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Deep eutectic solvents used as catalysts for synthesis of 1,10-phenanthroline by improved Skraup reaction

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Abstract

In this study, three different choline chloride-based deep eutectic solvents were synthesized. And it is the first time to synthesize 1,10-phenanthroline through an improved Skraup reaction using deep eutectic solvent as the new catalyst from acrolein and 8-aminoquinoline. The deep eutectic solvents were characterized by Fourier transform infrared (FT-IR), ^{1}H nuclear magnetic resonance (^{1}H NMR), pH/mV meter, and thermogravimetric analysis (TGA). The research results show that the deep eutectic solvent formed by sulfanilic acid and choline chloride has the strongest acidity and highest catalytic active among the three deep eutectic solvents. Besides, the impacts of reaction parameters and molar ratio of raw materials on the reaction were also investigated. Under the optimized reaction conditions, the maximum selectivity and yield of 1,10-phenanthroline were achieved as 84.6 and 75.6%, respectively. The synthesis method, meanwhile, also has simple preparation process and low cheaper catalyst raw.

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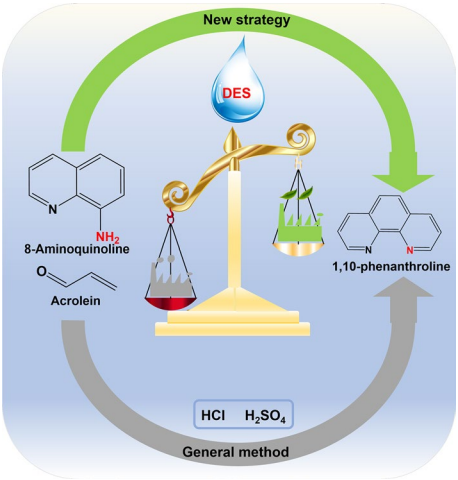
Graphical abstract



Replacing traditional sulfuric acid and hydrochloric acid with deep eutectic solvents (DESs) as new catalysts provides a more efficient, greener and more economical strategy for the synthesis of 1,10-phenanthroline by a new improved Skraup reaction.

Keywords Skraup reaction · 1,10-phenanthroline · Deep eutectic solvent · Choline chloride · Acrolein · 8-aminoquinoline

Introduction

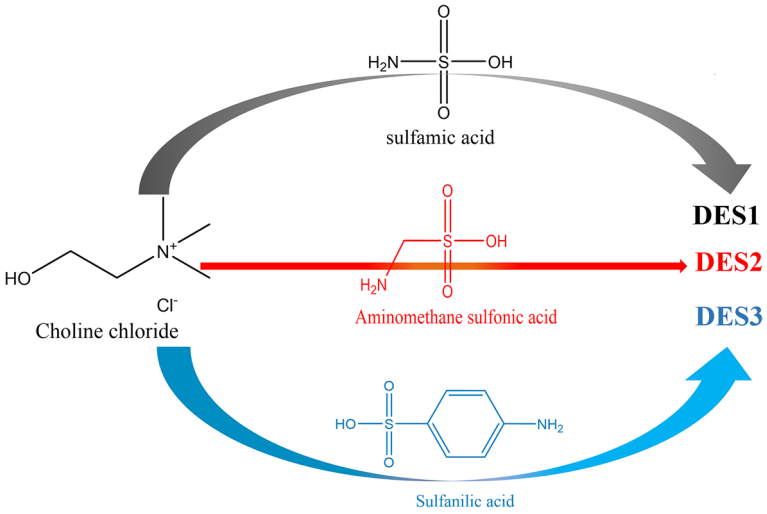
1,10-phenanthroline has been used for decades as a class of important nitrogen heterocyclic and chelating agents that form a multitude of coordination compounds with various metal ions [1]. By far, the researchers show a great interest in the supramolecular chemistry [2], pharmaceutical chemistry [3], catalytic chemistry [4] and organic functional materials [5] on 1,10-phenanthroline.

Due to the significant applications of 1,10-phenanthroline in the fields of chemistry and biology, some classic synthesis methods of 1,10-phenanthroline include Skraup [6], Friedlander [7] and Doebner-Von Miller [8] reactions. Otherwise, Povarov reaction [9] and photochemical electrocyclic reaction [10], in recent years, have also been as novel methods to the synthesis of 1,10-phenanthroline. These methods, however, usually carried out under harsh conditions such as strong acidity and high temperature so that it is difficult to control the reaction. More terribly, what are the limitations of these methods are complex reaction process, low yield, poor selectivity, and high corrosive. Thus, the development of efficient synthetic method for the preparation of 1,10-phenanthroline with mild reaction conditions is still a challenge problem. Chelucci et al. [11] studied the synthesis of 1,10-phenanthroline, with the yield of it reaching 67%, from

