

## Short communication

# Nano-SiO<sub>2</sub>@[DABCO(CH<sub>2</sub>CH<sub>2</sub>CO<sub>2</sub>H)]<sup>+</sup>[Br]<sup>-</sup> as an efficient and recyclable SCILL for water mediated facile synthesis of thiol-substituted N-aryl pentasubstituted pyrroles

Priya Mondal<sup>a</sup>, Sauvik Chatterjee<sup>b</sup>, Khondekar Nurjamal<sup>c</sup>, Suwendu Maity<sup>d</sup>, Asim Bhaumik<sup>b</sup>, Goutam Brahmachari<sup>c</sup>, Prasanta Ghosh<sup>d</sup>, Chhanda Mukhopadhyay<sup>a,\*</sup>

<sup>a</sup> Department of Chemistry, University of Calcutta, 92 APC Road, Kolkata 700009, India

<sup>b</sup> Department of Materials Science, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700 032, India

<sup>c</sup> Laboratory of Natural products & Organic Synthesis, Department of Chemistry, Visva-Bharati (a Central University), Santiniketan 731235, India

<sup>d</sup> Department of Chemistry, R. K. Mission Residential College, Narendrapur, Kolkata 700103, India

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## ABSTRACT

Nano sized silica supported DABCO based amphoteric ionic liquid coated combined catalytic system Nano-SiO<sub>2</sub>@[DABCO(CH<sub>2</sub>CH<sub>2</sub>CO<sub>2</sub>H)]<sup>+</sup>[Br]<sup>-</sup> has been synthesised in a very simple and convenient way. This newly synthesised SCILL has been characterised via FT-IR, SEM, HRTEM and EDAX spectra. The high efficiency of this catalyst was unquestionably recognised when 31 new thiol induced penta-substituted pyrroles were synthesised in water via two different schemes in high yields. This recyclable, quasi heterogeneous catalyst shows synergetic catalytic effect of acidic nano sized silica particles and amphoteric DABCO based ionic liquid.

## 1. Introduction

In the present times, the rising environmental pollution and its rigorous effect on recent world have attracted significant consideration [1,2]. It is vital to follow environmental benignity of chemical processes employing atom efficient procedures, green solvents, eliminating by-products or toxic materials and most importantly easy work-up and energy consumption methods [3]. All these criteria can be easily achievable by using an efficient catalyst [4,5]. Ionic liquids, starting their journey since 1914, have caused a radical change in synthetic chemistry [6]. Although the ionic liquid (IL) was initially introduced as a green solvent, has marched far beyond today, showing its significant role as solvent, catalyst, co-catalyst or sometimes dual solvent catalyst [7–9]. Functionalized ILs having acidic and basic functional groups have acted as “task-specific ionic liquids” in particular reactions [10,11]. 1, 4-Diazabicyclo [2.2.2] octane (DABCO), a cage-like tertiary amine is a very good alternative precursor for ionic liquid preparation to the previous imidazoles, pyrimidines and linear tertiary amines [12,13]. In spite of various importance of ionic liquids such as high boiling point, low vapour pressure and recyclability, they suffer from some drawbacks such as complex product separation, cumbersome catalyst revival and the use of mass amounts of ILs in biphasic systems resulting in outsized cost and instigate toxicological concerns [14,15].

It, therefore, leads to limited application of ionic liquid in chemical industry. Hence, supported IL systems are receiving up-growing interest in synthetic chemistry [16–18]. Supported Catalyst with Ionic Liquid Layer (SCILL) is the well known name of this category of catalyst [19]. High surface area of nanoparticles (NPs) favours the contact of the active sites of nanoparticles with ionic liquids to form the combined catalytic system. Among them, mesoporous silica nanoparticles act as a well known and well-established support system [20,21]. Combination of IL@NP system was achieved by two different immobilisation processes; either by covalent attachment of ionic liquids to the support surface or by depositing the ionic liquid phases on to the surface of the support system due to electronic interaction [22]. This is a quasi heterogeneous catalyst where advantages of both the homogenous and heterogeneous catalysts are united [23]. Nano sized silica acted as a very good heterogeneous catalyst whereas ionic liquids are highly dispersible in aqueous medium showing homogeneous nature [24].

Synthetic chemists are highly focused for developing various heterocyclic moieties [25,26]. Biological activities of these compounds offer interdisciplinary research area for organic, pharmaceutical, analytical and medicinal chemists [27]. Among all the heterocyclic compounds, pyrroles have a prominent position as it is the key structural part of living organisms like porphyrins, chlorins, and the corrins found in respectively heme, chlorophyll and vitamin B12 [28]. Pyrrole is also

\* Corresponding author.

E-mail address: [cmukhop@yahoo.co.in](mailto:cmukhop@yahoo.co.in) (C. Mukhopadhyay).

