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RESEARCH ARTICLE

Deep eutectic ionic liquids based on DABCO-derived quaternary ammonium salts: A promising reaction medium in gaining access to terpyridines

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Abstract Owing to the directional H-bonding, coordination and π-stacking abilities, terpyridines have been widely used as supramolecular tectons in molecular architectures, skeletons in molecular devices and metallopolymers, and are gaining importance in medicinal chemistry. In this paper, we have synthesized, characterized and applied deep eutectic ionic liquids (DEILs) based on 1,4-diazabicyclo[2.2.2]octane; triethylenediamine (DABCO)-derived quaternary ammonium salts for the preparation of terpyridines. These DEILs were synthesized through *N*-alkylation of DABCO with haloalkanes (1-bromopentane or 1-bromoheptane) followed by mixing and heating with methanol or polyethylene glycol as a hydrogen bond donor. The synthesized DEILs were structurally characterized by IR and NMR. The formation of deep eutectic solvent was confirmed by freezing point depression, it composition was investigated through phase diagram, and its thermal stability was determined through differential scanning calorimetry, derivative thermogravimetry and thermal gravimetric analysis studies. Further, these DEILs were investigated for their effectiveness towards synthesis of 2,2':6',2"-terpyridine, 3,2':6',3"-terpyridineand 4,2':6',4"-terpyridine derivatives through Kröhnke reaction. The results show that these three types of terpyridines can be obtained in reasonable yields (80%–97%) by the one-pot reaction of 2-, 3- or 4-acetylpyridine with a variety of aromatic aldehydes in the presence of DEIL as a reaction medium, sodium hydroxide as a base and ammonium acetate as a cyclizing agent. This methodology is highly efficient and cost-effective for synthesis of symmetrical as well as unsymmetrical terpyridines. Importantly, these DEILs can be reused several times without an obvious loss of activity and are non-toxic, low-volatile, biodegradable and highly thermally stable. Therefore, these DEILs as a non-conventional reaction medium for the synthesis of terpyridines provides appealing opportunities to be investigated in the domain of green synthesis.

Keywords terpyridine, deep eutectic solvent, ionic liquid, Kröhnke reaction, DABCO

1 Introduction

Terpyridines (generally abbreviated as terpy or tpy) are molecules that consists of three joined pyridine rings. Although there are many possible substitution patterns, the general term "terpyridine" almost exclusively refers to 2,2':6',2"-terpyridine **1**, the skeleton of which can be seen in Fig. 1. As a result of the 2,2':6',2"-substitution pattern, terpyridine serves as a tridentate chelating ligand, like a molecular 'claw', and forms stable coordination complexes with a broad spectrum of main groups, transition metals, and even lanthanides ions [1]. Other two types of terpyridines are 3,2':6',3"-terpyridine 2 and 4,2':6',4"-terpyridine 3 (Fig. 1).

The tremendous stability of coordination complexes of terpyridines with transition metals is attributed to the thermodynamic chelate effect. Additionally, *p*-acceptor/*s*-donor nature of a dative M-$N_{pyridine}$ bond contributes to the stability of the leading coordination complexes [2,3]. Large number of terpyridine-based complexes were synthesized by changing the transition metal, the characteristics of the other ligand participants of the coordination sphere and the pattern of substitution of the terpyridine ligand. These coordination compounds display exciting photophysical characteristics, which can be fine-tuned through the nature of the substitution pattern onto the terpyridine ligand. Terpyridines also have π-π stacking feature, directional H-bonding, high hydrolytic stability,

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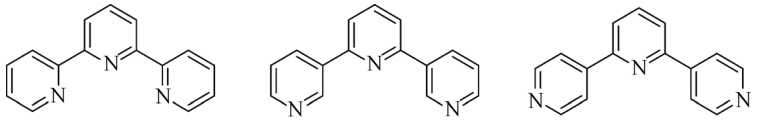


2,2':6',2"-terpyridine **1** 3,2':6',3"-terpyridine **2** 4,2':6',4"-terpyridine **3**

Fig. 1 Structure of terpyridine scaffolds

photoluminescence property, large electrical conductivity and low viscosity. They can form highly-ordered architectures (macrocyclic assemblies, spirometallodendrimers, triangular metallocycle, and hetero- and homo-metallotetramer) and can build symmetrical framework [4–6]. These properties are the reason that tpy complexes potentially have many practical applications in nanomaterials [7,8], chemosensors [8], magnetic resonance imaging contrastagents [9], material chemistry (specially in dye-sensitized solar cells and light-emitting diodes), biomarkers [10,11], medicinal chemistry (specially in antitumor chemotherapeutics) [12–14], catalysts [15], and supramolecular chemistry [16].

An easy synthesis of different terpyridine derivatives, on a large scale in excellent yield, requisites for the wide spectrum of applications. The methodologies for construction of the terpyridine skeleton involve variations of the pioneering approaches disclosed by Potts et al. [17] and Kröhnke [18], and more recently synthetic approaches based on Migita-Kosugi-Stille coupling [19–21], microwave irradiation (MWI) [22] and solvent-free conditions [23–25]. Among all these methodologies, Kröhnke technique has been regarded as the most convenient method to construct terpyridine frameworks. However, all these approaches suffer from major limitations and drawbacks. The Potts et al. [17] and Kröhnke [18] techniques usually show moderate to good yields (not excellent yields) and poor atom efficiency, and often require toxic reagents (such as aq. NH_3), large amounts of volatile organic solvents, and long reaction time. The use of organostannane compounds in Migita-Kosugi-Stille coupling reactions is also of a major issue owing to their toxicity. Additionally, in various cases, the purification from cyclohexanol byproducts is a time-consuming problem [26]. Although numerous classes of these entities can be synthesized in excellent yields, the optimal conditions for their construction are still poorly managed [27]. Synthesis of terpyridines under MWI has also been disclosed [22]. However, this method also has various shortcomings; for example, it is not applicable for large-scale synthesis, provides moderate yield and requires special devices and conditions.

The above limitations and drawbacks can be resolved by using the aforementioned solvent-free conditions. This is a shift of paradigm in the development of terpyridine skeletons in the context of both sustainable chemistry and the simplicity, generality, and ease of the procedure [28,29]. Side products and waste generation are also predominantly avoided, and the 1,5-diones and chalcones can be synthesized in high purity and yield. Nevertheless, the solvent-free approach also has limitation where run away and highly exothermic reactions prevail, leading to competing reactions.

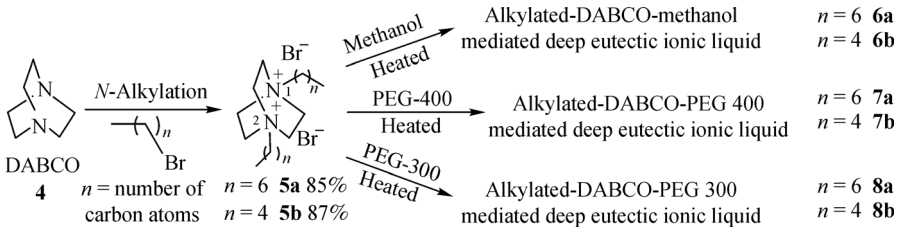
Owing to above mentioned limitations, the development of clean and simple methods or improvement in current approaches for the preparation of terpryidines is strongly desirable and is a major challenge for synthetic chemists. This challenge motivates us to improve Kröhnke reaction and therefore, in this research work, we investigate the application of deep eutectic ionic liquids (DEILs) from 1,4-diazabicyclo[2.2.2]octane; triethylenediamine (DABCO) and alkyl halide in the synthesis of 2,2':6',2"-terpyridines **1**, 3,2':6',3"-terpyridines **2** and 4,2':6',4"-terpyridines **3** through Kröhnke reaction. The basic aim of this research work is to decrease reaction time and toxicity, to increase yield of Kröhnke reaction and to develop a low volatile, biodegradable, recyclable and highly thermally stable system for Kröhnke reaction. We have successfully developed for the preparation of terpyridines a one-pot and cost-effective (due to high recyclability) DEIL approach which meets many criteria in terms of safety, the environment, legality, control and throughput.