polysubstituted pyridine as the original materials in a two-step process. Later, Abahmane et al. [12] investigated that the alumina-supported gold nanoparticles catalyzed the 1,2-cyclohexanedione and propargylamine toward synthesis of 1,10-phenanthroline with a yield of 75%. Furthermore, Cheng et al. [13] reported that an effective method to synthesis of a series of 1,10-phenanthroline derivatives by the Lewis acid-catalyzed cyclization reaction between 3-ethoxycyclobutanones and 8-aminoquinolines. In those studies, however, they offered some new routes for the synthesis of 1,10-phenanthroline and could obtain a certain yield of it, but most of them used the expensive raw materials and catalysts, which have a higher reaction cost so that it is not suitable for large-scale industrial production. So, we focused on the synthesis of 1,10-phenanthroline with simple methods and original materials. At the same time, what we considered was that the structural framework of 1,10-phenanthroline could not contain any substitution groups. So, the 8-aminoquinoline(8-AQ) was used as the ring-forming framework structure. Acrolein, in the Skraup reaction, glycerol was dehydrated under strong acid reaction conditions to form it [14], 15, was used for cyclization reaction.

Based on the above researches, it is clear that the development of an available catalyst with high activity and low cost maintains a challenge. Since the term deep eutectic solvent (DES) was proposed in 2001 by Abbott et al. [16], basic properties and potential applications of these systems have been investigated. At the same time, many researchers used the DESs as dual roles (solvent and catalyst) in many reactions. Otherwise, DESs are now as a new type of ionic liquid (IL) analogs, which have many similar properties and characteristics with ILs: a low vapor pressure, a relatively excellent chemical and thermal stability, strong solubility and modifiability [17]. However, ILs are formed from systems consisted mainly of a type of discrete anion and cation. In contrast, DESs contain a hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD), mixed together to form a homogeneous system. What is more, the process of the preparation for DESs is simple and high atom economy and the raw materials are cheap, which is beneficial for large-scale production. Shahabi et al. [18] researched that using choline chloride/tin(II) chloride DES as a green catalyst, under a relatively mild reaction conditions, for the synthesis of quinoline with the yield was as high as 92% through a one-pot, three components. However, there are no reports in the literature that using DES as a catalyst for the synthesis of 1,10-phenanthroline.

So, in this study, three different DESs were prepared by simple mixed heating HBDs of sulfamic acid, aminomethane sulfonic acid, sulfanilic acid and the same HBA choline chloride (ChCl). The preparation routes for DESs are shown in Scheme1. And it was used as the catalyst for the first time in the improved Skraup reaction aimed to the synthesis of 1,10-phenanthroline with a higher yield and mild reaction conditions. The catalytic performances of DESs in the synthesis of 1,10-phenanthroline have been tested. Moreover, the physicochemical properties of DESs were characterized by Fourier transform infrared, ^{1}HNMR, pH/mV meter and thermogravimetric analysis. Meanwhile, the best catalytically active catalyst was found to be DES formed by choline chloride and sulfanilic acid. The optimum technological conditions were also optimized.



Scheme 1 Synthesis of DESs

Experimental section

Materials

8-Aminoquinoline (98%) and acrolein (95%) were purchased from Jiangsu Aikon Biopharmaceutical R&D Co., Ltd. 1,10-phenanthroline (>99%) was purchased from Sinopharm Chemical Reagent Co., Ltd. Sulfamic acid (AR) and choline chloride (AR) were purchased from Shanghai Macklin Biochemical Co., Ltd. Aminomethane sulfonic acid (98%) was purchased from Shanghai Meryer Chemical Technology Co., Ltd. Sulfanilic acid (99.5%) was purchased Shanghai Tengzhun Biotechnology Co., Ltd. Sulfuric acid (98%) and p-toluenesulfonic acid (AR) were obtained from Chengdu Kelong Chemical Co., LTD, China. All the Methanol, Ethanol, Acetonitrile, N,N-Dimethylformamide and Dimethyl sulfoxide were A.R. grade reagents and were purchased from Guangdong Guanghua Sci-Tech Co., Ltd. All the reagents were used as received without further purification.

Deep eutectic solvents preparation

The preparation method of deep eutectic solvents was by heating the mixture of choline chloride and hydrogen bond donor. In a typical process, choline chloride (ChCl) with HBD in the specified molar ratio was mixed. The deep eutectic solvents were obtained by mixing the two components and heated in an oil bath until a colorless homogeneous liquid was simply formed. Then, the DES was dried in a vacuum drying oven at about 70 °C for 4 h, which was then stored in a desiccator for further use.

Characterizations of deep eutectic solvents

The DESs were characterized by Fourier transform infrared (FT-IR) spectra were obtained with Thermo Fisher Nicolet 670 in the wavelength range of 4000 cm^{-1} to 500 cm^{-1} and the resolution was 4 cm^{-1}, using KBr powders. ^{1}H nuclear magnetic resonance (NMR) spectra were carried out on a Bruker Avance Neo 600 MHz type spectrometer at room temperature (600 MHz) and TMS as internal standard in DMSO. The acidity of DESs in organic solvent solution was investigated at a certain concentration of 0.025 g/mL, which was tested by the PHS-3C type pH/mV meter. Thermogravimetric analysis (TGA) was performed on a SDT Q600 V20.9 Build 20 thermal analyzer on the conditions of a heating rate of 5 °C min^{-1}, a nitrogen gas flow of 30 mL min^{-1}, over the 30–750 °C temperature range.