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the core structural framework of valuable drugs like top-selling cholesterol-lowering agent atorvastatin, the anticancer drug sunitinib or tallimustine, the analgesic drug zomepirac, the anthelmintic agent pyrvinium, and the anti-inflammatory drug tolmetin [29,30]. Pyrrole derived compounds are successful as COX-1/COX-2 inhibitors and also show cytotoxic activity against a variety of marine and human tumor models [31]. Pyrrole-derived compounds acted as very good anti-HIV, antibacterial, antifungal, antitumoral, antimalarial and antioxidant agent. [32] Apart from pharmaceutical industry, pyrrole moieties have notable importance in material science and supramolecular chemistry. For instance, polypyrroles are utilised as conducting materials in the preparation of electroluminescence devices whereas pyrrolic macrocycles are utilised as anion receptors [33]. Consequently, environmentally benevolent synthetic methodologies are still being developed for this compound class, although there are many conventional methods [34]; Since our research works are focused for the development of various organic compounds by the application of environmentally benign synthetic methodology, we also engaged ourselves for the development of a new series of pyrrole compounds. To the best of our knowledge, there was no previous report of aromatic and aliphatic thiol substituted pyrrole compounds. All the 31 new compounds of these two series have been successfully synthesised from water mediated reaction with the strong assistance of our synthesised Nano-SiO<sub>2</sub>@[DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup> (Nano-SiO<sub>2</sub>@IL).

## 2. Experimental

Please see Electronic Supporting Information (ESI 1).

## 3. Results and discussion

In order to obtain water mediated thiol induced pyrrole moieties from easily available starting materials, we have devoted a large part of our research for the synthesis of a quasi heterogeneous catalyst. Our newly synthesised Nano-SiO<sub>2</sub>@IL established itself as an efficient catalyst in this ongoing project. This catalyst has been characterised thoroughly by different spectral analysis

### 3.1. Catalyst characterisation

#### 3.1.1. NMR spectrum of [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup>

Our synthesised DABCO based amphoteric ionic liquid was first characterised by <sup>1</sup>H and <sup>13</sup>C NMR spectra (Fig. S1, ESI), obtained from Bruker 300 MHz instrument at 300 and 75 MHz, respectively. This NMR data suggest that the broad singlet peak at  $\delta$  3.97 ppm correspond to hydrogen atom attached with quaternary N atom, not of carboxylic hydrogen atom. Carboxylic group might be present as a carboxylate anion form in the solution phase ensuing extremely charged species

#### 3.1.2. HRMS spectra of [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup>

Synthesis of [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup> was again confirmed by HRMS spectra (fig. S2, ESI 1). The HRMS data of [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup> shows a molecular ion peak at  $m/z = 185.1281$

#### 3.1.3. FT-IR spectra of Nano-SiO<sub>2</sub>@IL

The infrared (IR) spectra were recorded in attenuated total reflection (ATR) mode in Perkin-Elmer Spectrum 100 spectrophotometer (Fig. 1). The IR analysis study for the SiO<sub>2</sub>@IL shows the presence of both SiO<sub>2</sub> and IL in one catalytic system. In the combined catalytic system, absorption bands at 802 cm<sup>-1</sup> and 1102 cm<sup>-1</sup> corresponds to symmetric stretching vibration and asymmetric stretching vibration of the Si-O-Si bond respectively. The strong absorption peak at 1642 cm<sup>-1</sup> corresponds to carbonyl group of carboxylic acid whereas absorption band at 3446 cm<sup>-1</sup> correspond to -OH stretching frequency of the active catalytic species, i.e. DABCO based amphoteric ionic liquid

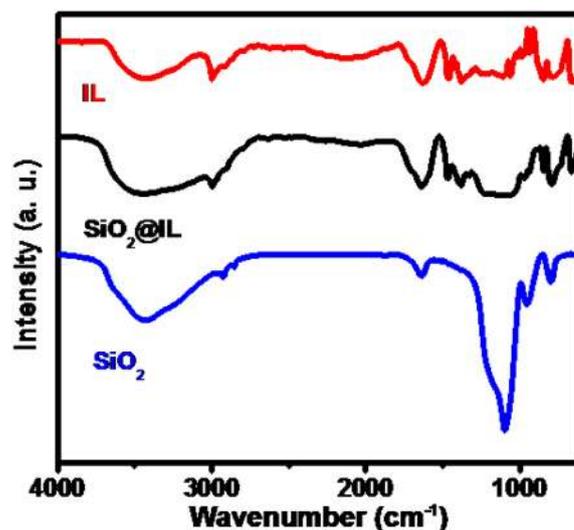


Fig. 1. FT-IR spectra of IL, SiO<sub>2</sub> and IL@SiO<sub>2</sub> in one frame.

