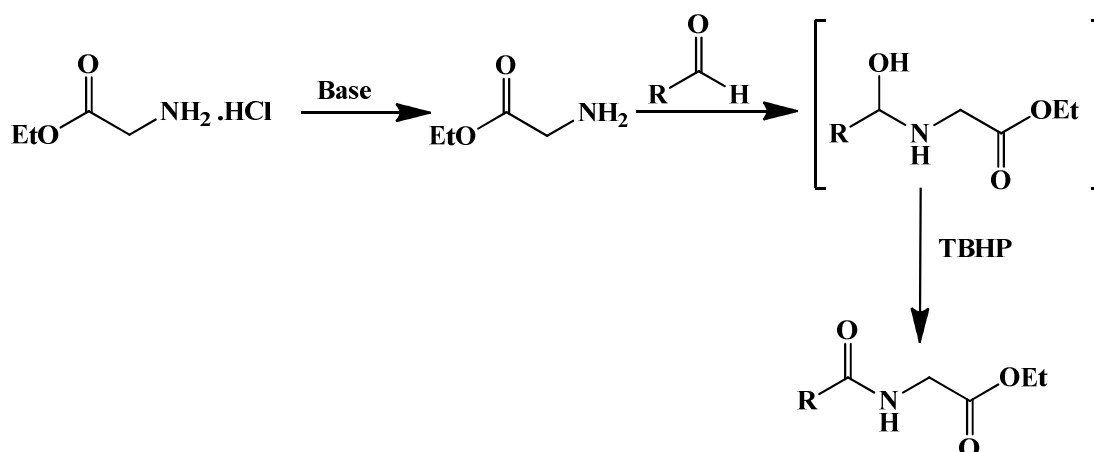
Scheme 3. Proposed mechanism for the conversion of aldehyde to primary amide using Cu based ILs

We were interested to show the applicability of this catalyst system in the synthesis of wide range of amides, such as secondary amides and tertiary amides. Cu based ILs and supported ILs catalysts were investigated in the synthesis of secondary amide (Table 3). Model reaction of benzaldehyde and glycine ethyl ester hydrochloride to form ethyl 2-benzamido acetate was chosen to optimize the reaction condition using [Bmim][Oac]-[Cu(Oac)₂]. Wide range of bases such as Na₂CO₃, K₂CO₃ and CaCO₃ were investigated. CaCO₃ exhibited the highest product yield (90%) when compared to other bases (Na₂CO₃ (61%), K₂CO₃ (69%)) investigated in this study using [Bmim][Oac]-[Cu(Oac)₂]. Influence of solvent show that reaction was facilitated in the presence of acetonitrile when compared to CH₂Cl₂, toluene, and H₂O. TBHP was found to be the best among various oxidants investigated in this study. Reaction proceeded very well at ambient temperature. Having optimized the reaction condition, various Cu based ILs and supported ILs were investigated in the synthesis of ethyl 2-benzamido acetate from benzaldehyde. All Cu based catalysts exhibited almost similar activity in this reaction. The activity of Nano-S-1-[Bmim][Oac]-[Cu(Oac)₂] was somewhat less when compared to [Bmim][Oac]-[Cu(Oac)₂] (Table 3). Scope of this catalytic protocol was extended for the wide range of aromatic aldehydes. Aromatic aldehydes were converted to aromatic amides in good to excellent yield by this protocol. Reactivity of aromatic aldehyde varies by varying the substituent (Table 3). Electron donating substituted (-OCH₃) aromatic aldehyde exhibited higher product yield when compared to electron withdrawing substituted (-NO₂) aromatic aldehyde. This protocol can also be applied to aliphatic aldehydes. In the case of heptanal, product yield was comparatively low when compared to benzaldehyde. The reaction proceeds via a hemiaminal intermediate that is oxidized to amide via a free-radical pathway (Scheme 4).

Table 3. Synthesis of secondary amide by the reaction of aldehyde and glycine ethyl ester hydrochloride using Cu based ILs catalyst.

