

Bis (1(3-trimethoxysilylpropyl)-3-methyl-imidazolium) copper tetrachloride attached to colloidal silica nanoparticles as an efficient catalyst for the preparation of propargylamines

Javad Safaei-Ghomi¹ · Seyed Hadi Nazemzadeh¹ · Hossein Shahbazi-Alavi¹

Received: 24 March 2017/Accepted: 12 July 2017 © Springer Science+Business Media B.V. 2017

Abstract In this research, we reported the successful preparation of bis (1(3trimethoxysilylpropyl)-3-methyl-imidazolium) copper tetrachloride tethered to colloidal silica nanoparticles and investigated its catalytic application for one-pot multicomponent preparation of propargylamines under microwave irradiation. Ionic liquid tethered to colloidal silica nanoparticles have been characterized by H NMR spectroscopy, scanning electron microscopy, energy dispersive spectroscopy, thermogravimetric analysis, and dynamic light scattering.

Graphical Abstract



Javad Safaei-Ghomi safaei@kashanu.ac.ir

Electronic supplementary material The online version of this article (doi:10.1007/s11164-017-3081-6) contains supplementary material, which is available to authorized users.

¹ Department of Organic Chemistry, Faculty of Chemistry, University of Kashan, Kashan, P.O. Box 87317-51167, Islamic Republic of Iran

Keywords Ionic liquid · Microwave · Colloidal silica nanoparticles · Propargylamines · Nanocatalyst · Multi-component reaction

Introduction

Propargylamines exhibit biological activities including anti-Parkinson's [1, 2], treatment of Alzheimer's disease [3, 4], anti-apoptotic [5], and oxidases inhibitors [6]. Propargylamines have been used as significant substrates and intermediates for the synthesis of diverse nitrogen compounds as imidazolidinones [7], oxazolidinones [8], pyrroles [9], pyrrolidines [10], quinolones [11], indolines [12], and pyridines [13]. Lately, reports have been presented on preparation of chiral allenes from chiral propargylamines using zinc iodide [14], silver nitrate [15], potassium gold(III) chloride [16], and zinc bromide [17]. Therefore, the advancement of easy procedures for the preparation of propargylamines is still favorable and in demand. The preparation of propargylamines has been achieved using different catalysts such as CuBr [18], PbS-Au [19], gold(III) salen [20], Cu(OH)_x-Fe₃O₄ [21], Zn(OAc)₂ 2H₂O [22], copper(I) in ionic liquids [23], copper(I)-bisimine complexes [24], zinc dust [25], copper zeolites [26], NiCl₂ [27], AgY zeolite [28], Cu-MOFs [29], and CuSBA-15 [30]. However, some of the reported methods endure drawbacks including long reaction times and undesirable reaction conditions. Hence, to avoid these restrictions, the exploration of an effective, rapidly accessible catalyst with high catalytic activity for the preparation of propargylamines is still favored. Recently, preparation and immobilization of ionic liquids (ILs) on nanoparticles have been widely considered [31–37]. Although ionic liquids encompass some use, their effective applications have been limited by some problems in their recovery, which lead to economic and environmental difficulties. These problems can be dominated by immobilization of ILs onto nanoparticles to obtain heterogeneous catalysts [38, 39]. Watanabe and co-workers have reported systematic investigations of colloidal stability, ionic transport, and viscoelastic properties of nanocomposites based on silica nanoparticles dispersed in ILs [40-43]. The authors exhibited that the surface chemistry and volume fraction of the particles can be used to control the stability and flow properties of the nanomaterials. The ionic liquids can be used as templates to functionalized silica under different conditions [44, 45]. Silica-based materials, particularly silica nanomaterials, exhibit numerous applications in many research areas including bionanomaterials, coating materials, and the development of surface modification of nanocatalysts because of their biocompatibility, chemical stability, and easy surface modification [46–48]. The structures of 1-ethyl-3methylimidazolium (Emim) and 1-butyl-3-methylimidazolium (Bmim) with transition metal chloride anions including $NiCl_4^{2-}$, $CoCl_4^{2-}$, and $PdCl_4^{2-}$ were studied [49–51]. Herein we reported the preparation of bis (1(3-trimethoxysilylpropyl)-3methyl-imidazolium) copper tetrachloride tethered to colloidal silica nanoparticles and investigated its catalytic application for one-pot multicomponent preparation of propargylamines under microwave irradiation (Scheme 1).