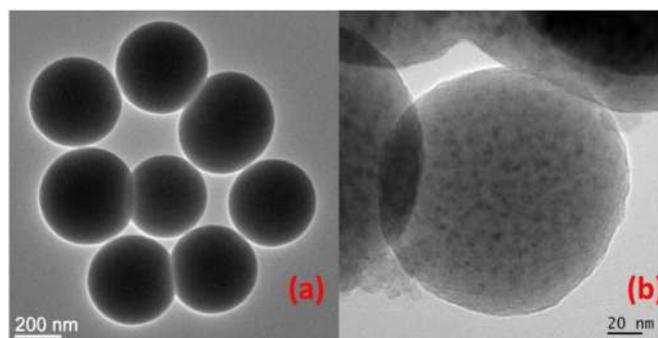


Fig. 2. HRTEM image of uncapped SiO<sub>2</sub> (a); and capped SiO<sub>2</sub> (b) in different magnification.

#### 3.1.4. HRTEM images analysis along with EDAX

The high resolution transmission electron microscopy images were recorded using JEOL JEM 2010 transmission electron microscopy (Fig. 2). The sample was prepared by dispersing the sample into ethanol and drop-casted that on carbon coated copper grid. The elemental composition was confirmed using EDAX data (fig. S3, ESI 1). The data shows that for SiO<sub>2</sub>@IL the presence of Si, O and Br. The elemental composition of the Nano-SiO<sub>2</sub>@IL shows 7.5 times SiO<sub>2</sub> was immobilised on the ionic liquid by weight. The morphology obtained from different parts of the grid reveals formation of uniformly distributed spherical SiO<sub>2</sub> nano particle with particle diameter 80–150 nm the presence of ionic liquid was also evident from the TEM images. When the synthesis was carried out without use of the ionic liquid the SiO<sub>2</sub> particle diameter was 350–400 nm. The smaller SiO<sub>2</sub> nano-particle formation can be explained due to the presence of the ionic liquid which played a capping role during the nano-particle formation. In-situ addition of IL controls the growth of nanoparticle formation, prevents the agglomeration of nano sized oxide particles

#### 3.1.5. SEM images

Morphology of our prepared catalytic system was understood by taking SEM image (Fig. 3). This image represents morphology of capped nano sized silica particles that showed morphology was noticeably changed after getting layered by ionic liquids compare to uncapped nanoparticles.

#### 3.1.6. Zeta potential

Ionic nature and stability of Nano-SiO<sub>2</sub>@IL was judged by

**Table 1**  
Effect of different reaction parameters<sup>a</sup>.

Entry	Catalyst	Solvent	Temp (° C)	Time (h)	Yield <sup>b</sup> (%)
1	None	H <sub>2</sub> O	100	1	Not isolated
2	Basic alumina	H <sub>2</sub> O	100	36	10
3	Et <sub>3</sub> N	H <sub>2</sub> O	100	36	20
4	SiO <sub>2</sub> NP	H <sub>2</sub> O	100	36	40
5	3-bromo propionic acid	H <sub>2</sub> O	100	36	38
6	[AMIM] <sup>+</sup> Br <sup>-</sup>	H <sub>2</sub> O	100	36	18
7	[DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	H <sub>2</sub> O	100	36	35
8	Normal SiO <sub>2</sub> + [DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	H <sub>2</sub> O	100	36	53
9	SiO <sub>2</sub> NP + [DABCO(C <sub>2</sub> CO CH <sub>2</sub> CH <sub>2</sub> COOH OH)] <sup>+</sup> [Br] <sup>-</sup>	H <sub>2</sub> O	100	36	62
10	SiO <sub>2</sub> -[AMIM] <sup>+</sup> Br <sup>-</sup>	H <sub>2</sub> O	100	24	54
11	Nano-SiO <sub>2</sub> @[DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	H <sub>2</sub> O	100	8	94
12	Nano-SiO <sub>2</sub> @[DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	H <sub>2</sub> O	60	20	55
13	Nano-SiO <sub>2</sub> @[DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	EtOH	70–80	20	88
14	Nano-SiO <sub>2</sub> @[DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	CH <sub>3</sub> CN	70–80	20	69
15	Nano-SiO <sub>2</sub> @[DABCO(CH <sub>2</sub> CH <sub>2</sub> COOH)] <sup>+</sup> [Br] <sup>-</sup>	DMF	120–130	20	33

<sup>a</sup> Reaction conditions: all reactions were carried out using phenyl glyoxal (1 mmol), para toluidine (1 mmol), ethyl acetoacetate (1 mmol) and phenyl glyoxal (1 mmol) under different reaction conditions. 0.2 mmol for homogeneous catalyst and 25 mg for heterogeneous catalyst were used.

<sup>b</sup> Isolated yields.

measuring Zeta potential value. Zeta potential value ( $\zeta$ ) of the fresh catalyst was  $-33.0$  mV. This result showed high degree of stability of the catalyst in water medium (Fig. S4, ESI 1).