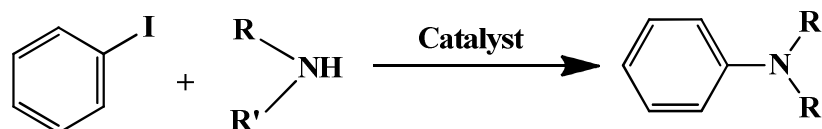
E. No.	Catalyst	Reactant	Product yield (%)
1	[Bmim][OAc]-[Cu(OAc) ₂]		90
2	[Bmim][Cl]-[CuCl]		91
3	[Bmim][Cl]-[CuCl ₂]		94
4	Nano-S-1-[Bmim][OAc]-[Cu(OAc) ₂]		82
5	[Bmim][OAc]-[Cu(OAc) ₂]		93
6	[Bmim][OAc]-[Cu(OAc) ₂]		72
7	[Bmim][OAc]-[Cu(OAc) ₂]		45

Reaction condition: Catalyst (5.0 mol %), aldehyde (1.0 mmol), glycine ethyl ester hydrochloride (1.2 mmol), calcium carbonate (1.1 mmol), tert-butyl hydroperoxide (1.1 mmol), acetonitrile (0.2 mL), reaction temperature (333 K), time (6 h).



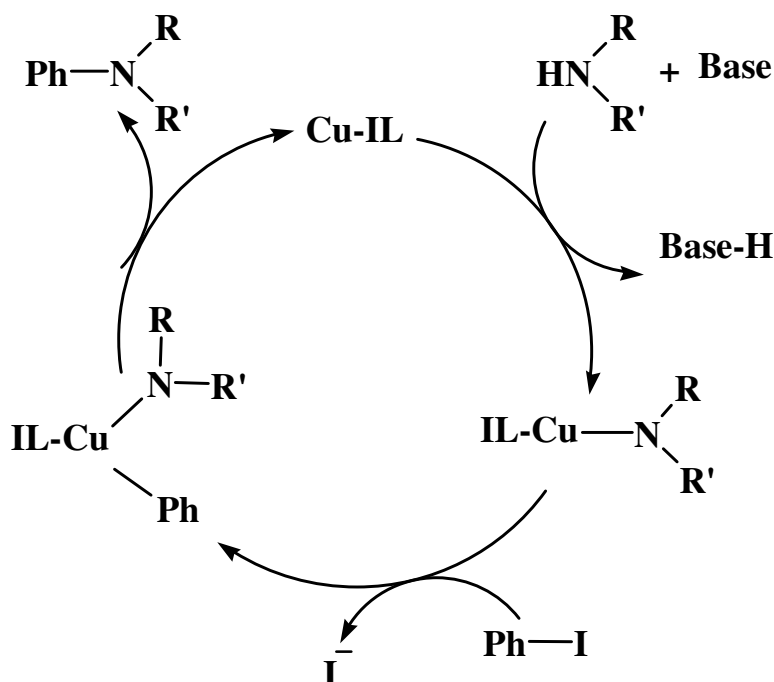
Scheme 4. Proposed mechanism for the synthesis of secondary amide from aldehyde using Cu based ILs.