The synthesis and analysis of 1,10-phenanthroline

Generally, the experiment was carried out in a 100 mL three-necked flask with a thermometer, a condensing tube and a gas absorption device of sodium hydroxide solution. In a typical reaction process, a certain amount of 8-aminoquinoline and DES catalyst and solvent were placed into the flask and allowed to melt at a certain temperature under magnetic agitation. When the reaction mixture was quickly heated to designed temperature, the acrolein was added into the flask, too. After reaction, the reaction products were cooled to room temperature for further analysis. A high-performance liquid chromatography (HPLC, Waters e2695) equipped with a 2414 refractive index (RI) detector and Asahipak column (NH_2P-50 4E, No. N1670026) was used to analysis the products. Methanol/water/Triethylamine (0.65:0.35:0.0005) mixture was used as an eluent for the analysis with the flow rate of 1 mL/min. The temperature of RI detector was maintained at 40 °C throughout the analysis. The temperature of RI detector was maintained at 40 °C throughout the analysis. Conversion of 8-aminoquinoline (Con.) and 1,10-phenanthroline selectivity (Sel.) was defined according to the following equations. (1–3):

$$Con.\% \frac{moles\ of\ reacted\ 8-a\min oquinoline}{moles\ of\ initial\ 8-a\min oquinoline} * 100 \tag{1}$$

$$Sel.\% = \frac{moles\ of\ producted\ 1,10-phenanthroline}{moles\ of\ reacted\ 8-a\min oquinoline} * 100 \tag{2}$$

$$Yield.\% = Con. * Sel.\ \ 100\% \tag{3}$$

Results and discussions

Screening of DESs catalysts

The catalytic activity of DESs with different molar ration of hydrogen bond acceptor (HBA) and hydrogen bond donor (HBD) in the synthesis of 1,10-phenanthroline from acrolein and 8-amionquionline has been investigated. The result is shown in Table 1. It is demonstrated that the yield of 1,10-phenanthroline follows the trend of SFA > SMA > ASA when the HBD is not the same one. Furthermore, it also can be seen when the HBD as the same, the yield follows as the HBD: HBA molar ration of 1:2 is the best one. Thus, the HBD: HBA molar ration of 1:2 DESs system formed by sulfamic acid, aminomethane sulfonic acid and sulfanilic acid with choline chloride were named DES1, DES2 and DES3, respectively, which were selected for the synthesis of 1,10-phenanthroline, and the reaction conditions were further explored.

The ratios of 1:1,1:2, and 2:1 are refer to the molar ration of two compounds. SMA: sulfamic acid, ASA: aminomethane sulfonic acid, SFA: sulfanilic acid.

FT-IR spectra analysis of DESs

To confirm whether the DESs were synthesized, the sulfamic acid, aminomethane sulfonic, sulfanilic acid and DESs were characterized by FT-IR as shown in Fig. 1. As observed in Fig. 1a, the characteristic peak appeared at around 3158 cm^{-1} and 3412 cm^{-1} were belonged to asymmetrical stretching vibration of N–H of sulfamic acid and the 2455 cm^{-1} was the stretching vibration of -NH_2. In contrast, with the addition of choline chloride, the absorption peak at around 2455 cm^{-1} of DES1 was disappeared, and the absorption peaks of 3158 cm^{-1} and 3412 cm^{-1} blue-shifted to 3208 cm^{-1} and 3416 cm^{-1} with an enhanced absorption band. It may be caused by hydrogen bonds formed through the interaction of materials [19]. Similarly, as illustrated in Fig. 1b, the characteristic absorption peaks at around 754 cm^{-1} and 1606 cm^{-1} were attributed to the out-of-plane wagging vibration of N–H and scissoring vibration of $-NH_2$. The addition of choline

Table 1 The catalytic performance of different DESs [a]

Number	Cat(10wt%)	Ration	Con (%)	Sel (%)	Yield (%)
1	SMA/Chcl	1/1	76.8	57.9	44.5
2	SMA/Chcl	1/2	70.0	66.0	46.2
3	SMA/Chcl	2/1	68.0	59.2	40.3
4	ASA/Chcl	1/1	58.5	52.6	30.8
5	ASA/Chcl	1/2	63.5	62.3	39.6
6	ASA/Chcl	2/1	56.5	60.2	34.0
7	SFA/Chcl	1/1	76.3	70.1	53.5
8	SFA/Chcl	1/2	71.9	84.1	60.5
9	SFA/Chcl	2/1	72.3	72.1	52.1

[a]Reaction conditions: V(DMF) = 10 mL, n(8-AQ) = 1 mmol, n(Acrolein) = 1.5 mmol, cat = 10wt% of 8-AQ, T = 130 ℃ t = 4 h