### 3.1.7. Optimisation of catalyst

Considering diethyl acetylenedicarboxylate, 4-methoxy aniline, phenyl glyoxal and 4-chloro benzene thiol as substrates for our model reactions, we have performed various reactions varying catalysts, solvents, time and temperature to optimise the reaction condition (Table 1). In view of environmental benignity, we have tried to produce our desired compound in aqueous medium. We did not get any desired compound from aqueous medium reaction in absence of catalyst. Hence we have added basic catalysts in the reaction medium like heterogeneous basic alumina or homogeneous Et<sub>3</sub>N and able to isolate little amount of desired compounds. Next we have added various acidic catalysts like SiO<sub>2</sub> NP, 3-bromo propionic acid and then amphoteric DABCO based ionic liquid [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup>. We got maximum yield in case of DABCO based amphoteric ionic liquid. Next we have added [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup> and SiO<sub>2</sub> NP simultaneously but not in immobilised condition (entry 9). Later, they were added in immobilised condition to check the positivity of quasi-heterogeneous nature of catalysts (entry 10 and 11). Till now, we got optimum yield when we have performed the reaction in case of nano silica supported DABCO based amphoteric ionic liquid coated combined catalytic system under aqueous medium and refluxing condition (entry 11). Yield of the reaction decreased with lowering the reaction temperature and was also appreciable when we have performed the reaction in ethanol medium under refluxing condition (entry 13). Reaction was also inefficient when we have performed the reaction in polar aprotic solvent or high boiling point solvent

### 3.1.8. Catalyst loading

Subsequently, to determine the finest amount of catalyst required, the reaction was performed in the presence of different amounts of

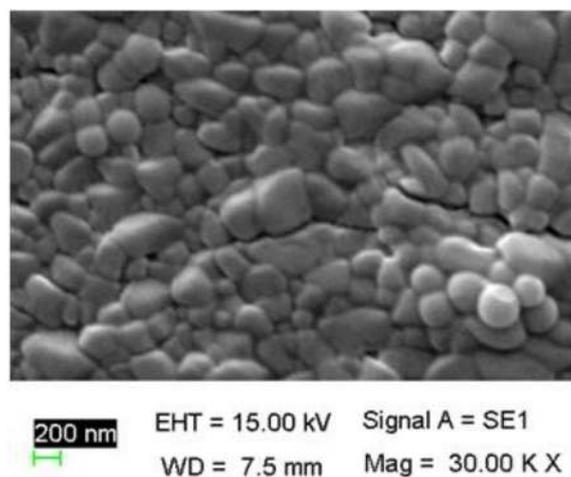


Fig. 3. SEM images of combined capped silica.

catalyst, Nano-SiO<sub>2</sub>@IL (fig. S6, ESI 1). In this catalyst loading graph, it has been shown that prominent enhancement in the yield of the product with increasing amount of catalyst used, up to 20 Mol%, more than which resulted in no further enhancement in product yield. In order to employ the least amount of catalyst, we inhibited ourselves to using 20 Mol% of catalyst all through the reaction

### 3.1.9. Substrate scope

To generalise a methodology, it is necessary to vary substrates with various substituents. Pyrrole based drugs have multiple curative activities with medicinal very good future, depending on the substitution prototypes of the core skeleton. Therefore, progression of more simplistic and environmentally benevolent methodology where different functional groups are incorporated at diverse positions of this core