Scheme 1 Preparation of propargylamines using ionic liquid tethered to colloidal silica nanoparticles

Experimental

General

We used the Milestone microwave (Microwave Labstation, MLS GmbH-ATC-FO 300) for synthesis. NMR spectra were recorded on a Bruker 400 MHz spectrometer with CDCl₃ as solvent and TMS as internal standard. CHN compositions were measured with a Carlo ERBA Model EA 1108 analyzer. DLS was accomplished with Malvern. In order to study the morphology and particle size of the synthesis structures MNPs, FE-SEM images and EDS spectra of the products were visualized by a Sigma ZEISS, Oxford Instruments Field Emission Scanning Electron Microscope. The temperature-programmed desorption of ammonia (NH₃-TPD) was obtained using Auto Chem. II 2920 equipment.

Preparation of ionic liquid/nano-colloidal silica

In a typical procedure, 0.098 mL of colloidal silica nanoparticles (LUDOX SM colloidal silica 30 wt.% suspension in H₂O) was diluted in 3 mL of deionized water, and 1.8 mmol of 1-(3-trimethoxysilylpropyl)-3-methyl-imidazolium chloride (IL) was added slowly with continuous stirring during 1 h. Then, 0.15 g of CuCl₂·2H₂O was added and refluxed for 24 h. After 24 h, IL functionalized silica nanoparticles was separated by centrifugation and washed with acetone and methanol for four times, then, IL/Cu²⁺/SiO₂ was dried by lyophilization/freeze-drying. The purity of the resultant IL/Cu²⁺/SiO₂ was confirmed using ¹H NMR spectrum. The Cu loading was measured using XRF to be 4.7 wt.%.

General procedure for the preparation of propargylamines

A mixture of morpholine or piperidine (1.2 mmol), benzaldehydes (1 mmol), phenylacetylene (1.2 mmol), and 10 mg of bis (1(3-trimethoxysilylpropyl)-3-methyl imidazolium) copper tetrachloride tethered to silica nanoparticles (nanocatalyst) in toluene (15 mL) was irradiated in a microwave oven at 50 °C and 400 W for the time indicated in Tables 1 and 2. After completion of the reaction (monitored by TLC), ethyl acetate was added. The catalyst was insoluble in ethyl acetate and it could, therefore, be recycled by a simple filtration. The crude product obtained was purified by column chromatography using ethyl acetate-*n*-hexane to afford the pure desired product. The structures of the products were studied using ¹H NMR and ¹³C NMR spectra (see supporting information).

Table 1 Optimization of reaction conditions using different catalysts under microwave irradiation (300-500 W)



	1a	2b 3	4a	
Entry	Solvent (MWI)	Catalyst	Time (min)	Yield (%) ^b
1	Toluene (400 W)	No catalyst	45	7
2	H ₂ O (500 W)	CuCl ₂ (5 mol%)	35	45
3	Toluene (400 W)	Fe ₃ O ₄ (4 mol%)	35	18
4	Toluene (400 W)	ZrOCl ₂ (3 mol%)	35	33
5	Toluene (400 W)	ZnO (4 mol%)	35	39
6	Toluene (400 W)	Ni(OAC)2 (2 mol%)	35	40
7	Toluene (400 W)	IL/silica (200-600 mesh) (15 mg)	30	60
8	Toluene (400 W)	IL/nano-Fe ₃ O ₄ (12 mg)	25	64
9	CH ₂ Cl ₂ (400 W)	IL ^a /nano-colloidal silica (10 mg)	30	55
10	THF (400 W)	IL/nano-colloidal silica (10 mg)	30	68
11	Toluene (300 W)	IL/nano-colloidal silica (10 mg)	25	77
12	Toluene (400 W)	IL/nano-colloidal silica (8 mg)	25	83
13	toluene (400 W)	IL/nano-colloidal silica (10 mg)	25	86
14	Toluene (400 W)	IL/nano-colloidal silica (12 mg)	25	86
15	Toluene (500 W)	IL/nano-colloidal silica (10 mg)	25	86