2 Experimental

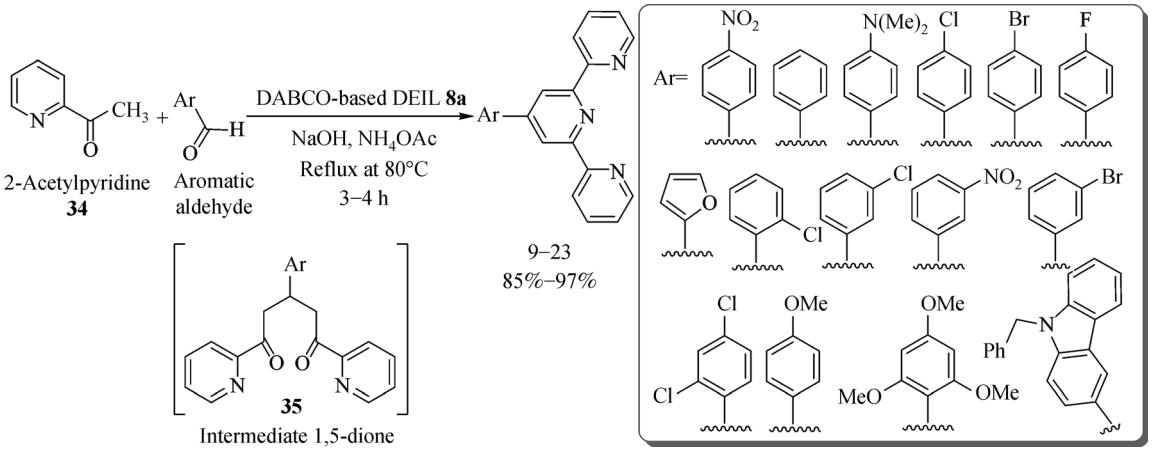
In this work, the synthesized DEILs are shown in Scheme 1. Scheme 2 describes the synthetic routine of terpyridine derivatives and the products are listed in Fig. 2 and Fig. 3, respectively.

2.1 Materials and general methods

The reagents, solvents and other chemicals were obtained from Fluka, Merck and Sigma-Aldrich and utilized without further purification. Aromatic aldehyde viz. 9-benzyl-9H-carbazole-3-carbaldehyde (a precursor for the synthesis of **13**, **28** and **33**) was prepared by the reported procedure of Al Mousawi et al. [58]. ^{1}H NMR spectra were recorded on a Varian Gem2300 300 MHz spectrometer with TMS as an internal standard, and chemical shifts are expressed in ppm unit with respect to residual solvent peaks ($\delta_{TMS} = 0$ ppm). All melting points were recorded on a Mel-Temp melting



Scheme 1 Synthesis of deep eutectic ionic liquids



Scheme 2 Synthesis of 2,2':6',2"-terpyridines by using alkylated DABOC-PEG-300 based DEILs

point device. The reaction progress was monitored by TLC using pre-coated silica gel-60 plates. For determination of freezing points of synthesized samples, two methods were used viz. rotary evaporation and freeze drying, which were performed on a Labconco 7750020 freeze dryer and a Buchi R-200 rotary evaporator, respectively. Thermal characterizations were carried out on a PerkinElmer thermogravimetric analyzer and a Thermo Scientific DSC instrument.

2.2 General procedure for synthesis of DABCO-ILs

In a round-bottom flask (100 mL), DABCO **4** (1 g, 8.92 mmol, and 2 equiv) was added along with 50 mL DCM and toluene in a ratio of 5:3 at room temperature, and then 1-bromopentane or 1-bromoheptane (19.36 mmol, and 4.4 equiv) was poured. The resulting mixture was heated to reflux (117°C–121°C), and the progress of the reaction was monitored by TLC using the solvent system of 10% EtOAc in hexane. After completion of reaction, the reaction mixture was cooled at room temperature and the product was isolated by filtration. After washed with cold toluene (20 mL × 6), the product was dried under reduced pressure to afford required ILs (**5a** or **5b**) as a yellowish thick oil.

2.3 General procedure for synthesis of terpyridines

In a round-bottom flask (100 mL), HBD (methanol, PEG-300 or PEG-400) and DABCO-mediated IL (**5a** or **5b**) were added in a ratio of 2:1. The resulting mixture was heated at 80°C–85°C until it was homogenized. Then, acetylpyridine (2-acetylpyridine, 3-acetylpyridine or 4-acetylpyridine; 1.21 g, 10 mmol) and sodium hydroxide (0.5 g, 10 mmol) were introduced into the mixture. After vigorously stirring at room temperature for 20 min, aromatic aldehyde (5 mmol) was added and the mixture was vigorously stirred for a further three hours, during which the mixture became deep-red. Then, excess NH_4OAc (5 g) was added, and the mixture was heated at 80°C for appropriate time (2–6 h; monitored by TLC using the solvent system of 10% EtOAc in hexane) to afford a dark semi-crystalline material. Finally, ice water was added, and the precipitates were collected by filtration (for recycling, the aqueous phase in filtrate was reused under identical reaction conditions). The product was washed with a mixture (40 mL × 2) of H_2O and MeOH in a ratio of 5:1, and recrystallized from 95% EtOH.

2.4 Spectral data

2.4.1 1,4-Diheptyl-1,4-diazabicyclo[2.2.2]octane-1, 4-diium bromide **5a**

Appearance: bright yellowish thick oil; Yield: 85%; R_f: 0.89 (*n*-hexane:EtOAc (5:5)); IR (KBr, cm^{-1}): 854, 1120, 1201, 1317, 1390, 1629, 2859, 2930, 3418; ^1H NMR

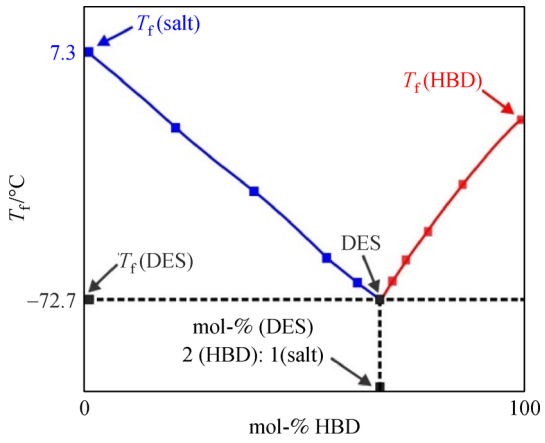


Fig. 2 List of synthesized 2,2′:6′,2″-terpyridines

(300 MHz, $CDCl_3$): δ_H 3.91 (s, 12 H), 3.60–3.49 (m, 4 H), 1.71 (app brs, 4 H), 1.36–1.25 (m, 16 H), 0.87 (t, 6 H, J = 6.4 Hz); Anal. calcd for $C_{20}H_{42}Br_2N_2$: C, 51.07; H, 9.00; Br, 33.98; N, 5.96. Found: C, 51.08; H, 9.03; Br, 33.95; N, 5.92.

2.4.2 1,4-Dipentyl-1,4-diazabicyclo[2.2.2]octane-1,4-diium bromide **5b**

Appearance: dark yellowish thick oil; Yield: 87%; R_f: 0.81 (*n*-hexane:EtOAc (5:5)); IR (KBr, cm^{-1}): 856, 1060, 1118, 1209, 1319, 1389, 1468, 1629, 2061, 2509, 2871, 2961, 3424; ^{1}H NMR (300 MHz, $CDCl_3$): δ_H 3.89 (s, 12 H), 3.68–3.60 (t, J = 8.4 Hz, 4 H), 1.73–1.69 (m, 4 H), 1.35–1.26 (m, 8 H), 0.89 (t, J = 6.8 Hz, 6 H); Anal. calcd for $C_{16}H_{34}Br_2N_2$: C, 46.39; H, 8.27; Br, 38.58; N, 6.76. Found: C, 46.43; H, 8.29; Br, 38.60; N, 6.77.