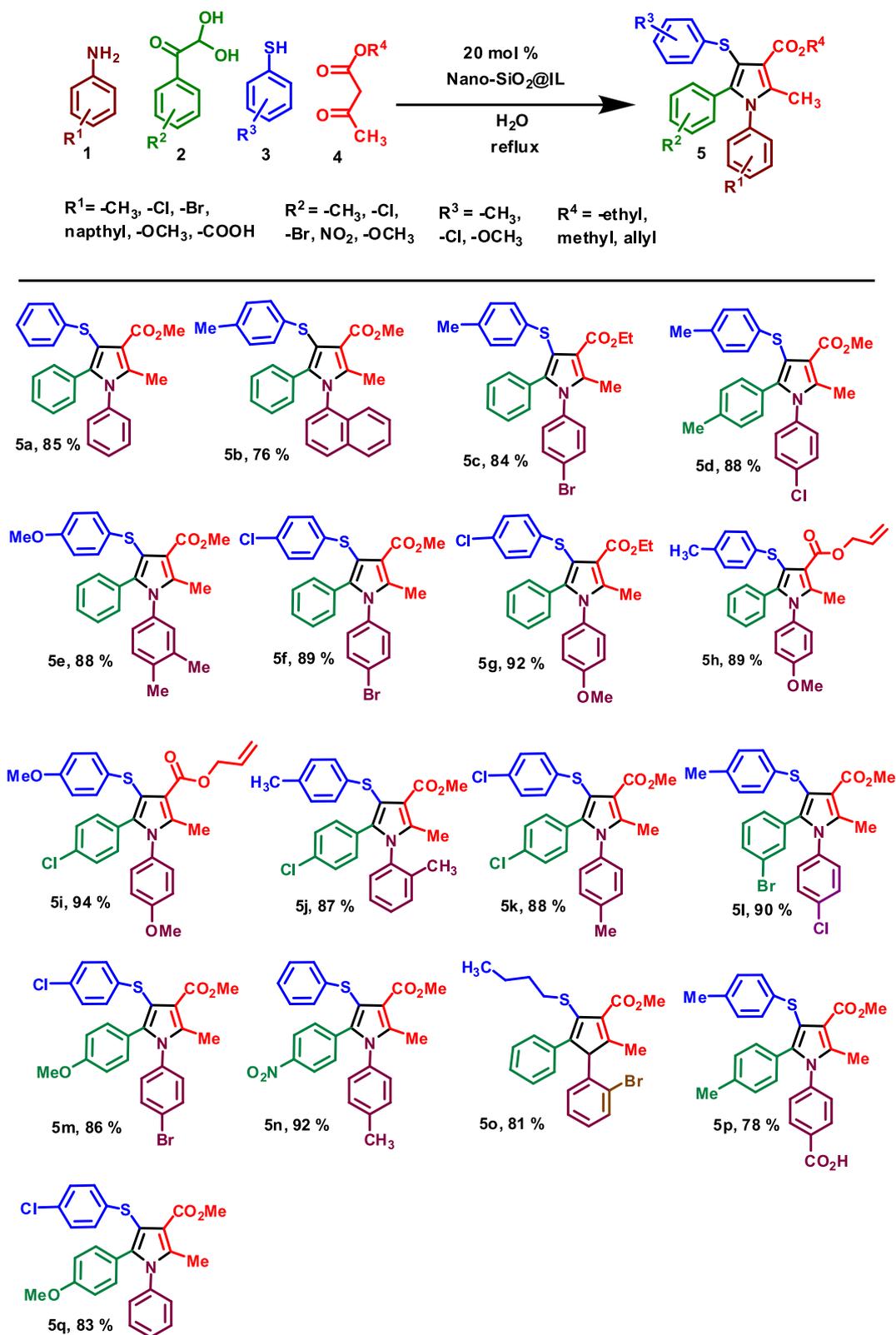
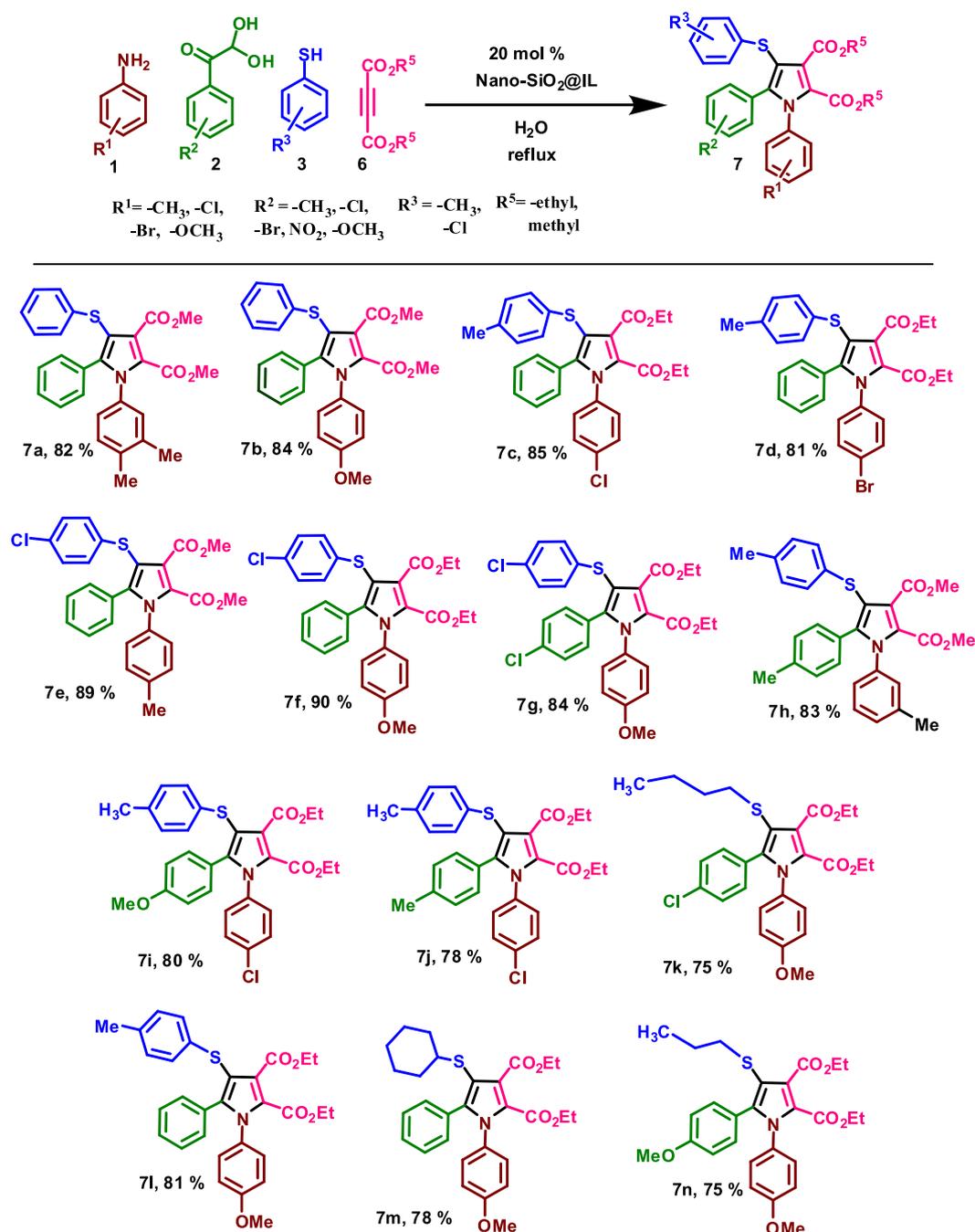