Phenylacetylene (1.2 mmol), morpholine (1.2 mmol), and benzaldehyde (1 mmol)

^a Bis (1(3-trimethoxysilylpropyl)-3-methyl-imidazolium) copper tetrachloride = ionic liquid = IL

^b Isolated yield

	R H H	+ ^{IL} Ph	/nano-colloidal silica MWI (400 W) toluene		Ph
	X= C, O	l l		X= C, O	
Entry	Amine	R	Product	Time (min)	Yield (%) ^a
1	Morpholine	Н	4a	25	86
2	Morpholine	4-Cl	4b	25	90
3	Morpholine	2-Me	4c	30	82
4	Morpholine	4-Me	4d	30	84
5	Morpholine	2-Cl	4 e	25	88
6	Piperidine	$4-NO_2$	4f	25	94
7	Piperidine	4-OMe	4g	30	82
8	Piperidine	2-Cl	4h	25	90
9	Piperidine	3-Me	4i	30	85
10	Piperidine	4-Br	4j	25	93
11	Piperidine	Н	4k	25	88
12	Piperidine	4-Cl	41	25	92

 Table 2
 Synthesis of propargylamines using ionic liquid/nano-colloidal silica (nanocatalyst)

Phenylacetylene (1.2 mmol), morpholine or piperidine (1.2 mmol) arylaldehydes (1 mmol), and nanocatalyst (10 mg) in toluene under microwave irradiation (400 W)

^a Isolated yield

Results and discussion

Characterization of the nanocatalyst

Figure 1a and b exhibit the ¹H NMR spectra for the 1(3-trimethoxysilylpropyl)-3methyl-imidazolium chloride and bis (1(3-trimethoxysilylpropyl)-3-methyl-imidazolium) copper tetrachloride tethered to colloidal silica nanoparticles in dimethyl sulfoxide (DMSO), respectively. The H NMR spectra of both materials are consistent with expected results for untethered and silica-tethered ionic liquids. Meanwhile, the ¹³C NMR spectrum for the bis (1(3-trimethoxysilylpropyl)-3methyl-imidazolium) copper tetrachloride tethered to colloidal silica nanoparticles in DMSO is shown in Figure S1 (see supplementary information).

Figure 2 shows FE-SEM image of bis (1(3-trimethoxysilylpropyl)-3-methylimidazolium) copper tetrachloride tethered to silica nanoparticles (nanocatalyst). The SEM image displays particles with diameters in the nanometer range. Figure 3 represents the TEM (Transmission electron microscope) image of nanocatalyst. These nanoparticles with a diameter of 25–35 nm exhibit a uniform spherical shape.



◄ Fig. 1 a ¹H NMR spectrum of 1(3-trimethoxysilylpropyl)-3-methyl-imidazolium chloride and b bis (1(3-trimethoxysilylpropyl)-3-methyl-imidazolium) copper tetrachloride tethered to colloidal silica nanoparticles (nanocatalyst) in dimethyl sulfoxide (DMSO)









In order to investigate the size distribution of nanocatalysts, DLS (dynamic light scattering) measurements of the nanoparticles were showed in Fig. 4.

The elemental compositions of the nanocatalyst were studied by energy dispersive spectroscopy (EDS). EDS confirmed the attendance of Si, O, N, C, Cl, and Cu in the compound (Fig. 5).



Fig. 4 DLS of nanocatalyst



Fig. 5 EDS of nanocatalyst

Thermogravimetric analysis (TGA) considers the thermal stability of the ionic liquid of untethered to SiO_2 (pure ionic liquid) and silica-tethered ionic liquids (Fig. 6). The curve displays a weight loss about 36.8% for ionic liquid/nano-colloidal silica from 240 to 550 °C, resulting from the destruction of organic spacer attaching to the nanoparticles. Hence, the nanocatalyst was stable up to 240 °C, confirming that it could be stably used in organic reactions at temperatures in the range of 80–160 °C.



Fig. 6 TGA of IL and nanocatalyst

The amount of acid sites can be calculated by NH₃-TPD. The total acidity (mmol NH₃ g_{cat}^{-1}) of catalyst was 0.32. Lewis acidic ionic liquids with anions based on CuCl₂ are mainly responsible for acidity activity.