Tertiary amide can be synthesized by the reaction of haloarene and secondary amide. In this study, a model reaction between 2-pyrrolidinone and iodobenzene leads to the formation of tertiary amide (Table 4). Wide range of bases such as Na_2CO_3 , K_2CO_3 , CsCO_3 , and K_3PO_4 were investigated. K_3PO_4 exhibited the highest product yield (79 %) when compared to other bases (Na_2CO_3 (12 %), K_2CO_3 (15 %), and CsCO_3 (32 %) investigated in this study using $[\text{Bmim}][\text{Cl}]-[\text{CuCl}_2]$. Influence of solvent show that reaction was facilitated in the presence of N,N'-dimethylformamide (DMF) when compared to toluene and xylene. Having optimized the reaction condition, various Cu based neat and supported ILs catalysts were investigated. Among the catalysts investigated, $[\text{Bmim}][\text{Cl}]-[\text{CuCl}_2]$ exhibited higher activity. The activity of Nano-S-1- $[\text{Bmim}][\text{Cl}]-[\text{CuCl}_2]$ was somewhat low when compared to $[\text{Bmim}][\text{Cl}]-[\text{CuCl}_2]$. Reaction with bromobenzene and chlorobenzene was not facilitated. However, a wide range of secondary amides and amines were able to convert to tertiary amides and amines with this protocol. Some of these representative examples are given in Table 4. Mechanism for the formation of amides and amines is provided in Scheme 5. This mechanism is consistent with the Ullmann mechanism, in which nucleophile coordination, oxidative addition, followed by reductive elimination lead to form the product.

Table 4. Synthesis of tertiary amides/amines by the reaction of iodobenzene and secondary amides/secondary amines using Cu based ILs catalyst.

E. no.	Catalyst	Amine/Amide	Product yield (%)
1	[Bmim][Cl]-[CuCl ₂]		79
2	[Bmim][Cl]-[CuCl]		58
3	[Bmim][OAc]-[Cu(OAc) ₂]		57
4	Nano-S-1-[Bmim][Cl]-[CuCl ₂]		65
5	Nano-S-1-[Bmim][Cl]-[CuCl ₂]		78
6	Nano-S-1-[Bmim][Cl]-[CuCl ₂]		42

Reaction condition: Catalyst (5.0 mol %), iodobenzene (1.0 mmol), secondary amide/amine (1.2 mmol), DMF (2 mL), K₃PO₄ (3.0 mmol), reaction temperature (383 K), time (24 h).



Scheme 5. Proposed mechanism for Cu based ILs catalyzed conversion of secondary amide/amine to tertiary amide/amine.

4. Conclusion

Copper based ionic liquid catalysts were found to be excellent catalysts for the synthesis of amides. Wide range of amides such as benzamide, 2-benzamido acetate, tertiary amides and their derivatives were successfully prepared in good to excellent yield. For easy recovery and recyclability, nanocrystalline silicalite supported Copper based ionic liquids were successfully prepared. Large external surface area and abundant surface silanol groups of nanocrystalline silicalite were important for the preparation of supported catalyst. Heterogenized Copper based ionic liquids were found to be efficient catalysts for these reactions. Supported Copper based ionic liquid catalysts exhibited no loss in the activity even after five recycles in the synthesis of benzamide. Hot filtration test further confirmed that catalyst was not leached during the reaction.

Acknowledgements

Authors thank Council of Scientific and Industrial Research, New Delhi for financial assistance (CSIR grant 01(2802)/14/EMR-II). Authors are also thankful to Director IIT Ropar for his constant encouragement.

Supporting Information

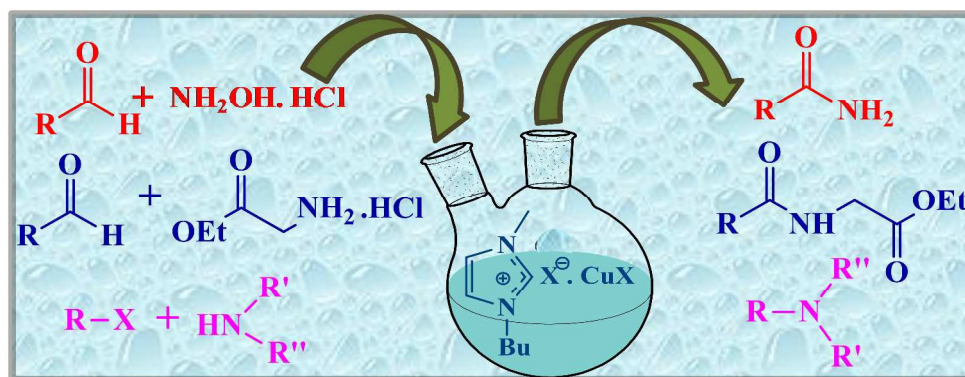
The Supporting Information contains additional characterization results.