Fig. 4. General synthesis scheme and substrate scope of thiol induced pyrrole compounds with  $\beta$ -keto ester (In the bracket compound numbers and their respective percentage of isolated yields are shown).

structure is still needed to expand the versatility of this scaffold in various curative applications. Based on our abovementioned optimised reaction conditions in hand, this multicomponent reaction can be readily diversified through a combination of an array of aniline, various substituted or unsubstituted phenyl glyoxal, various aromatic, alicyclic

or aliphatic thiol and different  $\beta$ -keto ester

Besides unsubstituted anilines, we were able to employ electron donating ( $-\text{Me}, -\text{Cl}, -\text{Br}, -\text{OMe}$ ), electron withdrawing ( $-\text{CO}_2\text{H}$ ) as well as sterically hindered group (naphthyl) containing anilines with good to excellent yields. Here not only substituted and unsubstituted



**Fig. 5.** General synthesis scheme and substrate scope of thiol induced pyrrole compounds with dialkyl acetylenedicarboxylate (In the bracket compound numbers and their respective percentage of isolated yields are shown).

aromatic thiols were successfully used but also aliphatic thiols were also able to produce desired product with moderate yield. Most interestingly, we were able to diversify our product with various substituted (4-methyl, 4-chloro, 3-bromo, 4-methoxy and 4-nitro) and unsubstituted phenyl glyoxal. Our 4th substrate  $\beta$ -keto ester was also diversified properly. When we have analysed substituent effect, it was shown that we got maximum yield with amine having maximum electron donor group. Substituent effect is similar in case of aromatic thiols. Greater the nucleophilicity, greater the enhancement of yield. Although there occurs exception in case of naphthyl amine (**5b**) and aliphatic thiol (**5o**). It may be due to high reactivity and low boiling point of aliphatic thiol. Steric crowding factor must be the main cause of less effective reaction in **5b**. The products were shown in Fig. 4 along with their percentage yield.

Interestingly, we were able to diversify our product using dialkyl acetylenedicarboxylate as precursors instead of  $\beta$ -keto esters along with substituted and unsubstituted aromatic amine, phenyl glyoxal, aromatic, alicyclic or aliphatic thiols under the same reaction conditions.

The structure of products is shown in the above Fig. 5 along with their percentage yields. Here we obtained moderate to excellent yields. Expectedly, product yield was increased with the nucleophilicity of aniline and thiols and electrophilicity of phenyl glyoxal. There was no previous report of thiol group incorporation at the four position of pyrrole ring.

### 3.1.10. Crystal structure

We have confirmed the structure of the product undoubtedly by X-ray crystallographic analysis of compound **5c** (CCDC 1945057) and **7f**

(CCDC 1945058), ORTEP representation of these crystals are shown in (fig. S7, ESI 1)

### 3.1.11. Reaction mechanism

A reasonable reaction mechanism for the formation of fully functionalised thiol induced pyrroles, catalyzed by Nano-SiO<sub>2</sub>@IL is shown in scheme S1 (ESI). Reaction commences with nucleophilic addition of aromatic amine towards β-keto ester for the formation of enamine compound C. on the other hand, thiol reacted with phenyl glyoxal for the formation of intermediate E followed by the reaction between intermediate C and intermediate F to form intermediate G. next, this intermediate undergoes cyclisation and after the elimination of water, aromatization occurred and formed final product H. Here all the reaction steps were wonderfully catalyzed by Nano-SiO<sub>2</sub>@IL. Acidic surface of nano sized silica enhances the electrophilicity of carbonyl Centre, simultaneously carboxylic proton acted as very good proton donor. Since here DABCO is monosubstituted, one of the two N centres is free along with lone pair and other N Centre is substituted with propionic acid. All along this mono substituted DABCO based ionic liquid is amphoteric in nature. Thus, owing to synergetic catalytic effect of the Nano-SiO<sub>2</sub>@IL system, the reactivity is increased enormously from the first step to the last

Similar type of reaction mechanism was followed when reaction was carried out with dialkyl acetylenedicarboxylate instead of β-keto ester. The probable reaction mechanism was shown in Scheme S2 (ESI 1). Here reaction commences with nucleophilic attack of substituted or unsubstituted aniline with dialkyl acetylenedicarboxylate to form intermediate B. Reaction between phenyl glyoxal and various thiols was same as before and formed intermediate D followed by cyclisation between these two intermediates and got final pyrrole compound J after elimination of water.