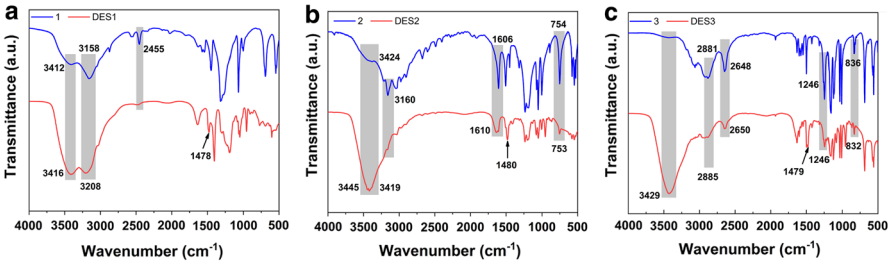


Fig. 1 FT-IR spectra of sulfamic acids (**a**), aminomethane sulfonic (**b**), sulfanilic acid (**c**) and DESs

chloride reduced the absorption intensity of the out-of-plane wagging vibration of N–H and the peak of scissoring vibration of $-NH_2$ was moved to 1610 cm^{-1}. Furthermore, the stretching vibration absorption peaks of N–H at around 3419 cm^{-1} and 3445 cm^{-1} were significantly enhanced, which could correspond to the formation of a large number of hydrogen bonds [20]. In Fig. 1c, there was no significant shift in the absorption peaks of the out-of-plane wagging vibration of N–H at 836 and 832 cm^{-1} and the stretching vibration of C-N at 1246 cm^{-1}, which is consistent with the results reported by literature [19]. However, in the band from 2500 to 3000 cm^{-1}, the absorption peaks of hydroxyl groups on the sulfonic acid groups were weakened. In the meantime, the strength of the absorption band at 3429 cm^{-1} was significantly increased, which would further be conducive to show that hydrogen bonds were formed between choline chloride and sulfanilic acid [21].

In addition, the asymmetrical stretching vibration of the terminal methyl group of choline chloride was also observed at the 1479 cm^{-1} in the FT-IR spectra of the three DESs suggested that the structure of Ch^+ was not destroyed, which could further be indicated choline chloride and the HBDs were mainly connected by hydrogen bonds [22].

^{1}HNMR spectra analysis of DESs

The hydrogen bond interaction of DESs was also investigated by ^{1}H NMR technique as shown in Fig. 2. As illustrated in Fig. 2a, the H signal at 12.16 ppm of sulfamic acids has a higher field shift and moves to 12.04 ppm after the formation of the DES. Similarly, the H signal at 6.03 ppm of aminomethane sulfonic also moves to 5.92 ppm as shown in Fig. 2c. In addition, we found that the H signal at 12.09 ppm of -OH of sulfanilic acid has a lower field shift moves to 12.61 ppm in Fig. 2e, which may because of the deshielding and steric effects of benzene ring. These results prove the formation of hydrogen bonds between the HBA and HBD [22] [23]. Besides, the chemical shift of H signal in choline chloride has no obvious chemical shift before and after the formation of DESs, which would be conducive to show that the structure of choline chloride did not change significantly. The results were consistent with the results of FT-IR analysis.