2.4.3 4'-Phenyl-2,2':6',2"-terpyridine **9**

Appearance: off-white solid; Yield: 96%; R_f: 0.47 (*n*-hexane:EtOAc (1:9)); m.p.: 209°C; IR (KBr, cm^{-1}): 797, 890, 994, 1393, 1469, 1549, 1568, 1584; ^{1}H NMR (300 MHz, $CDCl_3$): δ_H 7.63–7.53 (m, 5 H), 7.95 (dd, J = 4.8, 6.4 Hz, 2 H), 8.05 (dd, J = 6.4, 8.0 Hz, 2 H), 8.69 (d, J = 8.0 Hz, 2 H), 8.70 (s, 2 H), 8.83 (d, J = 4.8 Hz, 2 H); Anal. calcd for $C_{21}H_{15}N_3$: C, 81.53; H, 4.89; N, 13.58. Found: C, 81.50; H, 4.87; N, 13.63.

2.4.4 *N*,*N*-Dimethyl-4-(2,2':6',2"-terpyridin-4'-yl)aniline **10**

Appearance: green solid; Yield: 92%; R_f: 0.50 (*n*-hexane: EtOAc (1:9)); m.p.: 229°C; IR (KBr, cm^{-1}): 798, 893, 995, 1400, 1470, 1557, 1570, 1583; ^{1}H NMR (300 MHz, $CDCl_3$): δ_H 3.04 (s, 6 H), 6.83 (dt, J = 2.0, 9.0 Hz, 2 H), 7.31–7.36 (m, 2 H), 7.84–7.90 (m, 4 H), 8.66 (dt, J = 1.1, 8.0 Hz, 2 H), 8.74 (s, 2 H), 8.72–8.76 (m, 2 H); Anal. calcd for $C_{23}H_{20}N_4$: C, 78.38; H, 5.72; N, 15.90. Found: C, 78.35; H, 5.73; N, 15.82.

2.4.5 4'-(2-Furyl)-2,2':6',2"-terpyridine **11**

Appearance: milk white solid; Yield: 91%; R_f: 0.40 (*n*-hexane:EtOAc (1:9)); m.p.: 203°C; IR (KBr, cm^{-1}): 792, 892, 993, 1391, 1469, 1650, 1767, 1884; ^{1}H NMR (300 MHz, $CDCl_3$): δ_H 6.58 (dd, J = 3.4, 1.8 Hz, 1 H), 7.10 (d, J = 3.2 Hz, 1 H), 7.36 (ddd, J = 7.4, 1.0 , 4.8 Hz, 2 H), 7.59 (d, J = 1.2 Hz, 1 H), 7.87 (dt, J = 7.8, 1.9 Hz, 2 H), 8.64 (d, J = 8.0 Hz, 2 H), 8.71 (s, 2 H), 8.74 (d, J = 4.8 Hz, 2 H); Anal. calcd for $C_{19}H_{13}N_3O$: C, 76.24; H, 4.38; N, 14.04; O, 5.35. Found: C, 76.26; H, 4.45; N, 14.08; O, 5.38.

2.4.6 4'-(4-Methoxyphenyl)-2,2':6',2"-terpyridine **12**

Appearance: off-white solid; Yield: 94%; R_f: 0.53 (*n*-hexane:EtOAc (1:9)); m.p.: 153°C; IR (KBr, cm^{-1}): 400, 515, 565, 620, 660, 730, 790, 790, 990, 1040, 1075, 1230. 1290, 1300, 1300, 1440, 1520, 1565, 1600, 1600, 3015, 3055; ^{1}H NMR (300 MHz, $CDCl_3$): δ_H 3.9 (s, 3 H), 7.5–7.0 (m, 4 H), 8.1–7.7 (m, 4 H), 8.7 (m, 6 H); Anal. calcd for $C_{22}H_{17}N_3O$: C, 77.86; H, 5.05; N, 12.38; O, 4.71. Found: C, 77.86; H, 5.05; N, 12.38; O, 4.71.

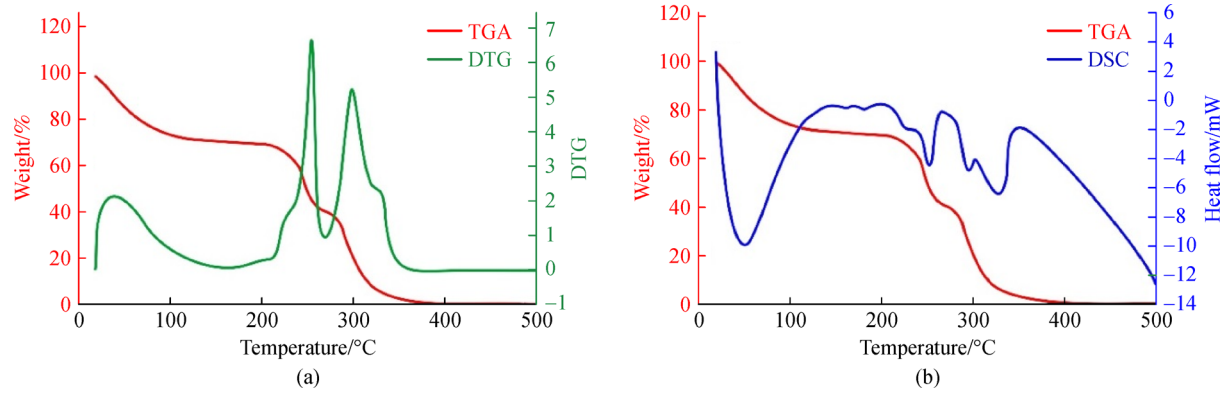


Fig. 3 List of synthesized 3,2':6',3"-terpyridines and 4,2':6',4"-terpyridines

2.4.7 3-([2,2':6',2"-Terpyridin]-4'-yl)-9-benzyl-9H-carbazole **13**

Appearance: pale yellow solid; Yield: 94%; R_f: 0.53 (methanol:chloroform (1:9)); m.p.: decomposed at 170°C; IR (KBr, cm^{-1}): 401, 621, 791, 1042, 1567; ^1H NMR (300 MHz, DMSO-d_6): δ_H 4.51 (m, J = 9.0 Hz, 2 H), 7.26 (m, J = 9.0 Hz, 1 H), 7.23 (m, J = 9.0 Hz, 2 H), 7.27 (t, J = 10.0 Hz; 1 H), 7.33 (m, J = 8.0 Hz, 2 H,), 7.55 (m, 3 H), 7.69 (d, J = 10.0 Hz, 1 H), 7.82 (d, J = 10.0 Hz, 1 H), 8.06 (m, 3 H), 8.41 (d, J = 10.0 Hz, 1 H), 8.72 (d, J = 10.0 Hz, 2 H), 8.81 (m, 3 H), 8.86 (s, 2 H); Anal. calcd for $C_{34}H_{24}N_4$: C, 83.58; H, 4.95; N, 11.47. Found: C, 83.56; H, 4.97; N, 11.42.

2.4.8 4'-(2-Chlorophenyl)-2,2':6',2"-terpyridine **14**

Appearance: off-white solid; Yield: 89%; R_f: 0.64 (*n*-hexane:EtOAc (1:9)); m.p.: 140°C; IR (KBr, cm^{-1}): 749, 779, 790, 991, 1040, 1088, 1392, 1442, 1467, 1551, 1567, 1585; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.70–7.50 (m, 4 H), 8.05 (dd, J = 8.4, 5.2 Hz, 2 H), 8.27 (dd, J = 8.4, 8.0 Hz, 2 H), 8.47 (d, J = 8.0 Hz, 2 H), 8.51 (s, 2 H), 8.81 (d, J = 5.2 Hz, 2 H); Anal. calcd for $C_{21}H_{14}ClN_3$: C, 73.36; H, 4.10; N, 12.22. Found: C, 73.29; H, 4.11; N, 12.24.