### 3.1.12. Hot filtration and leaching test

Hot filtration and leaching test was performed as a proof of heterogeneity present in the sample [35,36]. This was described in full details in supplementary section (ESI 4)

### 3.1.13. Recycling experiment

In order to validate the recyclability of Nano-SiO<sub>2</sub>@IL catalyst, recycling experiment (fig. S8, ESI 1) has been conducted where the formation of compound 5c from the respective starting materials under optimised conditions was considered as a standard reaction. At the end of the reaction, the crude mixture was diluted with ethyl acetate (10 mL) and the catalyst was easily recovered by filtration using a sintered glass funnel. It was washed with ethyl acetate (5/10 mL) few more times to eradicate adhered organic compound and dried under vacuum. Next, to verify the activity of the catalyst, a recycling experiment was carried out using the recovered catalyst for the succeeding reactions. In a test of six cycles, it was observed that the catalyst could be reused with high catalytic activity. Comparison of chemical structure of both the fresh and recovered active catalytic species, i.e. DABCO based amphoteric ionic liquid was done by verifying carbonyl stretching absorption of carboxylate anion since the carbonyl stretching absorption is one of the strongest IR absorptions and is very useful in structure determination. Characteristic absorption peaks of active catalytic species i.e. DABCO based IL comes at 1644 and 3455 cm<sup>-1</sup> respectively that correspond to -C=O and -O-H stretching frequencies. There was almost no alteration in the characteristic peak corresponds to S-O-Si stretching frequency confirming no alteration in chemical structure. CHN analysis data of both the fresh (C: 26.88%, H: 4.01%, N: 5.1%) and recovered (C: 26.12%, H: 4.07%, N: 5.9%) catalyst was performed and found almost same percentage of carbon, hydrogen and nitrogen. This result suggested a strong binding force in between IL and nano-SiO<sub>2</sub>. In order to test the morphological change, SEM (fig. S8, ESI 1) and TEM analysis (fig. S9, ESI 1) was also done. The result showed that there is no considerable alteration in morphology. For the

elemental characterisation, of the recovered catalyst, EDAX analysis (fig. S10, ESI 1) was also done. These experiments have shown that the Nano-SiO<sub>2</sub>@IL had sufficient stability and could reproduce the product several times with almost similar efficiency

## 4. Conclusions

This is the first report of the synthesis of thiol induced pyrrole moieties. Here, two different schemes were mentioned with one reactant replacement. Another most satisfactory fact is that 31 new compounds were generated and all the reactions were carried out in aqueous medium. All these compounds could not be produced in aqueous mediated reaction without strong assistance of quasi heterogeneous catalyst Nano-SiO<sub>2</sub>@IL, our newly reported SCILL. This is a nano sized silica supported DABCO based amphoteric ionic liquid covered combined catalytic system where we got synergetic catalytic effect of nano sized silica and [DABCO(CH<sub>2</sub>CH<sub>2</sub>COOH)]<sup>+</sup>[Br]<sup>-</sup>. This catalyst could be recovered easily from reaction mixture and can be recycled several times without significant loss of catalytic activity

## Credit author statement

Priya Mondal: doing all experiments on synthesis, characterisation, writing, review.

Sauvik Chatterjee: doing all catalyst characterisation.

Khondekar Nurjamaal: taking NMR data.

Suvendu Maity: taking crystal data and solving and writing.

Asim Bhaumik: supervision, writing and review of catalyst data.

Goutam Brahmachari: supervision of NMR spectra.

Prasanta Ghosh: supervision of crystal data.

Chhanda Mukhopadhyay\*: concept, writing, review, editing and supervision.

## Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.catcom.2020.105966>.

## References

- [1] C. Kokel, B. Torok Schafer, *Green Chem.* 19 (2017) 3729–3751.
- [2] B. Banerji, S. Adhikarya, L. Majumdera, S. Ghosha, *Asian J. Org. Chem.* 8 (2018) 514–525.
- [3] V. Sadhasivam, R. Balasaravanan, A. Siva, *Appl Organometal Chem.* 33 (8) (2019) e4994, <https://doi.org/10.1002/aoc.4994>.
- [4] L. Han, Z. Zhou, *Appl Organometal Chem.* 33 (4) (2019), <https://doi.org/10.1002/aoc.4755>.
- [5] H. Li, P.S. Bhadury, B. Song, S. Yang, *RSC Adv.* 2 (2012) 12525–12551.
- [6] D. Kim, Y. Moon, D. Ji, H. Kim, D. Cho, *ACS Sustainable Chem. Eng.* 4 (2016) 4591–4600.
- [7] J. Restrepo, P. Lozano, M.I. Burguete, E.G. Verdugo, S.V. Luis, *Catal. Today* 255 (2015) 97–101.
- [8] D. Zhang, C. Zhou, R. Wang, *Catal. Commun.* 22 (2012) 83–88.
- [9] A. Karakulina, A. Gopakumar, I. Akaok, B.L. Roulier, T. Lagrange, S.A. Katsyuba, S. Das, P.J. Dyson, *Angew. Chem.* 128 (2016) 300–304.
- [10] N. Jamasbi, M.I. Khanghah, F. Shirini, H. Tajik, M.S.N. Langarudi, *New J. Chem.* 42 (2018) 9016–9027.
- [11] Q.X. Luo, B. An, M. Ji, J. Zhang, *Mater. Chem. Front.* 2 (2018) 219–234.
- [12] A. Ying, Z. Li, J. Yang, S. Liu, S. Xu, H. Yan, C. Wu, *J. Org. Chem.* 79 (2014) 6510–6516.