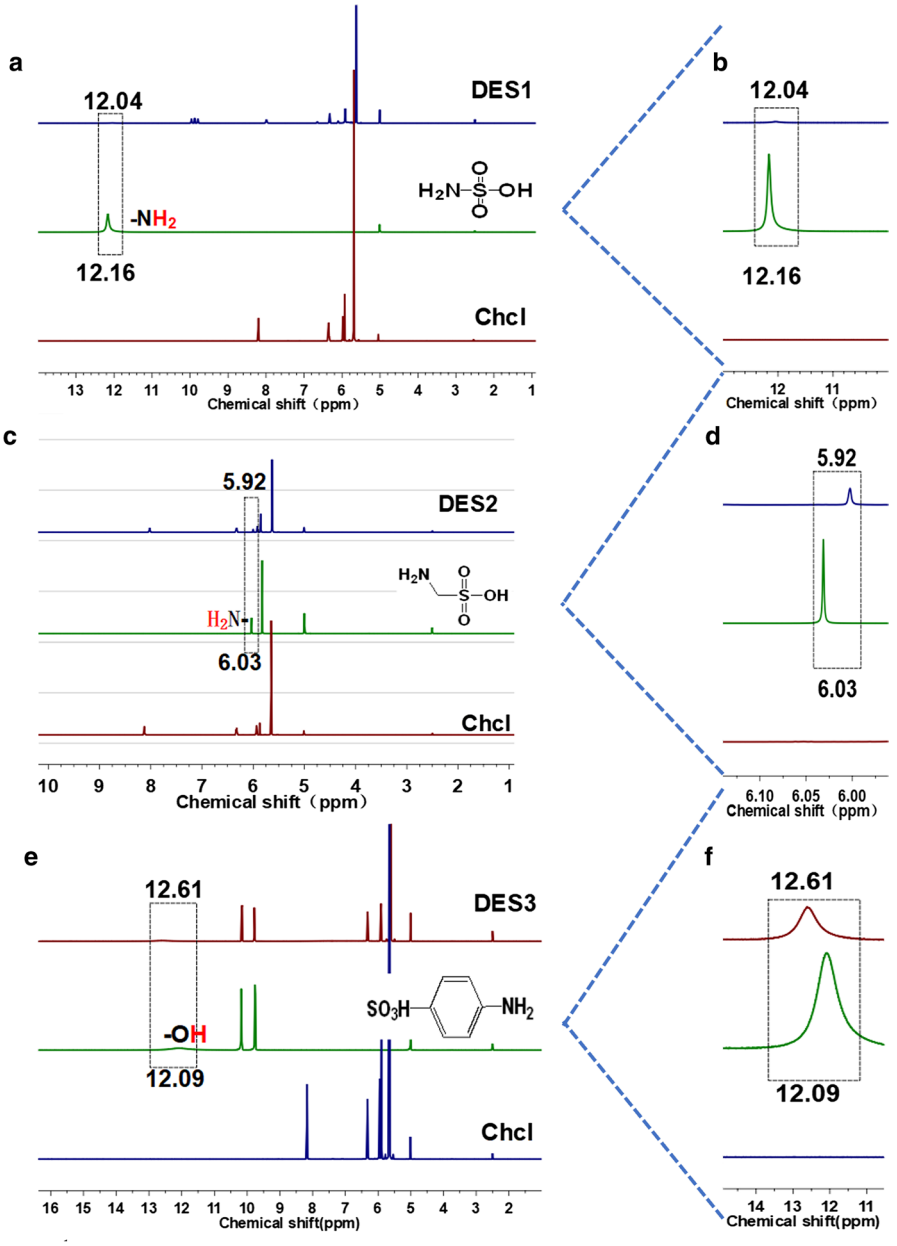


Fig. 2 ^{1}H NMR spectra of sulfamic acids and DESs and corresponding enlarged image

Acidity of DESs in N,N-dimethylformamide (DMF) and Dimethyl sulfoxide (DMSO)

It is a matter of great concern to focus on the acidity for DESs as the acidic catalyst, and there are many researches which expound the acidity of DESs by

performing pH measurements [24]. So, in order to explore the acidity of three DESs under the reaction conditions, the influence of temperature on the pH value of DESs at a concentration of 0.025 g/mL with DMF and DMSO as the organic solvent were investigated as shown in Fig. 3. According to Fig. 3a, temperature has a remarkable effect on acidity and the pH value of DESs can be ordered as follows: DES2 > DES1 > DES3. Meanwhile, when the temperature increased from 85 to 145 °C, the pH value of three DESs were decreased rapidly. However, the pH value of DES2 at 160 °C was observed to rise gradually, which could be resulted by the weakened hydrogen bonds or part of Ch^+ would be just released [25] at a higher temperature. Similarly, in Fig. 3b, the pH value trend of DES in DMSO is consistent with that in DMF. In addition, the pH value of the DESs is dependent upon the hydrogen bond donor.

Thermogravimetric analysis of DESs

To investigate the thermal stability of DESs, the DESs were studied by TGA under the protection of nitrogen as shown in Fig. 4. The DES1 and DES3 showed prominent thermodynamic stability when the temperature did not exceed about 240 °C. The TG curves of DES1 and DES3 lost 3.76% and 7.77% between 30 and 236 °C, which was in connection with the removal of physic-adsorbed H_2O. As the temperature continues to rise, DES1 and DES3 began to decompose and reached the maximum decomposition rate at 326 and 240 °C, respectively. The decomposition temperature of DES2 is lower than DES1 and DES3, however, which is further proved that the pH value increases because of the release part of Ch^+ after the temperature exceeds 145 °C. Therefore, it can be concluded that DESs can act as stable compounds to catalyze the improved Skraup reaction.