2.4.9 4'-(2,4-Dichlorophenyl)-2,2':6',2"-terpyridine **15**

Appearance: off-white solid; Yield: 90%; R_f: 0.52 (*n*-hexane:EtOAc (1:9)); m.p.: 176°C; IR (KBr, cm^{-1}): 793, 816, 993, 1402, 1468, 1544, 1568, 1583; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.51–7.54 (m, 3 H), 7.70 (dd, J = 8.4, 6.0 Hz, 2 H), 8.05 (dd, J = 8.4, 8.0 Hz, 2 H), 8.48 (s, 2 H), 8.77 (d, J = 8.0 Hz, 2 H), 8.81 (d, J = 6.0 Hz, 2 H); Anal. calcd for $C_{21}H_{13}Cl_2N_3$: C, 66.68; H, 3.46; N, 11.11. Found: C, 66.73; H, 3.51; N, 11.20.

2.4.10 4'-(2,4,6-Trimethoxyphenyl)-2,2':6',2"-terpyridine **16**

Appearance: bright solid; Yield: 88%; R_f: 0.84 (*n*-hexane: EtOAc (1:9)); m.p.: 188°C; IR (KBr, cm^{-1}): 659, 788, 827, 1008, 1086, 1389, 1416, 1441, 1469, 1546, 1568, 1586; ^1H NMR (300 MHz, $CDCl_3$): δ_H 3.76 (s, 3 H), 3.94 (s, 3 H), 3.98 (s, 3 H), 7.14 (s, 2 H), 7.56–7.52 (m, 2 H), 8.07–8.03 (m, 2 H), 8.67 (d, J = 8.0 Hz, 2 H), 8.69 (s, 2 H), 8.79 (d, J = 3.6 Hz, 2 H); Anal. calcd for $C_{24}H_{21}N_3O_3$: C, 72.16; H, 5.30; N, 10.52. Found: C, 72.23; H, 5.21; N, 10.43.

2.4.11 4'-(4-Nitrophenyl)-2,2':6',2"-terpyridine **17**

Appearance: yellow solid; Yield: 92%; R_f: 0.40 (*n*-hexane: EtOAc (1:9)); m.p.: 160°C; IR (KBr, cm^{-1}): 694, 754, 789, 854, 991, 1107, 1350, 1386, 1415, 1550, 1567, 1584; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.53 (dd, J = 7.2, 6.4 Hz, 2 H), 8.04 (dd, J = 8.4, 7.25 Hz, 2 H), 8.20 (d, J = 9.2 Hz, 2 H), 8.63 (d, J = 9.2 Hz, 2 H), 8.66 (d, J = 8.4 Hz, 2 H), 8.74 (s, 2 H), 8.85 (d, J = 6.4 Hz, 2 H); Anal. calcd for $C_{21}H_{14}N_4O_2$: C, 71.18; H, 3.98; N, 15.81. Found: C, 71.08; H, 4.08; N, 15.80.

2.4.12 4'-(3-Nitrophenyl)-2,2':6',2"-terpyridine **18**

Appearance: white powder; Yield: 91%; R_f: 0.43 (*n*-hexane:EtOAc (1:9)); m.p.: 180°C; IR (KBr, cm^{-1}): 733, 781, 885, 993, 1075, 1348, 1390, 1470, 1527, 1567, 1585; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.55 (dd, J = 7.2, 5.6 Hz, 2 H), 7.88 (dd, J = 8.4, 8.0 Hz, 1 H), 8.04 (dd, J = 8.0, 7.2 Hz, 2 H), 8.42 (d, J = 8.4 Hz, 1 H), 8.63 (d, J = 8.0 Hz, 1 H), 8.64 (s, 1 H), 8.68 (d, J = 8.0 Hz, 2 H), 8.77 (s, 2 H), 8.83 (d, J = 5.6 Hz, 2 H); Anal. calcd for $C_{21}H_{14}N_4O_2$: C, 71.18; H, 3.98; N, 15.81. Found: C, 71.26; H, 4.02; N, 15.70.

2.4.13 4'-(4-Chlorophenyl)-2,2':6',2"-terpyridine **19**

Appearance: white solid; Yield: 93%; R_f: 0.55 (*n*-hexane: EtOAc (1:9)); m.p.: 155°C; IR (KBr, cm^{-1}): 789, 826, 1012, 1091, 1383, 1411, 1441, 1469, 1546, 1567, 1585; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.55 (dd, J = 6.8, 5.2 Hz, 2 H), 7.66 (d, J = 8.8 Hz, 2 H), 7.99 (d, J = 8.8 Hz, 2 H), 8.07 (dd, J = 8.0, 6.8 Hz, 2 H), 8.64 (d, J = 8.0 Hz, 2 H), 8.72 (s, 2 H), 8.83 (d, J = 5.2 Hz, 2 H); Anal. calcd for $C_{21}H_{14}ClN_3$: C, 73.36; H, 4.10; N, 12.22. Found: C, 73.31; H, 4.12; N, 12.19.

2.4.14 4'-(4-Bromophenyl)-2,2':6',2"-terpyridine **20**

Appearance: white solid; Yield: 94%; R_f: 0.50 (*n*-hexane: EtOAc (1:9)); m.p.: 146°C; IR (KBr, cm^{-1}): 789, 823, 889, 1408, 1490, 1550, 1567, 1584; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.53 (dd, J = 6.8, 5.2 Hz, 2 H), 7.78 (d, J = 8.0 Hz, 2 H), 7.91 (d, J = 8.0 Hz, 2 H), 8.04 (dd, J = 8.0, 6.8 Hz, 2 H), 8.67 (d, J = 8.0 Hz, 2 H), 8.71 (s, 2 H), 8.82 (d, J = 5.2 Hz, 2 H); Anal. calcd for $C_{21}H_{14}BrN_3$: C, 64.96; H, 3.63; N, 10.82. Found: C, 65.01; H, 3.68; N, 10.78.

2.4.15 4'-(4-Fluorophenyl)-2,2':6',2"-terpyridine **21**

Appearance: white solid; Yield: 97%; R_f: 0.29 (*n*-hexane: EtOAc (1:9)); m.p.: 185°C; IR (KBr, cm^{-1}): 733, 788, 832, 991, 1039, 1161, 1225, 1386, 1416, 1466, 1512, 1552, 1567, 1585; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.40 (d, J = 8.8 Hz, 2 H), 7.53 (d, J = 8.8 Hz, 2 H), 7.99 (dd, J = 8.8, 5.2 Hz, 2 H), 8.05 (dd, J = 8.8, 8.4 Hz, 2 H), 8.67 (d, J = 8.4 Hz, 2 H), 8.70 (s, 2 H), 8.77 (d, J = 5.2 Hz, 2 H); Anal. calcd for $C_{21}H_{14}FN_3$: C, 77.05; H, 4.31; N, 12.84. Found: C, 69.97; H, 4.34; N, 12.87.

2.4.16 4'-(3-Bromophenyl)-2,2':6',2"-terpyridine **22**

Appearance: white solid; Yield: 91%; R_f: 0.50 (*n*-hexane: EtOAc (1:9)); m.p.: 167°C; IR (KBr, cm^{-1}): 755, 788, 883, 994, 1074, 1351, 1391, 1475, 1525, 1565, 1585; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.436–7.397 (m, 3 H), 7.612 (d, 1 H), 7.892 (d, J = 8.4 Hz, 1 H), 7.955 (dd, J = 8.9, 5 Hz, 2 H), 8.081 (s, 1 H), 8.789–8.719 (m, 6 H); Anal. calcd for $C_{21}H_{14}BrN_3$: C, 64.96; H, 3.63; N, 10.82. Found: C, 65.16; H, 3.52; N, 10.96.