Investigation of catalytic activity for synthesis of propargylamines

After characterizing the nanocatalysts, we evaluated and optimized diverse reaction parameters for the preparation of propargylamines by the reaction of phenylacetylene, morpholine, and benzaldehyde as a model reaction. To obtain the desire reaction conditions for the synthesis of compound 4a, we investigated some catalysts and solvents under microwave irradiation (Table 1). Screening of different catalysts such as CuCl₂, Fe₃O₄, ZrOCl₂, ZnO, Ni(OAC)₂, and nanocatalyst (ionic liquid/nano-colloidal silica) revealed ionic liquid/nano-colloidal silica as the most effective catalyst to perform this reaction under microwave irradiation. In further studies on the catalyst loading, we realized that yield of compound 4a remained almost the same when 12 mg of liquid/nano-colloidal silica was used (Table 1). Use of lower catalyst loading (8 mg) afforded 4a in 83% yield. In this study, microwave irradiation is used as a green and beneficial method for preparation of propargylamines. In order to investigate the effect of intensity of microwave power on reaction, the reaction was also performed at different powers of the microwave irradiation (Table 1). The best results were obtained under microwave irradiation (400 W) in toluene and the reaction gave satisfying results in the presence of bis (1(3-trimethoxysilylpropyl)-3-methyl-imidazolium) copper tetrachloride (ionic liquid) tethered to colloidal silica nanoparticles as catalyst.

With these acceptable results in hand (Table 1, entry 13), we then investigated the feasibility of the reaction using diverse aromatic aldehydes as substrates. The



Scheme 2 Mechanism for the synthesis of propargylamines using ionic liquid-tethered to colloidal silica nanoparticles

results show the present catalytic method is extensible to a wide diversity of substrates to create a variety-oriented library of propargylamines.

A proposed mechanism for the synthesis of propargylamines using nanocatalyst is shown in Scheme 2. At the start, the activated aldehyde by nanocatalyst is condensed with the secondary amine to give an iminium ion in situ, meanwhile, the nanocatalyst activates the C–H bond of the terminal alkyne to generate a copperacetylide intermediate. The copper-acetylide intermediate then undergoes nucleophilic attack onto the iminium ion to give propargylamines [52–55]. In the present study Cu^{II}-IL/SiO₂ itself acts as the active catalyst generating an initial copper(II) acetylide intermediate by the reaction between a Cu^{II} species in IL/SiO₂ with a terminal alkyne. This copper acetylide intermediate reacts with the iminium ion generated in situ from activated aldehyde and amine to give the corresponding propargylamine. The Cu^{II}-IL/SiO₂ catalyst is regenerated for subsequent reactions. Cu^{II} specie in ionic liquid is more accessible to organic substrates than other catalysts containing of Cu^{II} species.

We also considered reusability of the bis (1(3-trimethoxysilylpropyl)-3-methylimidazolium) copper tetrachloride tethered to colloidal silica nanoparticles (IL/ $Cu^{2+/}SiO_2$) as a catalyst under microwave irradiation for the synthesis of product **4a**, and it was found that product yields decreased to a small extent on each reuse (run 1, 86%; run 2, 86%; run 3, 85%; run 4, 85%; run 5, 84%). (Fig S2; see supplementary information). After completion of the reaction, ethyl acetate was added. The catalyst was insoluble in ethyl acetate and it could, therefore, be recycled by centrifuging. The nanoparticles were then washed three to four times with dichloromethane. The recycling ability of the catalyst was tested for five runs, providing almost similar yields of the desired product. The extreme stability of the nanocatalyst is mainspring of the continuous and high catalytic activity. The morphology of nanoparticles was investigated by scanning electron microscopy (SEM) before use and after reusing five times, as shown in Fig S3 (see supplementary information). Interestingly, the shape and size of the nanoparticles remained unchanged before and after reaction. We suppose that, this is also the possible reason for the extreme stability of the nanoparticles presented herein.

Conclusion

In conclusion, we demonstrated an efficient method for the preparation of propargylamines using ionic liquid tethered to colloidal silica nanoparticles under microwave irradiation. The present catalyst provides active sites for the synthesis of propargylamines. The advantages of this method are the use of an efficient catalyst, little catalyst loading, short reaction times, use of microwaves as clean method, and excellent yields.