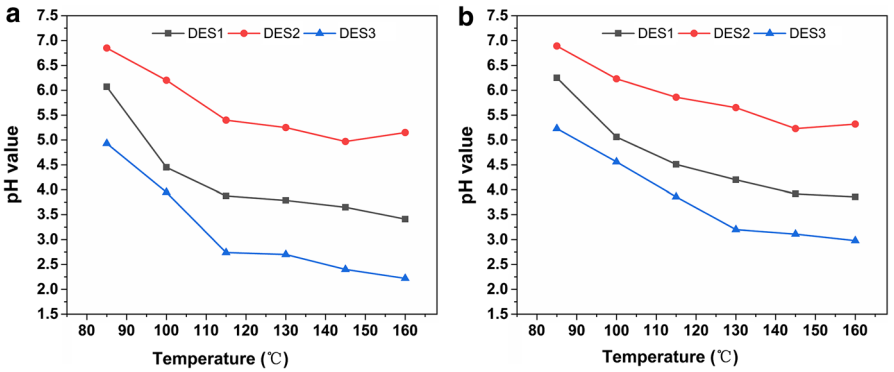


Fig. 3 Effect of temperature on pH in an organic solvent of DESs

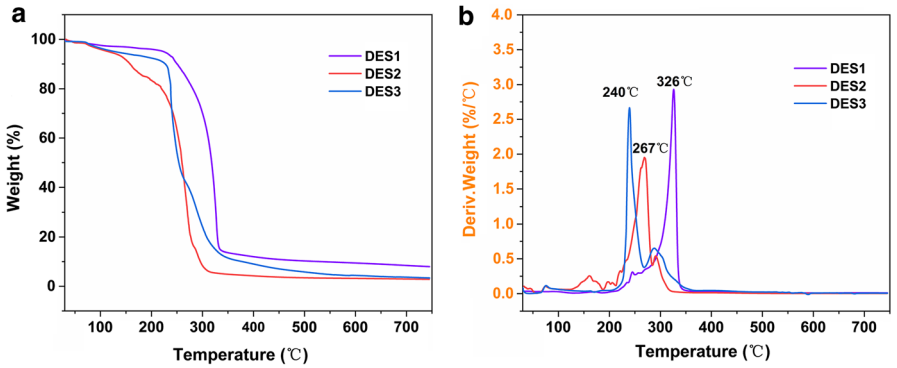


Fig. 4 TG and DTG curves of DESs

Evaluation of catalytic performance of DESs

To investigate the catalytic activity of DESs, 8-aminoquinoline (8-AQ) was dissolved in different solvents for exploratory reactions. Unfortunately, the target product of 1,10-phenanthroline had not been obtained, no matter whether the type of catalysts, the amount of catalysts, the reaction temperature, and the reaction time were changed when in the protic solvent such as methanol or ethanol solutions. The reason is may that the hydrogen bond system of DESs was destroyed in protic solvents, thus losing its catalytic activity. Subsequently, the effects of DESs catalyze 8-AQ and acrolein for the synthesis of 1,10-phenanthroline by improved Skraup reaction in the aprotic solvents DMF and dimethyl sulfoxide (DMSO) were investigated. The results are listed in Table 2.

When a single component was used as a catalyst to catalyze the reaction, the conversion and selectivity of the sulfamic acid catalyst were the highest, 85.2 and 29.5%, respectively. In the meanwhile, it can be seen that it was failure to obtain the target product when choline chloride was used as a catalyst. But the difference is the catalytic performance of three DESs showed good catalytic effect and DES3 exhibits the best catalytic effect, with 71.9% conversion rate, which is much better than the DES1(70.0%) and DES2(68.5%). It can be seen that the stronger the acidity of DESs, the highest catalytic activity. Otherwise, the catalytic acidity of all the DESs is much better than the single component, which would be conducive to show that the choline chloride has interacted the HBDs. However, although DES3 has the best catalytic activity in DMSO solvent compared with the DES1 and DES2, it is lower than in the DMF solvent. This is mainly because DMSO decomposed into formaldehyde [26] when heated under acidic condition and formaldehyde reacts with the amino group on 8-aminopuinoline to form Schiff base [27] and other by-products. So, DES3 and DMF were selected as the best catalyst and reaction solvent for the investigation and optimization of the next process conditions.

Table 2 The catalytic performance of different DESs [a]

Number	Cat(10wt%)	Solvent	Con.(%)	Sel.(%)	Yield (%)
1	Chcl	DMF	–	–	–
2	Sulfamic acid	DMF	85.2	29.5	25.1
3	Aminomethane sulfonic acid	DMF	83.1	29.1	24.2
4	Sulfanilic acid	DMF	82.8	24.8	20.5
5	DES1	DMF	70.0	66.0	46.2
6	DES2	DMF	68.5	67.8	46.5
7	DES3	DMF	71.9	84.1	60.5
8	DES1	DMSO	75.6	44.8	33.9
9	DES2	DMSO	72.2	47.0	34.0
10	DES3	DMSO	76.1	50.6	38.5

[a]Reaction conditions: V(Solvent) = 10 mL, n(8-AQ) = 1 mmol, n(Acrolein) = 1.5 mmol, cat = 10wt% of 8-AQ, T = 130 ℃ t = 4 h

Influence of reaction conditions on reaction results

A large amount of by-products might be formed in the process of 8-AQ and acrolein to 1,10-phenanthroline with different reaction conditions. Thus, the influence of reaction parameters such as reaction temperature, the amount of catalysts, the molar ratio of material and reaction time on the reactions was investigated to achieve high yield, as exhibited in Fig. 5. As an important reagent for cyclization, acrolein is considered to have a low boiling point and is prone to self-polymerization under the influence of temperature [28]. Therefore, the effect of reaction temperature on the reaction performance was first studied, and the results are shown in Fig. 5a. As the temperature increases, the conversion of 8-aminoquinoline gradually decreases, while the yield and selectivity of 1,10-phenanthroline show a tendency to increase first and then decrease, which is caused by the self-polymerization of acrolein at higher temperature and some side reactions. The highest yield 60.5% can be obtained at 130 °C with the conversion are 71.9%. Hence, 130 °C was to be selected the optimal reaction temperature.