2.4.17 4'-(3-Chlorophenyl)-2,2':6',2"-terpyridine **23**

Appearance: white solid; Yield: 90%; R_f: 0.70 (*n*-hexane: EtOAc (1:9)); m.p.: 152°C; IR (KBr, cm^{-1}): 733, 787, 884, 994, 1079, 1350, 1391, 1472, 1523, 1562, 1582; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.404 (dd, J = 5.4 Hz, 2 H), 7.471 (m, 2 H), 7.826 (d, J = 4 .4 Hz, 1 H), 7.948–7.917 (m, 3 H), 8.775–8.699 (m, 6 H); Anal. calcd for $C_{21}H_{14}ClN_3$: C, 73.36; H, 4.10; N, 12.22. Found: C, 73.12; H, 4.21; N, 12.36.

2.4.18 4'-Phenyl-3,2':6',3"-terpyridine **24**

Appearance: yellow solid; Yield: 91%; R_f: 0.34 (*n*-hexane: EtOAc (1:9)); m.p.: 211°C; IR (KBr, cm^{-1}): 734, 856, 995, 1354, 1454, 1599, 1630, 1684; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.26–7.59 (m, 5 H), 7.91 (m, 2 H), 8.22 (m, 2 H), 8.95 (d, J = 1.7 Hz, 2 H), 8.73 (m, 2 H), 9.42 (m, 2 H); Anal. calcd for $C_{21}H_{15}N_3$: C, C, 81.53; H, 4.89; N, 13.58. Found: C, C, 81.53; H, 4.79; N, 13.64.

2.4.19 4-([3,2':6',3"-Terpyridin]-4'-yl)-*N*,*N*-dimethylaniline **25**

Appearance: off-white solid; Yield: 85%; R_f: 0.80 (*n*-hexane:EtOAc (1:9)); m.p.: 223°C; IR (KBr, cm^{-1}): 777, 883, 997, 1490, 1489, 1597, 1590, 1593; ^1H NMR (300 MHz, $CDCl_3$): δ_H 3.03 (s, 6 H), 6.80 (m, 2 H), 7.28–7.68 (m, 4 H), 7.88 (m, 2 H), 8.45 (d, J = 1.8 Hz, 2 H), 8.68 (m, 2 H), 9.69 (m, 2 H); Anal. calcd for $C_{23}H_{20}N_4$: C, 78.38; H, 5.72; N, 15.90. Found: C, 78.33; H, 5.82; N, 15.91.

2.4.20 4'-(Furan-2-yl)-3,2':6',3"-terpyridine **26**

Appearance: white solid; Yield: 87%; R_f: 0.35 (*n*-hexane: EtOAc (1:9)); m.p.: 206°C; IR (KBr, cm^{-1}): 745, 856, 973, 1451, 1459, 1670, 1787, 1889; ^1H NMR (300 MHz, $CDCl_3$): δ_H 6.60 (dd, J = 3.4, 1.8 Hz, 1 H), 7.04 (dd, J = 3.4, 0.9 Hz, 1 H), 7.50 (m, 2 H), 8.10 (dd, J = 1.8, 0.9 Hz, 1 H), 8.42 (m, 2 H), 8.49 (d, J = 1.7 Hz, 2 H), 8.72 (m, 2 H), 9.37 (m, 2 H); Anal. calcd for $C_{19}H_{13}N_3O$: C, 76.24; H, 4.38; N, 14.04; O, 5.35. Found: C, 76.45; H, 4.65; N, 14.56; O, 5.37.

2.4.21 4'-(4-Methoxyphenyl)-3,2':6',3"-terpyridine **27**

Appearance: off-white solid; Yield: 85%; R_f: 0.52 (*n*-hexane:EtOAc (1:9)); m.p.: 157°C; IR (KBr, cm^{-1}): 430, 624, 666, 791, 1078, 1377, 1445, 1567, 1688, 3056; ^1H NMR (300 MHz, $CDCl_3$): δ_H 3.87 (s, 3 H), 7.00 (m, 2 H), 7.55 (m, 2 H), 7.76 (m, 2 H), 8.33 (m, 2 H), 8.45 (d, J = 1.7 Hz, 2 H), 8.68 (m, 2 H), 9.07 (m, 2 H); Anal. calcd for $C_{22}H_{17}N_3O$: C, 77.86; H, 5.05; N, 12.38; O, 4.71. Found: C, 77.67; H, 5.87; N, 12.54; O, 4.23.

2.4.22 3-([3,2':6',3"-Terpyridin]-4'-yl)-9-benzyl-9H-carbazole **28**

Appearance: white crystalline solid; Yield: 80%; R_f: 0.30 (methanol:chloroform (1:9)); m.p.: decomposed at 165°C; IR (KBr, cm^{-1}): 400, 621, 744, 1033, 1569; ^1H NMR (300 MHz, DMSO-d_6): δ_H 5.62 (s, 2 H), 6.96 (m, 2 H), 7.19–7.34 (m, 4 H), 7.53 (m, 1 H), 7.62 (m, 1 H), 7.78 (m, 2 H), 7.97 (m, 1 H), 8.11 (dd, J = 7.5, 0.5 Hz, 1 H), 8.29 (m, 1 H), 8.30–8.37 (m, 4 H), 8.65–8.71 (m, 3 H), 9.26 (m, 2 H); Anal. calcd for $C_{34}H_{24}N_4$: C, 83.58; H, 4.95; N, 11.47. Found: C, 83.12; H, 4.85; N, 11.34.

2.4.23 4'-Phenyl-4,2':6',4"-terpyridine **29**

Appearance: off-white solid; Yield: 96%; R_f: 0.42 (*n*-hexane:EtOAc (1:9)); m.p.: 200°C; IR (KBr, cm^{-1}): 796, 897, 993, 1392, 1455, 1555, 1566, 1581; ^1H NMR (300 MHz, $CDCl_3$): δ_H 7.43–7.58 (m, 3 H), 7.80–7.91 (m, 6 H), 8.63 (d, J = 1.7 Hz, 2 H), 8.72 (dd, J = 5.5, 1.9 Hz, 4 H); Anal. calcd for $C_{21}H_{15}N_3$: C, 81.53; H, 4.89; N, 13.58. Found: C, 81.67; H, 4.79; N, 13.48.

2.4.24 4-([4,2':6',4"-Terpyridin]-4'-yl)-*N*,*N*-dimethylaniline **30**

Appearance: orange solid; Yield: 93%; R_f: 0.70 (*n*-hexane: EtOAc (1:9)); m.p.: 156°C; IR (KBr, cm^{-1}): 780, 844, 996, 1423, 1480, 1556, 1576, 1582; ^1H NMR (300 MHz, $CDCl_3$): δ_H 3.03 (s, 6 H), 6.81 (m, 2 H), 7.34 (m, 2 H), 7.74 (m, 4 H), 8.47 (d, J = 1.7 Hz, 2 H), 8.84 (m, 4 H); Anal. calcd for $C_{23}H_{20}N_4$: C, 78.38; H, 5.72; N, 15.90. Found: C, 78.39; H, 5.76; N, 15.80.

2.4.25 4'-(Furan-2-yl)-4,2':6',4"-terpyridine **31**

Appearance: white solid; Yield: 95%; R_f: 0.60 (*n*-hexane: EtOAc (1:9)); m.p.: 188°C; IR (KBr, cm^{-1}): 791, 860, 960, 1390, 1456, 1630, 1764, 1890; ^1H NMR (300 MHz, $CDCl_3$): δ_H 6.63 (dd, J = 3.4, 1.8 Hz, 1 H), 7.08 (dd, J = 3.4, 0.9 Hz, 1 H), 7.66 (s, 1 H), 8.11 (m, 5 H), 8.54–8.59 (m, 4 H); Anal. calcd for $C_{19}H_{13}N_3O$: C, 76.24; H, 4.38; N, 14.04; O, 5.35. Found: C, 76.27; H, 4.39; N, 14.39; O, 5.36.

