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The choline chloride/hydroquinone carboxylic acid-based DES as a novel catalyst for the green synthesis of dihydrochromeno[4,3-*d*]pyrimidinediones

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A novel deep eutectic solvent (ChCl/HCA-DES) was prepared by combining two moles of choline chloride (ChCl) with one mole of hydroquinone carboxylic acid (HCA), based on the results from the eutectic point phase diagram, and characterized by FT-IR, ^{1}H NMR, TGA/DTA, densitometry, viscometry, and refractive index analyses. Then, it was subsequently employed as an efficient, environmentally friendly and sustainable catalytic system for the synthesis of dihydrochromeno [4,3-*d*] pyrimidinediones via the three-component condensation reaction of 4-hydroxycoumarin, aromatic aldehydes, and urea at 60 °C under solvent-free conditions. This green protocol offers high yields, short reaction times, and catalyst reusability.

Keywords Natural deep eutectic solvent, Choline chloride, Hydroquinone carboxylic acid, Homogeneous catalysis, Multicomponent reactions

Multicomponent reactions (MCRs) are a powerful and efficient class of chemical transformations that involve the simultaneous interaction of three or more reactants to produce one or more products in a single-step process. These reactions have gained significant attention in synthetic organic chemistry due to their ability to construct complex molecular architectures with high efficiency and minimal waste[1–5].

According to the principles of green chemistry, solvents used in chemical processes must meet strict criteria for low toxicity and environmental safety. Deep eutectic solvents (DESs) are cost-effective, eco-friendly solvents and recyclable/reusable organocatalysts for various organic transformations. DESs are now widely recognized as a new class of ionic liquid (IL) analogues because they share several characteristics with them. Although DESs and ILs have similar physical properties, their chemical characteristics suggest distinct application areas. Research into DESs began in 2001 and has rapidly expanded since then, highlighting their potential as environmentally benign solvents and catalysts[6].

The innovative choline-based DES catalyst offers multiple advantages, including good product yields, short reaction times, low cost of starting materials, and mild reaction conditions. DESs can be easily prepared by simply mixing and heating their components without the need for additional purification, making them environmentally friendly solvents capable of dissolving a diverse range of compounds, such as salts, proteins, drugs, amino acids, surfactants, sugars, and polysaccharides.

DESs are typically formed by combining two components: a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA). This interaction significantly lowers the melting point of the mixture compared to the individual components. The unique properties of DESs arise from strong intermolecular interactions between their constituents, allowing them to exist as a liquid at room temperature or slightly above[7]–[8].

Type III DESs, formed from choline chloride and hydrogen bond donors, are particularly versatile. They are non-toxic, biodegradable, cost-effective, and capable of solvating a wide range of compounds. The properties of these DESs can be easily tuned by selecting appropriate HBDs, making them suitable for diverse chemical and catalytic applications[9].

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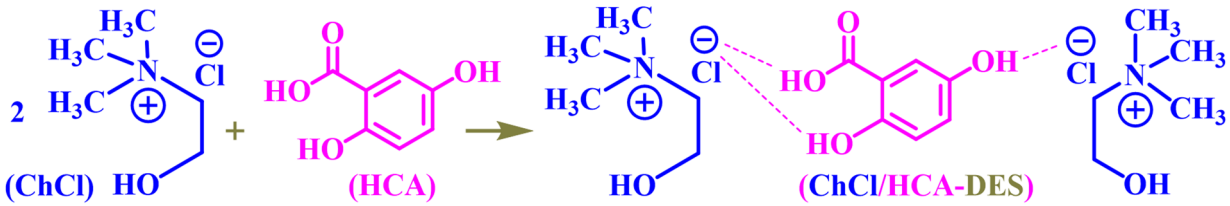
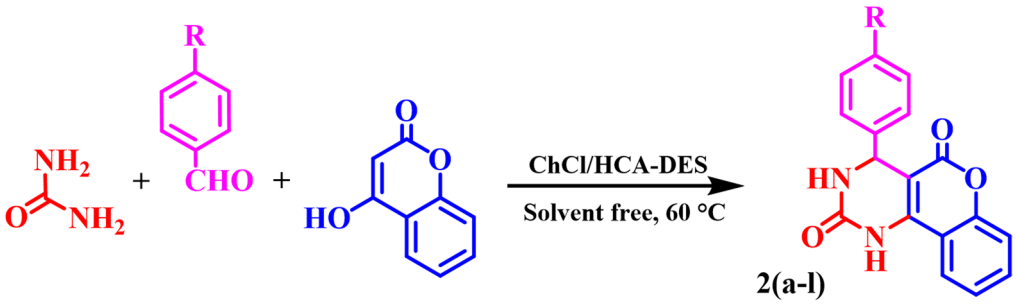


Scheme 1. Preparation of ChCl/HCA-DES.