- [13] N. Seyyedi, F. Shirini, M. Safarpour, N. Langarudi, *RSC Adv.* 6 (2016) 44630–44640.
- [14] A. Pourjavadi, S.H. Hosseini, S.A.A. Meibody, S.T. Hosseini, *C. R. Chimie.* 16 (2013) 906–911.
- [15] C.P. Mehnert, E.J. Mozeleski, R.A. Cook, *Chem. Commun.* (2002) 3010–3011.
- [16] C.P. Mehnert, R.A. Cook, N.C. Dispenziere, M. Afeworki, *J. Am. Chem. Soc.* 124 (2002) 12932–12933.
- [17] Y.Q. Yu, D.Z. Xu, *Tetrahedron* 71 (2015) 2853–2857.
- [18] A. Rostami, O. Pourshiani, Y. Navasi, N. Darvishi, S. Saadati, *New J. Chem.* 41 (2017) 9033–9040.
- [19] S.F. Miller, H.B. Friedrich, C.W. Holzappel, *Chemcatchem* 4 (2012) 1337–1344.
- [20] Q. Zhang, F. Yang, F. Tang, K. Zeng, K. Wu, Q. Cai, Su. Yao, *Analyst* 135 (2010) 2426–2433.
- [21] A. Ramazani, A. Mahyari, H. Lashgari, K. Slepokurac, T. Lis, *Helvetica Chimica Acta* 94 (2011) 611–622.
- [22] A. Banerjee, R. Theron, R.W.J. Scott, *ChemSusChem* 5 (2012) 109–116.
- [23] A.J. Reay, I.J.S. Fairlamb, *Chem. Commun.* 51 (2015) 16289–16307.
- [24] A. Amoozadeh, S. Rahmani, M. Bitaraf, F.B. Abadi, E. Tabrizian, *New J. Chem.* 40 (2016) 770–780.
- [25] E. Baydar, M.G. Gunduz, V.S. Krishna, R. Simsek, D. Sriram, S.O. Yildirim, R.J. Butcher, C. Safak, *Res. Chem. Intermed.* 43 (2017) 471–7489.
- [26] A. Mondal, C. Mukhopadhyay, *Eur. J. Org. Chem.* (2017) 6299–6313.
- [27] A. Mondal, B. Naskar, S. Goswami, C. Prodhon, K. Chaudhuri, C. Mukhopadhyay, *Org. Biomol. Chem.* 16 (2018) 302–315.
- [28] T. Vivekanand, P. Vinoth, B. Agieshkumar, N. Sampath, A. Sudalai, J.C. Menéndez, V. Sridharan, *Green Chem.* 17 (2015) 3415–3423.
- [29] V. Estevez, M. Villacampa, J.C. Menendez, *Chem. Soc. Rev.* 39 (2010) 4402–4421.
- [30] R. Mishra, A. Jana, A.K. Panday, L.H. Choudhury, *Org. Biomol. Chem.* 16 (2018) 3289–3302.
- [31] Z. Su, W. Gu, S. Qian, S. Xue, C. Wang, *Eur. J. Org. Chem.* (2018) 1019–1025.
- [32] Z. Gong, Yu Lei, P. Zhou, Z. Zhang, *New J. Chem.* 41 (2017) 10613–10618.
- [33] X. Feng, Q. Wang, W. Lin, G.L. Dou, Z.B. Huang, D.Q. Shi, *Org. Lett.* 15 (2013) 2542–2545.
- [34] L. Akelis, J. Rousseau, R. Juskenas, J. Dodonova, C. Rousseau, S. Menuel, D. Prevost, S. Tumkevicius, E. Monflier, F. Hapiot, *Eur. J. Org. Chem.* (2016) 31–35.
- [35] B. Yu, J.N. Xie, C.L. Zhong, W. Li, L.N. He, *ACS Catal.* 5 (2015) 3940–3944.
- [36] A.K. Patra, A. Dutta, A. Bhaumik, *Chem. Eur. J.* 19 (2013) 12388–12395.