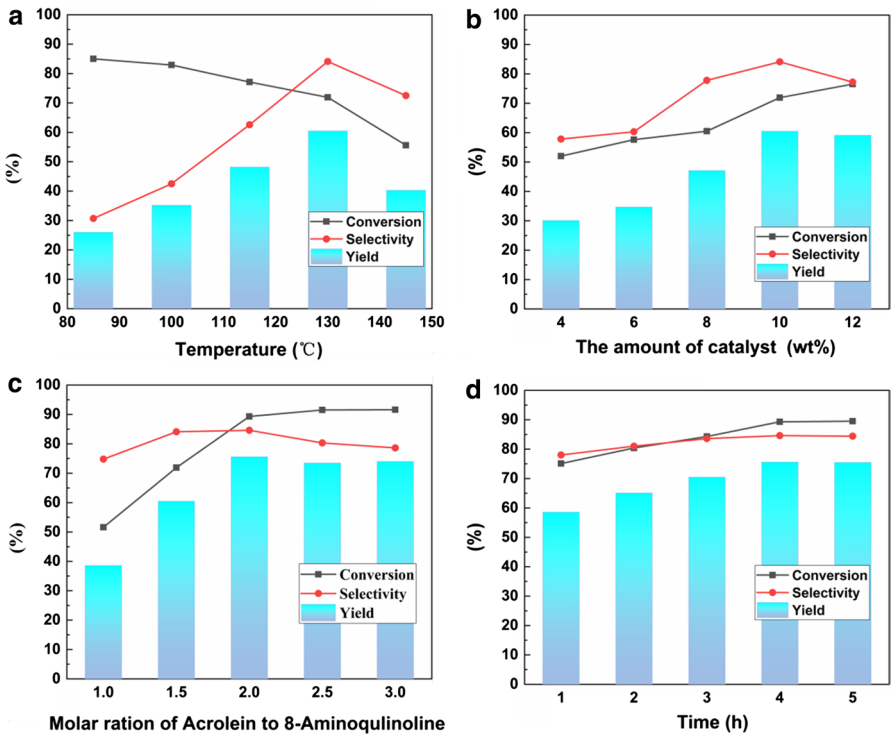


Fig. 5 Effect of different reaction conditions on reaction performance: (**a**) Reaction temperature (acrolein:8-aminoqulinoline (1.5:1), cat(10wt%),4 h), (**b**) The amount of catalyst (acrolein:8-aminoqulinoline (1.5:1),130 ℃, 4 h), (**c**) Molar ration of acrolein to 8-amionqulinoline (130 ℃, cat(10wt%), 4 h), (**d**) Reaction time (acrolein:8-aminoqulinoline (2:1),130 ℃, cat(10wt%)

The effect of the amount of DES3 on the reaction is shown in Fig. 5b. When the amount of DES3 is 4 wt% of 8-aminoquionline, the 8-aminoquinoline conversion rate and product yield are 52.0% and 30.1%, respectively. When the amount of DES3 is continuously increased, the conversion and selectivity are also increased. The highest target product yield 60.5% and selectivity 84.1% can be obtained with the amount of 10wt% of catalyst. However, when the amount of the catalyst exceeds 10wt%, the selectivity is reduced. It may be because the excessive amount of catalyst accelerates the occurrence of some side reactions. Therefore, the optimal catalyst dosage of 10 wt% was selected for further study.

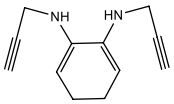
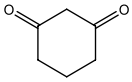
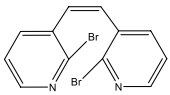
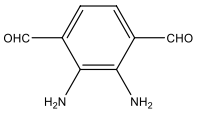
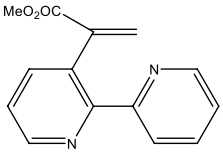
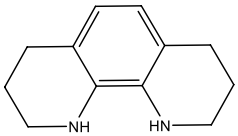
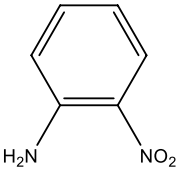
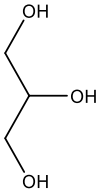
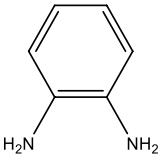
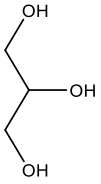
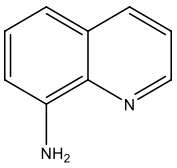
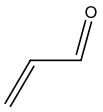
The influence of the molar ratio of acrolein to 8-aminoquinoline on the reaction was also investigated. As shown from Fig. 5(c), with the increase in the amount of acrolein, the conversion of 8-AQ and the yield of 1,10-phenanthroline increased to 89.3% and 75.6% by the molar ratio to 2:1. After that, increasing the amount of acrolein did not significantly improve the product yield. It may be because acrolein had a relatively high concentration in the reaction system and a part of itself polymerizes, so that too much acrolein did not participate in the actual reaction process [29]. Finally, effect of reaction time on the conversion of 8-AQ and the yield of 1,10-phenanthroline was investigated at time of 1, 2, 3, 4, and 5 h. As seen in Fig. 5d, when the reaction time extend from 1 to 4 h, the 1,10-phenanthroline yield increased from 58.6 to 75.6%. Further prolongating it to 5 h, the 1,10-phenanthroline yield was not significantly enhanced. Therefore, 4 h was considered to be the optimal reaction time. Based on the analysis of the actual experimental results above, the optimal conditions for synthesis of 1,10-phenanthroline by improved Skraup reaction were temperature 130 °C, molar ratio of acrolein to 8-aminoquinoline ratio 2:1, DES amount 10 wt% of the mass of 8-AQ and time 4 h. Under the optimal reaction conditions, the yield of the product can reach 75.6%,which was similarly reported in literature [12].