Scheme 2. Synthesis of **2(a–l)** using ChCl/HCA-DES.

DESs represent a promising category of solvents with distinctive properties that enable them to act as effective catalysts in various reactions. Their ability to optimize reaction conditions while remaining environmentally safe makes them valuable tools in modern synthetic chemistry and catalysis[10–13]. Furthermore, DESs have been extensively applied in chemical and industrial processes. Their unique characteristics, such as low toxicity and the potential to reduce activation energy, make them attractive for enhancing chemical transformations. Overall, DESs pave the way for greener chemical synthesis and catalysis, contributing to sustainable practices in the field. In this study, a novel ChCl/HCA-based DES is introduced as an efficient and environmentally friendly catalyst for the synthesis of dihydrochromeno[4,3-*d*]pyrimidinediones, highlighting its unique combination of non-toxicity, recyclability, and broad applicability, which underscores the novelty and significance of this work.

Coumarins and fused pyrimidines, including chromenopyrimidines, are significant classes of compounds with diverse biological activities. Coumarins are well-known for their anticoagulant and antioxidant properties, while fused pyrimidines show promise in antiviral, anticancer, and antimicrobial applications. Continued studies on their mechanisms of action and therapeutic potential further emphasize their importance in medicinal chemistry and drug development[14–21].

In continuation of our research on novel catalytic systems, the ChCl/HCA-DES was prepared by mixing two moles of choline chloride (ChCl) with one mole of hydroquinone carboxylic acid (HCA) (Scheme 1). The DES was characterized using FT-IR, ^{1}H NMR, TGA/DTA, densitometry, viscosity, refractive index, and determination of the eutectic point.

The obtained ChCl/HCA-DES was then employed as an effective catalyst for the synthesis of biologically active compounds, namely dihydrochromeno[4,3-*d*]pyrimidinediones **2(a–l)**, via the three-component condensation reaction of 4-hydroxycoumarin, aromatic aldehydes, and urea under solvent-free conditions at 60 °C (Scheme 2).

The key advantages of this protocol include a clean reaction profile, the use of DESs as environmentally friendly catalysts, the elimination of toxic solvents, mild reaction conditions, short reaction times, simple purification, high atom economy, excellent yields, and the use of commercially available low-cost starting materials.

Experimental

General

All chemicals were purchased from commercial suppliers and used without further purification. Thin-layer chromatography (TLC) was performed on silica gel 60 F-254 plates. Thermogravi-metric analysis (TGA) and differential thermal analysis (DTA) were carried out using an SDT Q600 V20.9 Build 20 instrument. Density measurements were obtained with an HR200 densitometer. Viscosity was measured using a DVNext Cone/Plate Rheometer, and refractive indices were recorded with a Digital Abbe Refractometer (CAR-02). Fourier-transform infrared (FT-IR) spectra were recorded on a Perkin-Elmer spectrometer using KBr pellets. Melting points were determined with a Stuart melting point apparatus. Nuclear magnetic resonance (NMR) spectra were acquired using a Bruker DRX-250 spectrometer.

General procedure for the preparation of ChCl/HCA-DES

A mixture of ChCl and HCA (molar ratio 2:1) was stirred and heated until a homogeneous clear liquid formed (~ 60 °C, ~ 30 min). The resulting DES was dried at room temperature and stored for further use as an effective catalytic system in subsequent reactions.

General procedure for the synthesis of 2(a-l)

The reaction of 4-hydroxycoumarin (1 mmol, 162 mg), urea (1 mmol, 60 mg), and the corresponding aldehyde (1 mmol) was carried out at 60 °C for an appropriate time in the presence of ChCl/HCA-DES (1 mmol, 432 mg). The progress of the reaction was monitored by TLC (n-hexane/ethyl acetate, 4:6). Upon completion, the reaction mixture was filtered and washed with ethanol. The products were characterized using FT-IR, ^{1}H NMR, ^{13}C NMR, mass spectrometry, and melting point analysis. The reaction mixture was insoluble in ethanol, whereas ChCl/HCA-DES was soluble.