References

1. J. P. Hallett and T. Welton, *Chem. Rev.*, 2011, **111**, 3508-3576.
2. N. V. Plechkova and K. R. Seddon, *Chem. Soc. Rev.*, 2008, **37**, 123-150.
3. R. D. Rogers and K. R. Seddon, *Science*, 2003, **302**, 792-793.
4. J. Dupont, R. F. De Souza and P. A. Z. Suarez, *Chem. Rev.*, 2002, **102**, 3667-3692.
5. S. Zhang, J. Sun, X. Zhang, J. Xin, Q. Miao and J. Wang, *Chem. Soc. Rev.*, 2014, **43**, 7838-7869.
6. M. A. P. Martins, C. P. Frizzo, D. N. Moreira, N. Zanatta and H. G. Bonacorso, *Chem. Rev.*, 2008, **108**, 2015-2050.
7. H. O. Bourbigou and L. Magna, *J. Mol. Catal. A: Chem.*, 2002, **182**, 419-437.
8. T. L. Greaves and C. J. Drummond, *Chem. Rev.*, 2008, **108**, 206-237.
9. J.E. Bara, *Ind. Engg. Chem. Res.*, 2011, **50**, 13614-13619.
10. B. Kaur and R. Srivastava, *Colloids Surf. B.*, 2014, **118**, 179-187.
11. B. Kaur and R. Srivastava, *Electrochim. Acta.*, 2014, **133**, 428-439.
12. C. J. Mathews, P. J. Smith, T. Welton, A. J. P. White and D. J. Williams, *Organometallics*, 2001, **20**, 3848-3850.
13. F. V. Rantwijk and R. A. Sheldon, *Chem. Rev.*, 2007, **107**, 2757-2785.
14. S. Pandey, *Anal. Chim. Acta.*, 2006, **556**, 38-45.
15. T. Erdmenger, C. G. Sanchez, J. Vitz, R. Hoogenboom and U. S. Schubert, *Chem. Soc. Rev.*, 2010, **39**, 3317-3333.
16. V. I. Parvulescu and C. Hardacre, *Chem. Rev.*, 2007, **107**, 2615-2665.
17. A. Ying, Z. Li, J. Yang, S. Liu, S. Xu, H. Yan and C. Wu, *J. Org. Chem.*, 2014, **79**, 6510-6516.
18. A. Ying, S. Xu, S. Liu, Y. Ni, J. Yang and C. Wu, *Ind. Eng. Chem. Res.*, 2014, **53**, 547-552.
19. A. Ying, Y. Ni, S. Xu, S. Liu, J. Yang and R. Li, *Ind. Eng. Chem. Res.*, 2014, **53**, 5678-5682.
20. A. Ying, S. Liu, J. Yang, and H. Hu, *Ind. Eng. Chem. Res.*, 2014, **53**, 16143-16147.
21. J. Yang, S. Liu, H. Hu, S. Ren and A. Ying, *Chinese J. Chem. Eng.*, 2015, **23**, 1416-1420.
22. A. Ying, Z. Li, Y. Ni, S. Xu, H. Hou and H. Hu, *J. Ind. Eng. Chem.*, 2015, **24**, 127-131.