2.4.26 4'-(4-Methoxyphenyl)-4,2':6',4"-terpyridine **32**

Appearance: bright solid; Yield: 94%; R_f: 0.59 (*n*-hexane: EtOAc (1:9)); m.p.: 160°C; IR (KBr, cm^{-1}): 730, 791, 980, 1240. 1300, 1460, 1523, 1570, 3019, 3055; ^1H NMR (300 MHz, $CDCl_3$): δ_H 3.89 (s, 3 H), 7.05 (ddd, J = 8.9, 1.6, 0.4 Hz, 2 H), 7.67 (ddd, J = 8.9, 1.6, 0.4 Hz, 2 H), 7.96–8.05 (m, 6 H), 8.78 (m, 4 H); Anal. calcd for $C_{22}H_{17}N_3O$: C, 77.86; H, 5.05; N, 12.38; O, 4.71. Found: C, 77.90; H, 5.06; N, 12.40; O, 4.76.

2.4.27 3-([4,2':6',4"-Terpyridin]-4'-yl)-9-benzyl-9H-carbazole **33**

Appearance: yellow solid; Yield: 90%; R_f: 0.57 (methanol: chloroform (1:9)); m.p.: decomposed at 170°C; IR (KBr, cm^{-1}): 445, 623, 800, 1078, 1580, 1601, 1633; ^1H NMR (300 MHz, DMSO-d_6): δ_H 5.62 (s, 2 H), 6.97 (m, 2 H), 7.19–7.35 (m, 3 H), 7.49–7.66 (m, 3 H), 7.97 (dd, J = 6.1, 1.8 Hz, 1 H), 8.05–8.14 (m, 5 H), 8.29 (m, 1 H), 8.54 (d, J = 2.0 Hz, 2 H), 8.68 (m, 1 H), 8.84 (m, 4 H); Anal. calcd for $C_{34}H_{24}N_4$: C, 83.58; H, 4.95; N, 11.47. Found: C, 83.60; H, 4.92; N, 11.48.

3 Results and discussion

3.1 Synthesis of DABCO-alkyl halide based deep eutectic ionic liquids

DABCO-alkyl halide based DEILs were recently reported by Ali Ghumro et al. [30] and Faisal et al. [31]. They observed that these DEILs were highly appropriate for sysnthesis of variety of 1*H*-tetrazoles (by click chemistry), indoles (by Fischer indole synthesis) and acridine analogous. In this work, we investigate the effectiveness of these DEILs towards synthesis of terpyridines. DEILs (**6a**, **6b**, **7a**, **7b**, **8a** and **8b**) were synthesized according to the reported literature [30,31]. In detail, *N*-alkylation of DABCO with haloalkanes (1-bromopentane or 1-bromoheptane) produced quaternary ammonium salts **5a** and **5b**, which were then vigorously mixed with methanol, PEG-300 or PEG-400 as a hydrogen bond donor (HBD) and heated at 80°C to furnish alkylated-DABCO-derived DEILs (Scheme 1).

3.2 Effectiveness of DEILs towards terpyridine synthesis and reaction conditions optimization

To evaluate the effectiveness of these DEILs towards synthesis of terpyridines, all DEILs (**6a**, **6b**, **7a**, **7b**, **8a** and **8b**) were utilized for synthesis of **9**. The reaction of 2-acetylpyridine **34** with benzaldehyde in the presence of sodium hydroxide, ammonium acetate and a DABCO-based DEIL at 80°C for 3–3.5 h afforded **9**. As shown in Table 1, among all tested DEILs, the DABOC-PEG-300 (**8a)** afforded the highest yield (96%) and hence can be regarded as the most suitable DEIL for synthesis of terpyridines.

3.3 Characterization of DEILs through freezing point depression and phase diagram

Ali Ghumro et al. [30] had claimed that the **6a**, **6b**, **7a**, **7b**, **8a** and **8b** are DEILs. These DEILs were confirmed by determining freezing point depression and further characterized by differential scanning calorimetry (DSC), derivative thermogravimetry (DTG) and thermal gravimetric analysis (TGA). All these characterizations were performed on DEIL **8a** (and its precursors) because it displays the highest yield in the synthesis of terpyridines**.**

By definition, the deep eutectic composition is achieved when the mixture reaches the lowest freezing point among all possible mixing ratios [32]. The freezing temperature of DEILs is always much lower than the melting or freezing point of their starting materials. Hence, freezing point depression (ΔT_f) is the characteristic feature of the DEILs formation [33]. The freezing point of DEILs mainly depends on the composition and components of quaternary ammonium salts (QASs) and hydrogen bond donors. The greater the interaction between the components of the mixture, the larger the freezing point depression [34]. To determine the lowest freezing point among all possible mixing ratios of HBD and QAS, seven samples DES1-7 were synthesized by mixing PEG-300 and **5a** in different ratios of 1:1, 1.5:1, 2:1, 2.5:1, 1:1.5, 1:2 and 1:2.5, respectively, as shown in Table 2. Attempts to use some other mixing ratios (1:3, 3:1, 4:1 and 1:4) were unsuccessful as the two components did not properly mix in these cases.

The freezing point of these seven samples were

Table 1 Yield of terpyridine **9** with various deep eutectic ionic liquids.

Entry	DABCO-ILs	Refluxing time /h	Yield of **9** /%
1	**6a**	3.5	86
2	**6b**	3.5	84
3	**7a**	3	87
4	**7b**	3	82
5	**8a**	3	96
6	**8b**	3	92

determined by freeze drying method and rotary evaporation method (Table 2). The individual components, **5a** and PEG-300, melt at 7.3°C and −14°C, respectively. Among all the synthesized samples, DES3 (**8a**) has the lowest freezing point (−72.7°C) and hence, PEG-300 and **5a** with a 2:1 molar ratio is the deep eutectic composition. The large depression in freezing point of **8a** compared to its individual components confirms the formation of DEIL. It is also important to note that the freezing points are lower than room temperature, signifying that they are liquids at room temperature.

Schematic liquid-solid phase diagram for a binary system of PEG-300 and **5a** is illustrated in the Fig. 4. From this figure, it can be seen PEG-300 has a T_f of −14°C, and **5a** has T_f of 7.3°C. The liquidus lines slope downwards the freezing points of the pure entities and meet at a point called as the eutectic point (designated by the black box). At a molar ratio of 2:1 (PEG-300, 67.7 mol-%; **5a**, 32.3 mol-%), a eutectic mixture is formed at −72.7°C. DEILs have freezing points far below any of their starting materials. Upon mixing, the depression in freezing point arises from the formation of powerful HBD-HBA (hydrogen bonding acceptor) intermolecular interactions, which are optimum for the eutectic mixture composition [35,36].

3.4 Thermal study of DABCO-based DEIL

Differential scanning calorimetry (DSC), derivative thermogravimetry (DTG) and thermal gravimetric analysis (TGA) were used to estimate thermal stability of the alkylated-DABCO-mediated DEIL. For DEIL **8a**, Fig. 5(a) shows the overlap of TGA (red) and its first derivative (DTG data; green) graphs, and Fig. 5(b) shows the overlap of its TGA (red) and DSC (blue) graphs. In the first stage, there is a mass loss of almost 31% from 25°C–100°C. In this temperature range, the respective DSC signal reveals an endothermic course and is probably due to desorption of trapped water (adsorbed and interstitial water) and organic solvents (DCM, toluene, EtOAc and hexane), which were employed in the synthesis of DEIL **8a**. After the loss of organic solvents and trapped water, the mass remains constant up to 217°C, suggesting that DEIL **8a** is stable up to 217°C. Thereafter, the first decomposition stage occurs at 255°C as determined by the DTG, accompanied by a large mass loss of about 29% corresponding to loss of heptyl chains. As per DSC, this mass loss is also an endothermic course. Immediately after this step, the second decomposition stage occurs at 300°C as indicated by the DTG, accompanied by a sharp mass loss of about 41% corresponding to the thermal decomposition/burning of DABCO core and/or breaking of bonds. As per DSC, this mass loss is also an endothermic course. From the TGA, DSC and DTG, it can be concluded that DEIL **8a** could be used safely in organic reactions owing to its thermal stability up to 217°C.