Results and discussion

Preparation of the DES catalyst

ChCl/HCA-DES was prepared by heating and stirring a 2:1 molar mixture of choline chloride (ChCl) and hydroquinone carboxylic acid (HCA) until a homogeneous, transparent liquid was obtained (~ 60 °C). In line with the principles of green chemistry, solvents employed in the chemical industry are expected to exhibit low toxicity, environmental compatibility, and sustainability. DESs meet these requirements, being cost-effective, eco-friendly, and recyclable organo-catalysts that promote diverse organic transformations. The prepared ChCl/HCA-DES catalyst offers several advantages, including high product yields, short reaction times, inexpensive starting materials, and mild reaction conditions, making it a promising candidate for sustainable catalytic applications.

Characterization of the DES catalyst

The prepared ChCl/HCA-DES was comprehensively characterized using several analytical techniques. Structural and functional group confirmation was carried out by FT-IR and ^{1}H NMR spectroscopy. Thermal stability was assessed by TGA/DTA analysis, while the eutectic point was determined to validate the optimized molar ratio of the components. In addition, the physicochemical properties of the DES, including viscosity, refractive index, and density, were systematically measured to provide further insight into its stability and catalytic potential.

Characterization by FT-IR

Figure 1 shows the IR spectra of ChCl (**a**), HCA (**b**), the fresh DES (**c**), and the recovered DES (**d**).

In spectrum **(a)**, the broad absorption band observed at 3415 cm^{-1} is related to the OH group. The peak at 3000 cm^{-1} corresponds to the bond, and a relatively sharp absorption band at 1092 cm^{-1} is related to the C-O group.

In spectrum **(b)**, the peaks at 3373 and 1683 cm^{-1} are related to the O-H and C=O of the -COOH group, respectively. These two peaks can be seen in the **(a)**, **(b)**, and **(c)** spectra, which confirm the structure of the DES catalyst.

To confirm the structure of ChCl/HCA-DES of the recovered DES, the corresponding IR spectrum **(d)** was recorded, which shows that there is no significant difference between the fresh **(c)** and the recovered **(d)** IR spectra.

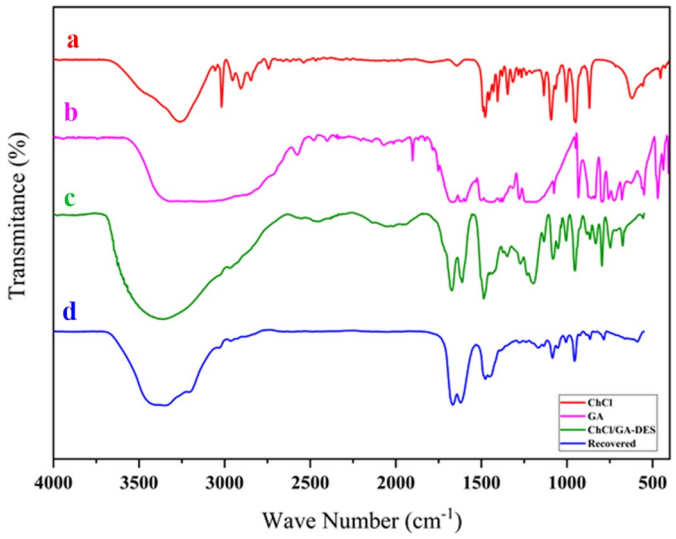


Fig. 1. The FT-IR spectra of (**a**), (**b**), (**c**), and (**d**).

Characterization by ^{1}H NMR.

The ^{1}H NMR spectrum of ChCl (Supp Info, 500 MHz, DMSO-d_6). The peaks at 5.66–5.63 (d, 1 H), 3.77–3.73 (d, 2 H), 3.40–3.36 (m, 2 H), and 3.10–3.06 (m, 9 H) ppm are related to the OH hydrogen, the CH_2 hydrogens, the second CH_2 hydrogens, and the nine CH_3 hydrogens, respectively.

The ^{1}H NMR spectrum of HCA (Supp Info, 400 MHz, DMSO-d_6). The peaks at 13.78 (s, 1 H) and 9.16 (s, 1 H) ppm are related to hydrogens of the two hydroxy groups at 2 (ortho) and 5 (meta) positions, respectively. The peak at 10.67 (s, 1 H) belongs to a hydrogen of the -COOH group. The peaks at 7.16–7.15 (s, 1 H), 6.98–6.95 (m, 1 H), and 6.80–6.78 (d, 1 H) ppm are related to the three hydrogens of a phenyl ring.

The ^{1}H NMR spectrum of DES catalyst (Supp Info, 250 MHz, DMSO-d_6). The peaks at 7.20–7.17 (d, 1 H), 7.00-6.93 (m, 1 H), and 6.76–6.69 (m, 1 H) ppm are related to the three hydrogens of a phenyl ring (HCA). Peaks at 6.00 ppm (s, 2 H) correspond to OH hydrogens, peaks at 3.79 ppm (s, 4 H) and 3.46–3.43 ppm (d, 4 H) correspond to CH_2 hydrogens, and peaks at 3.15–3.12 ppm (d, 18 H) correspond to CH_3 hydrogens of ChCl.