23. Z. Ma, J. Yu and S. Dai, *Adv. Mater.*, 2010, **22**, 261-285.
24. R. Kore and R. Srivastava, *J. Mol. Catal. A: Chem.*, 2011, **345**, 117-126.
25. R. Kore and R. Srivastava, *Tetrahedron Lett.*, 2012, **53**, 3245-3249.
26. R. Kore, B. Satpati and R. Srivastava, *Chem. Eur. J.*, 2011, **17**, 14360-14365.
27. C. P. Mehnert, *Chem. Eur. J.*, 2005, **11**, 50-56.
28. C. P. Mehnert, R. A. Cook, N. C. Dispenziere and M. Afeworki, *J. Am. Chem. Soc.*, 2002, **124**, 12932-12933.
29. R. Kore, M. Tumma and R. Srivastava, *Catal. Today*, 2012, **198**, 189-196.
30. S. E. Allen, R. R. Walvoord, R. P. Salinas and M. C. Kozlowski, *Chem. Rev.*, 2013, **113**, 6234-6458.
31. G. Evano, N. Blanchard and M. Toumi, *Chem. Rev.*, 2008, **108**, 3054-3131.
32. I. P. Beletskaya and A. V. Cheprakov, *Coord. Chem. Rev.*, 2004, **248**, 2337-2364.
33. R. Raudaskoski, E. Turpeinen, R. Lenkkeri, E. Pongrácz and R. L. Keiski, *Catal. Today*, 2009, **144**, 318-323.
34. M. Behrens, F. Studt, I. Kasatkin, S. Köhl, M. Hävecker, F. A. Pedersen, S. Zander, F. Girgsdies, P. Kurr, B. L. Knief, M. Tovar, R. W. Fischer, J. K. Nørskov and R. Schlögl, *Science*, 2012, **336**, 893-897.
35. P. Rani and R. Srivastava, *Tetrahedron Lett.*, 2014, **55**, 5256-5260.
36. B. Kaur, M. Tumma and R. Srivastava, *Ind. Eng. Chem. Res.*, 2013, **52**, 11479-11487.
37. J. G. Huddleston, A. E. Visser, W. M. Reichert, H. D. Willauer, G. A. Broker and R.D. Rogers, *Green Chem.*, 2001, **3**, 156-164.
38. F. Liu, L. Li, S. Yu, Z. Lv and X. Ge, *J. Hazard. Mater.*, 2011, **189**, 249-254.
39. A. M. Al-Sabagh, F. Z. Yehia, A. M. F. Eissa, M. E. Moustafa, Gh. Eshaq, A. M. Rabie and A. E. ElMetwally, *Polym. Degrad. Stab.*, 2014, **110**, 364-377.
40. W. Song, R. E. Justice, C. A. Jones, V. H. Grassian and S. C. Larsen, *Langmuir*, 2004, **20**, 4696-4702.
41. Y. Wang, D. Zhu, L. Tang, S. Wang and Z. Wang, *Angew. Chem. Int. Ed.*, 2011, **50**, 8917-8921.
42. S. Rostamnia, N. Nouruzi, H. Xin and R. Luque, *Catal. Sci. Technol.*, 2015, **5**, 199-205.
43. K. Yamaguchi, H. Kobayashi, T. Oishi and N. Mizuno, *Angew. Chem. Int. Ed.*, 2012, **51**, 544-547.

44. S. Ghosh, A. Bhaumik, J. Mondal, J. A. Mallik, S. Sengupta and C. Mukhopadhyay, *Green Chem.*, 2012, **14**, 3220-3229.
45. K. Shimizu, K. Ohshima and A. Satsuma, *Chem. Eur. J.*, 2009, **15**, 9977-9980.
46. D. Saberi and A. Heydari, *Tetrahedron Lett.*, 2013, **54**, 4178-4180.
47. A. S. Kumar, B. Thulasiram, S. B. Laxmi, V. S. Rawat and B. Sreedhar, *Tetrahedron*, 2014, **70**, 6059-6067.
48. K. Azizi, M. Karimi and A. Heydari, *Tetrahedron Lett.*, 2015, **56**, 812-816.
49. D. Saberi, S. Mansoori, E. Ghaderi and K. Niknam, *Tetrahedron Lett.*, 2016, **57**, 95-99.

Graphical Abstract**Highly efficient and recyclable copper based ionic liquid catalysts for amide synthesis***Poonam Rani and Rajendra Srivastava**

Copper based ionic liquids have been successfully prepared for the synthesis of primary, secondary and tertiary amides under mild reaction condition.