3.5 Synthesis of library of 2,2':6',2"-terpyridines and plausible mechanistic pathway

Next, we applied DEIL **8a** in the synthesis of different terpyridines. Terpyridines **9**–**23** were obtained in excellent yields (85%–97%) by the reaction of 2-acetylpyridine **34** with a variety of aromatic aldehydes in the presence of sodium hydroxide, ammonium acetate and DEIL **8a** at 80°C for 3–4 h (Scheme 2). This is a Kröhnke reaction that is divided into two stages: the first stage involves the formation of 1,5-dicarbonyl intermediate **35** through Robinson annulation, and the second stage involves the cyclization of **35** into pyridine ring [37,38]. The Robinson annulation involves two reactions: Aldol condensation, in which the reaction of two aldehydes or two ketones (or a ketone and an aldehyde) produces *β*-hydroxy-aldehyde or ketone and after dehydration *α*,*β*-unsaturated aldehyde or ketone; and Michael addition, in which a carbon-nucleophile undergoes conjugate addition to an *α*,*β*-unsaturated system [39]. Cyclization of 1,5-diketone **35** is a Leuckart type reaction which involves condensation with ammonia and dehydrogenation. In this reaction, ammonium acetate acts as cyclization agent to cyclize 1,5-diketone **35** into terpyridines and NaOH acts as base. KOH can also be used to replace NaOH. The yield, reaction time

Table 2 Freezing points of seven samples determined by rotary evaporation and freeze drying

Molar ratio of PEG-300:**5a**	Sample abbreviation	Freezing point /°C	
		Freeze drying	Rotary evaporation
1:1	DES1	−61.1	−61.4
1.5:1	DES2	−65.2	−65.3
2:1	DES3, **8a**	−72.7	−72.5
2.5:1	DES4	−60.5	−60.3
1:1.5	DES5	−55.2	−55.2
1:2	DES6	−49.1	−49.3
1:2.5	DES7	−45.1	−45.3

and structure of synthesized terpyridines are shown in Fig. 2. Noteworthy, in all cases, the yield is excellent.

3.6 Properties of DABCO-alkyl halide based deep eutectic ionic liquids

In synthetic chemistry, PEG-300 was employed owing to its negligible toxicity of PEG-300, and has become a famous reaction bath over the past few decades [40]. Moreover, this reaction bath fully meets the requirements of green chemistry, as it is potentially recyclable and also extremely miscible in water. On the other hand, DABCO **4** is readily available chemical and contains two active nitrogen units; as DABCO **4** is a solid, it offers extreme ease of handling and negligible toxicity. The alkylation of DABCO with various haloalkanes provides remarkable ILs. Hence, PEG-300 in combination with DABCO-mediated ILs makes this system versatile and extremely useful. Furthermore, according to literature, DES or DEIL systems are developed from a eutectic mixture of bases and Brønsted or Lewis acids, which contain a diversity of cationic or/and anionic species. They are categorized as ionic solvents possessing exclusive characteristics. In a mixture form, they incorporate one or more than one compound, to afford a eutectic with M.P considerable lower than either of the individual compounds [41]. In comparison with classical solvents, most of which are volatile organic compounds (used in previous approaches for synthesis of terpyridines), DES or DEILs have a very low vapor pressure and are thus non-flammable [42]. DES or DEILs also possess low densities, which make them extremely useful and can be liquid at a broad spectrum of temperatures, i.e., nearly −50°C for some DESs [43]. Therefore, this DEIL protocol can be regarded as an extremely useful and highly green approach. Green chemistry highlights pollution prevention and application of chemical method to eliminate or reduce the generation and use of dangerous chemical, and is thus safe for health and environmental [44].

During the synthesis of terpyridines, it was observed that the DABCO-based DEIL system was less volatile, nonflammable, nontoxic and highly thermal stable. Moreover, this system has excellent capacity to dissolve many chemicals, wide electrochemical window and large liquid range [45–47]. Additionally, the most prominent advantage of this DEIL protocol is that, in a one pot process, it provides acceptable yields in all cases without the formation of unwanted side products. Therefore, this approach is highly applicable, convenient and economic for the synthesis of terpyridines.

3.7 Synthesis of 3,2':6',3"-terpyridines and 4,2':6',4"-terpyridines using DABCO-based DEIL

Among all the three types of terpyridine, 2,2':6',2"-terpyridine are the most useful due to appropriate position of nitrogen atoms in 2,2':6',2"-terpyridine, which leads to the formation of strong coordination complexes. On the other hand, due to unsuitable position of nitrogen atoms in 3,2':6',3"-terpyridine and 4,2':6',4"-terpyridine, they are incapable to form strong complexes [1–4]. A large amount of research has focused on the synthesis of 2,2':6',2"-terpyridine [3,4], whereas rare investigations have been done for synthesis of 3,2':6',3"-terpyridine and 4,2':6',4"-terpyridine. For the synthesis of these two terpyridines, we have also investigated the effectiveness of alkylated-DABCO-mediated DEIL **8a**. According to the similar procedure for the synthesis of 2,2':6',2"-terpyridine, 3,2':6',3"-terpyridines **24**–**28** and 4,2':6',4"-terpyridine **29**–**33** were synthesized by using 3-acetylpyridine and 4-acetylpyridine, respectively. The yields, reaction time and structures of synthesized terpyridines are illustrated in Fig. 3. In all cases, the yield is satisfactory. In general, the yields of terpyridines decrease in the order 4,2':6',4"-terpyridine > 2,2':6',2"-terpyridine > 3,2':6',3"-terpyridine, and the corresponding reaction time follows the same order.

3.8 Reusability of DABCO-based DEILs

The DABCO-based DEILs were reused for several times for the synthesis of terpyridines to evaluate their recyclability [48]. As shown in Table 3, these DEILs can be recycled four times with only a slight loss of catalytic efficiency (Table 3).

3.9 Comparison of DABCO-based DEIL approach performance with other literature approaches

In the literature, the method to prepare terpyridine framework was usually through Kröhnke reaction. Hence, we compared our method with the literature methods for the synthesis of 4'-phenyl-2,2':6',2"-terpyridine **9**. As shown in Table 4, the reported approaches suffer from various disadvantages such as moderate yields, long reaction time in some cases (12 h), use of volatile organic solvents (MeOH, EtOH) and toxic reagent (NH_3) [17–20]. In contrast, DEIL **8a** is more efficient, reliable and cost-effective (due to high recyclability), providing **9** in a 96% yield (compared to 36%–89% yields by other approaches). Moreover, our approach is applicable for large-scale synthesis of terpyridines and does not require any special devices such as ultrasound and microwave.