The results show that the peak intensity of acidic and OH groups has decreased due to hydrogen bonding. These observations indicate hydrogen bonding interactions between HCA and ChCl, confirming the structure of the newly formed DES.

Characterization by eutectic point

To prepare the optimal new DES (ChCl/HCA-DES), it was necessary to determine the optimal ratio of ChCl and HCA in their mixture. Therefore, the corresponding eutectic point phase diagram was designed by creating different ratios of ChCl (m.p. 302 °C) and HCA (m.p. 206 °C). The data indicated that the optimal ratio was two moles of ChCl to one mole of HCA, which a transparent homogeneous liquid being obtained as a new DES at 25 °C (Fig. 2).

Characterization by TGA-DTA

TGA-DTA analysis was conducted to assess the thermal stability of ChCl/HCA-DES. As illustrated in the diagram, the first decomposition at 237.96 °C likely corresponds to the breaking of weak intermolecular interactions formed during catalyst preparation and the release of absorbed vapors. The second decomposition at 265.51 °C is expected associated with the breaking of hydrogen bonds within the ChCl/HCA-DES structure. The final decomposition at 350 °C, which extends up to 1000 °C, is likely related to the complete thermal decomposition of ChCl/HCA-DES (Fig. 3).

Physical characteristics (densitometer, viscosity, and refractive index)

The density of most DESs ranges from 1.0 to 1.35 g/cm^3 at 25 °C, which is higher than the density of water[22]. However, DESs containing metallic salts, such as $ZnCl_2$, exhibit densities in the range of 1.3 to 1.6 g/cm^3. The density of the ChCl/HCA-DES at room temperature is approximately 1.29 g/cm^3.

DESs often have high viscosities (> 100 P.s) as reported in the literature. The viscosity of the prepared ChCl/HCA-DES is about 109 P.s at room temperature[23].

The refractive index of DES typically falls within the range of 1.3 to 1.5; however, specific values can vary depending on the exact formulation and conditions. For example, the refractive index of a ChCl/HCA-DES is

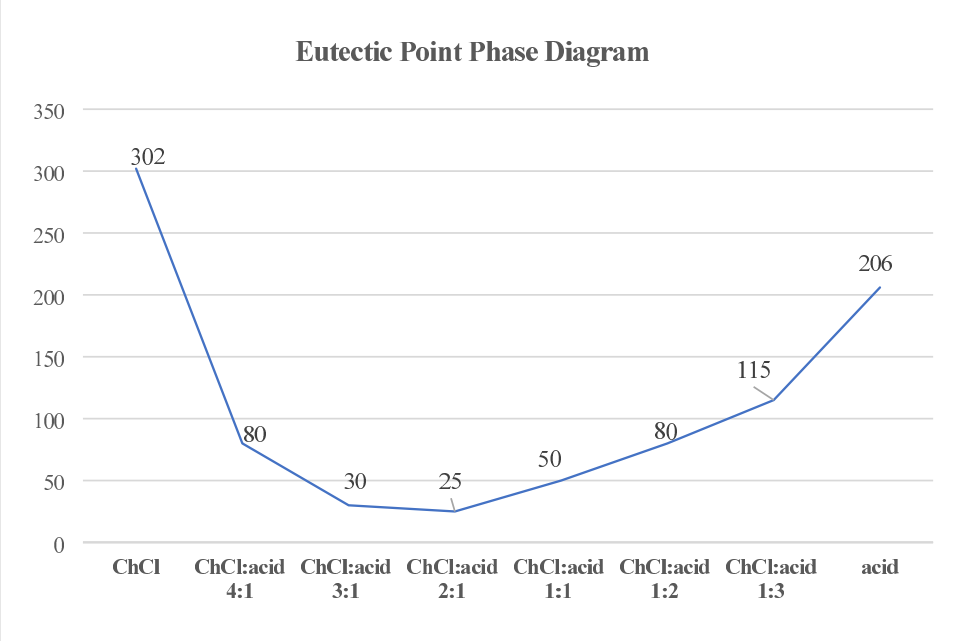


Fig. 2. The eutectic points phase diagram.