To assessment the catalytic properties of DES, some results of synthesis of 1,10-phenanthroline using different methods are summarized in Table 3. In most of the studies, lower yield of 1,10-phenanthroline was obtained and high catalyst amounts. Otherwise, some of the reagents and catalysts were expensive. In this study, it was reported that the 75.6% yield of 1,10-phenanthroline was obtained using DES as the new catalyst from acrolein and 8-aminoquinoline. Moreover, under the optimal reaction conditions, we used sulfuric acid and p-toluenesulfonic acid to replace of DES as catalysts for comparison, only the yield of 9 and 20%, respectively. So, it is remarkable when compared to conventional catalysts. Unfortunately, we were unable to successfully isolate the catalyst from the reaction system because the DESs were completely dissolved in the solution.

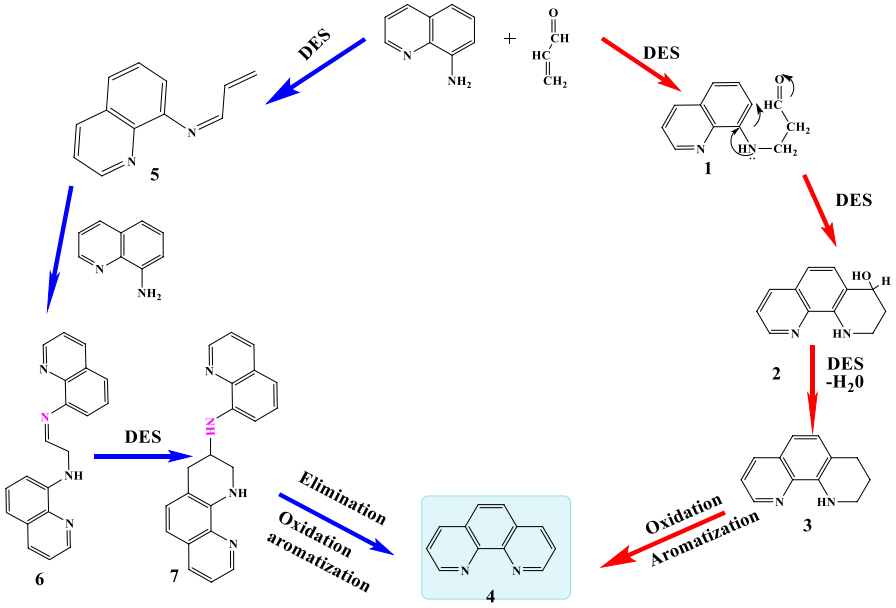
Plausible reaction pathway

Based on the research, a possible mechanism for synthesis of 1,10-phenanthroline from acrolein and 8-aminoquinoline in the presence of the DES catalyst is proposed in Scheme 2. The regioselective 1,4-

Table 3 Comparison of results with other studies. a: Yield by GC-area, b: Yield by HPLC, the others are isolated yield

Number	Solvent	Reagent A	Reagent B	Catalyst	Yield (%)	Ref
1				Au-NP@Al_2O_3	75[a]	[12]
2	DMF			Cu	67	[11]
3	EtOH			KOH	47	[30]
4	CH_3CN			$Zn(OTf)_2$	68	[10]
5	H_2O			Pd-NPs	78	[31]
6	H_2O			H_2SO_4	15	[6]
7	H_2O			H_2SO_4	45	[32]
8	DMF			DES	75.6[b]	This study

addition of 8-aminoquinoline to acrolein afforded the corresponding aldehyde **1**, and subsequent generate **3** via the process of cyclization and dehydration. Finally, the **3** oxidative aromatization would then provide the product 1,10-phenanthroline **4**.



Scheme 2 The plausible reaction pathway to form quinoline from 8-aminoquinoline and acrolein

Alternatively, it is possible that the formation of unsaturated imine **5** first through a condensation reaction. Subsequently, the imine **5** reacts with another 8-aminoquinoline to form double-quinoline-structured imine [33], which converts to **7** via hydrogenolysis. Finally, 8-aminoquinoline elimination and oxidative aromatization would then deliver the product **4**.

Conclusions

The use of acidic deep eutectic solvents as new homogeneous catalysts for the synthesis of 1,10-phenanthroline by improved Skraup reaction has been reported for the first time. Deep eutectic solvents were prepared using choline chloride and several sulfamic acid, aminomethane sulfonic acid and sulfanilic acid. On the other hand, the characterization results show that the formed DESs are mainly connected through the hydrogen bond interaction between the hydrogen bond donor and the hydrogen bond acceptor (choline chloride). The maximum selectivity and yield of 1,10-phenanthroline as 84.6% and 75.6% were achieved using DES3 formed by choline chloride and sulfanilic acid, which has the strongest acidity, within temperature 130 °C, molar ratio of acrolein to 8-aminoquinoline ratio 2:1, DES amount 10 wt% of the mass of 8-aminoquinoline and time 4 h. Moreover, the DESs system will be viewed as a new system for improved Skraup reaction of 8-aminoquinoline with acrolein and this result may provide a novel thought for other possible synthesis and applications of nitrogen-containing heterocyclic compounds.

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Declarations

Conflicts of interest There are no conflicts to declare.

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