4 Conclusions

We have successfully developed a one-pot, highly efficient method by using DABCO-derived quaternary ammonium salts as DEILs for the preparation of 2,2':6',2"-terpyridines, 3,2':6',3"-terpyridines, and 4,2':6',4"-terpyridines. This method meets many criteria in terms of safety such as

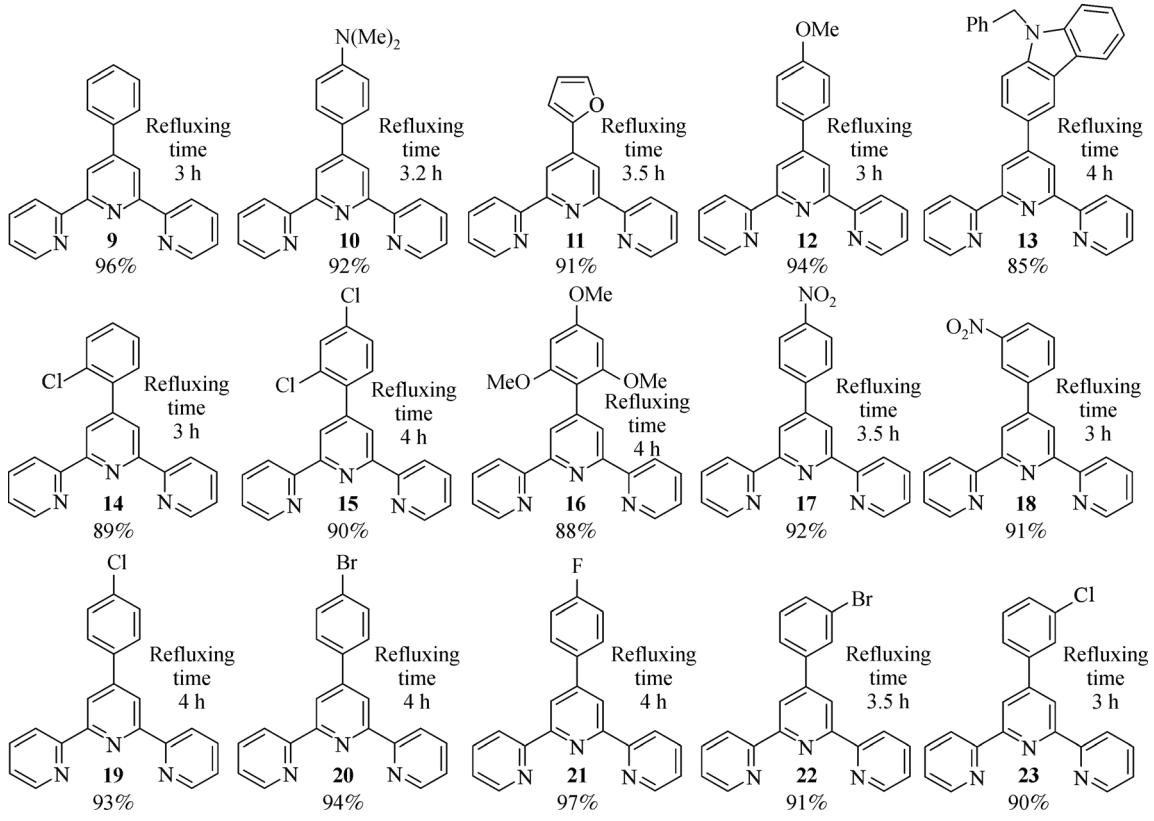


Fig. 4 Schematic phase diagram of **5a** in PEG-300.T_f: the freezing point; HBD: PEG-300; salt: **5a**. The solid lines (red and blue) show the freezing point as a function of mixture composition, and the dashed black lines depict the composition and temperature of the eutectic mixture

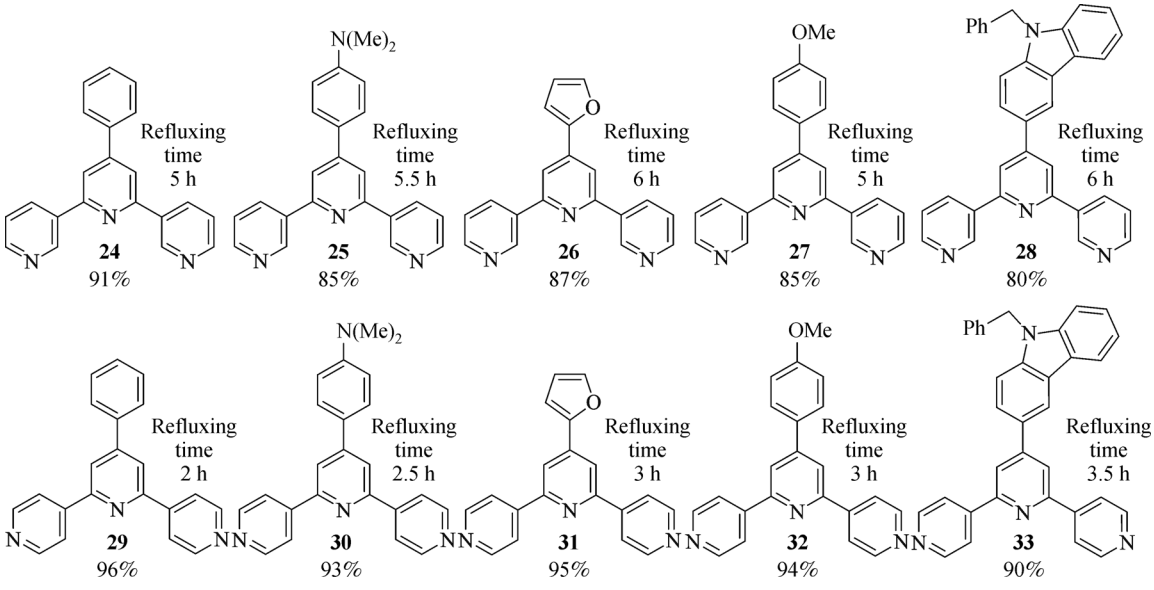


Fig. 5 (a) Overlap of DTG (green) and TGA (red) graphs for DEIL **8a**; (b) Overlap of DSC (blue) and TGA (red) graphs for DEIL **8a**

Table 3 Efficiency of recycled DEILs in synthesis of terpyridines

Entry	DEIL	Product	Yield/% of recovered DEIL				
			Cycle 1	Recycle 1	Recycle 2	Recycle 3	Recycle 4
1	**8a**	9	96	92	90	85	84
2	**8b**	9	92	86	84	83	80
3	**8a**	11	81	80	78	76	75
4	**8b**	11	78	72	72	71	70

Table 4 Synthesis of 4'-phenyl-2,2':6',2"-terpyridine under various conditions

Entry	Bases	Solvent	Reaction temperature/ °C	Reaction time/h	Yield/%	Recyclability	Ref.
1	KOH, NH_4OAc	MeOH	r.t.	12	57	No	[49]
2	KOH, aq. NH_3	EtOH	r.t.	2	53	No	[50]
3	KOH, aq. NH_3	EtOH	r.t.	8	36	No	[51]
4	KOH, NH_4OH	EtOH	r.t.	4	62	No	[52]
5	NaOH, aq. NH_3	EtOH	r.t.	12	69	No	[53]
6	NaOH, AcOH, NH_4OAc	Solvent free conditions	Reflux	2	89	No	[54]
7	NH_4OAc	H_2O	130	5	71	No	[55]
8	NH_4OAc	H_2O	MWI	0.4	82	No	[55]
9	NH_4OAc	Glycol	MWI	0.33	80	No	[22]
10	NaOH, NH_4OAc	Imidazolium-based IL	140	4	72	No	[56]
11	NaOH, NH_4OAc	PEG-300	100	4	55	No	[57]
12	NaOH, NH_4OAc	DEIL **8a**	80	3	96	Yes	This work

environment, legality, control, and throughput. Compared to the existing approaches, this method has advantages such as easy work-up, short reaction time (2–6 h), high yield (80%–97%), clean procedure, environment friendliness, low volatility, non-toxicity, biodegradability and high thermal stability. Moreover, these DEILs can be reused or recycled without significant loss of effectiveness. Therefore, this method may find applications in the synthesis of a variety of terpyridines.

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Conflicts of Interest The authors declare that they have no conflict of interest.

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