Acknowledgements The authors are grateful to the University of Kashan for supporting this work by Grant NO: 463562/VI.

References

- 1. M. Yogev-Falach, T. Amit, O. Bar-Am, M.B.H. Youdim, FASEB J. 17, 2325 (2003)
- 2. J.J. Chen, D.M. Swope, J. Clin. Pharmacol. 45, 878 (2005)
- 3. I. Bolea, A. Gella, M. Unzeta, J. Neural. Transm. 120, 893 (2013)
- A. Samadi, C. De Los Ríos, I. Bolea, M. Chioua, I. Iriepa, I. Moraleda, M. Bartolini, V. Andrisano, E. Gálvez, C. Valderas, M. Unzeta, J. Marco-Contelles, Eur. J. Med. Chem. 52, 251 (2012)
- 5. W. Maruyama, T. Yamamoto, K. Kitani, M.C. Carrillo, M. Youdim, M. Naoi, Mech. Ageing Dev. 116, 181 (2000)
- 6. H.B. Jeon, L.M. Sayre, Biochem. Biophys. Res. Commun. 304, 788 (2003)
- 7. M. Shi, Y.M. Shen, J. Org. Chem. 67, 16 (2002)
- 8. E.S. Lee, H.S. Yeom, J.H. Hwang, S. Shin, Eur. J. Org. Chem. 2007, 3503 (2007)
- 9. J. Weng, Y. Chen, B. Yue, M. Xu, H. Jin, Eur. J. Org. Chem. 2015, 3164 (2015)
- S. Morikawa, S. Yamazaki, Y. Furusaki, N. Amano, K. Zenke, K. Kakiuchi, J. Org. Chem. 71, 3540 (2006)
- 11. Y. Luo, Z. Li, C.J. Li, Org. Lett. 7, 2675 (2005)
- 12. D. Chernyak, N. Chernyak, V. Gevorgyan, Adv. Synth. Catal. 352, 961 (2010)
- 13. D.N. Penk, N.A. Robinson, H.M. Hill, M. Turlington, Tetrahedron Lett. 58, 470 (2017)
- 14. M. Periasamy, P.O. Reddy, N. Sanjeevakumar, Eur. J. Org. Chem. 2013, 3866 (2013)
- 15. V.K.Y. Lo, C.Y. Zhou, M.K. Wong, C.M. Che, Chem. Commun. 46, 213 (2010)
- 16. V.K.Y. Lo, M.K. Wong, C.M. Che, Org. Lett. 10, 517 (2008)
- 17. M. Periasamy, N. Sanjeevakumar, M. Dalai, R. Gurubrahamam, P.O. Reddy, Org. Lett. 14, 2932 (2012)

- 18. N. Gommermann, C. Koradin, K. Polborn, P. Knochel, Angew. Chem. Int. Ed. 42, 5763 (2003)
- 19. L.L. Chng, J. Yang, Y. Wei, J.Y. Ying, Adv. Synth. Catal. 351, 2887 (2009)
- 20. V.K.Y. Lo, Y. Liu, M.K. Wong, C.M. Che, Org. Lett. 8, 1529 (2006)
- 21. M.J. Aliaga, D.J. Ramón, M. Yus, Org. Biomol. Chem. 8, 43 (2010)
- 22. E. Ramu, R. Varala, N. Sreelatha, S.R. Adapa, Tetrahedron Lett. 48, 7184 (2007)
- 23. S.B. Park, H. Alper, Chem. Commun. 2005, 1315 (2005)
- 24. F. Colombo, M. Benaglia, S. Orlandi, F. Usuelli, G. Celentano, J. Org. Chem. 71, 2064 (2006)
- M.L. Kantam, V. Balasubrahmanyam, K.B.S. Kumar, G.T. Venkanna, Tetrahedron Lett. 48, 7332 (2007)
- 26. M.K. Patil, M. Keller, B.M. Reddy, P. Pale, J. Sommer, Eur. J. Org. Chem. 2008, 4440 (2008)
- 27. S. Samai, G.C. Nandi, M.S. Singh, Tetrahedron Lett. 51, 5555 (2010)
- 28. R. Maggi, A. Bello, C. Oro, G. Sartori, L. Soldi, Tetrahedron 64, 1435 (2008)
- 29. I. Luz, F.X.L. Xamena, A. Corma, J. Catal. 285, 285 (2012)
- 30. M. Srinivas, P. Srinivasu, S.K. Bhargava, M.L. Kantam, Catal. Today 208, 66 (2013)
- 31. J. Huang, T. Jiang, H. Gao, B. Han, Z. Liu, W. Wu, Y. Chang, G. Zhao, Angew. Chem. Int. Ed. 43, 1397 (2004)
- 32. R. Sandaroos, S. Damavandi, H.R. Molaei, Res. Chem. Intermed. 41, 1517 (2015)
- 33. D. Habibi, A. Shamsian, Res. Chem. Intermed. 41, 6245 (2015)
- 34. J. Safaei-Ghomi, R. Sadeghzadeh, H. Shahbazi-Alavi, RSC. Adv. 6, 33676 (2016)
- 35. H. Valizadeh, M. Amiri, A. Shomali, F. Hosseinzadeh, J. Iran. Chem. Soc. 8, 495 (2011)
- 36. M.V. Khedkar, T. Sasaki, B.M. Bhanage, ACS Catal. 3, 287 (2013)
- 37. J.Y. Jung, J.B. Kim, A. Taher, M.J. Jin, Bull. Korean Chem. Soc. 30, 3082 (2009)
- 38. S.S. Moganty, S. Srivastava, Y. Lu, J.L. Schaefer, S.A. Rizvi, L.A. Archer, Chem. Mater. 24, 1386 (2012)
- O.P. Khatri, K. Adachi, K. Murase, K.I. Okazaki, T. Torimoto, N. Tanaka, S. Kuwabata, H. Sugimura, Langmuir 24, 7785 (2008)
- 40. K. Ueno, A. Inaba, M. Kondoh, M. Watanabe, Langmuir 24, 5253 (2008)
- 41. K. Ueno, A. Inaba, Y. Sano, M. Kondoh, M. Watanabe, Chem. Commun. 24, 3603 (2009)
- 42. K. Ueno, S. Imaizumi, K. Hata, M. Watanabe, Langmuir 25, 825 (2009)
- 43. K. Ueno, Y. Sano, A. Inaba, M. Kondoh, M. Watanabe, J. Phys. Chem. B 114, 13095 (2010)
- 44. T. Wang, H. Kaper, M. Antonietti, B. Smarsly, Langmuir 23, 1489 (2007)
- 45. Y. Zhou, J.H. Schattka, M. Antonietti, Nano Lett. 4, 477 (2004)
- 46. H. Wei, L. Zhou, J. Li, J. Liu, E. Wang, J. Colloid Interface Sci. 321, 310 (2008)
- 47. M. Cho, W.S. Cho, M. Choi, S.J. Kim, B.S. Han, S.H. Kim, H.O. Kim, Y.Y. Sheen, J. Jeong, Toxicol. Lett. 189, 177 (2009)
- 48. J. Safaei-Ghomi, H. Shahbazi-Alavi, P. Babaei, Z. Naturforsch. 71, 849 (2016)
- 49. P.B. Hitchcock, K.R. Seddon, T. Welton, J. Chem. Soc., Dalton Trans. 17, 2639 (1993)
- 50. J.E.L. Dullius, P.A.Z. Suarez, S. Einloft, R.F. de Souza, J. Dupont, Organometallics 17, 815 (1998)
- 51. C. Zhong, T. Sasaki, M. Tada, Y. Iwasawa, J. Catal. 242, 357 (2006)
- 52. B. Karimi, M. Gholinejad, M. Khorasani, Chem. Commun. 48, 8961 (2012)
- 53. Z. Zarei, B. Akhlaghinia, RSC Adv. 6, 106473 (2016)
- J.V. Madhav, B.S. Kuarm, P. Someshwar, B. Rajitha, Y.T. Reddy, P.A. Crooks, Synth. Commun. 38, 3215 (2008)
- 55. S. Kaur, M. Kumar, V. Bhalla, Chem. Commun. 51, 16327 (2015)