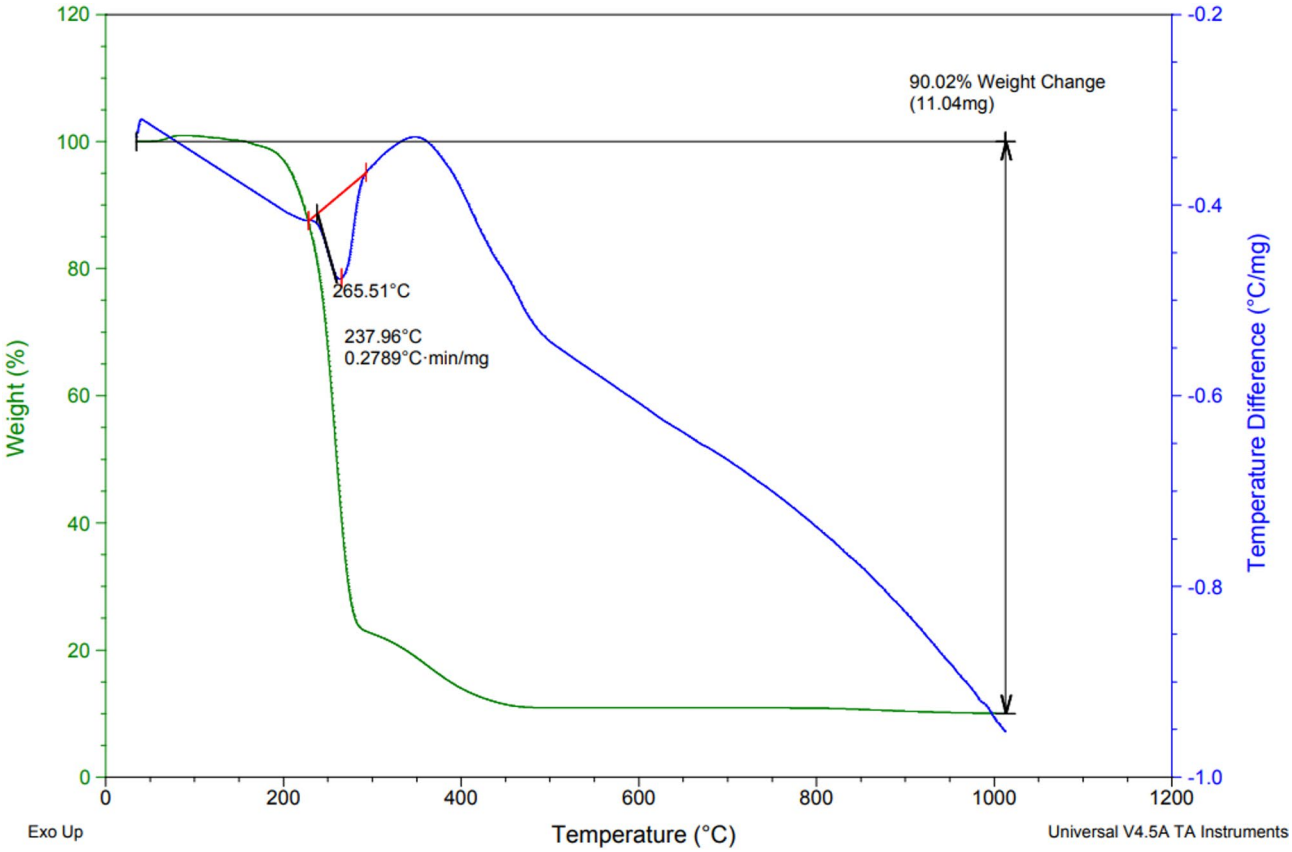


Fig. 3. The TGA-DTA pattern of ChCl/HCA-DES.

approximately 1.42, while the refractive index of our newly prepared ChCl/HCA-DES is about 1.50 nD[24] at room temperature.

Optimization of the reaction conditions (synthesis of 2b)

To optimize the reaction conditions, a model reaction (between 4-hydroxycoumarin, urea, and 4-chlorobenzaldehyde, with a 1:1:1 molar ratio) was conducted in various solvents, temperatures, and amounts of the ChCl/HCA-DES. The best result was obtained by performing the reaction with 1.0 mmol of the ChCl/HCA-DES catalyst at 60 °C in solvent-free conditions, which yields high conversions in short reaction times (Table 1).

Synthesis of diverse 2(a-l)

Based on the results obtained from the model reaction (synthesis of **2b**), **2(a-l)** were synthesized in similar reaction conditions (Table 2).

Spectral data of 2(a-l) (Fig. 4)

*4-Phenyl-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2a**)*
White solid, M.P.: 155–165 °C; IR (KBr) ν = 3441 (NH), 1675 (C = O), 1611 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6): δ_H = 7.87 (d, *J* = 18.1 Hz, 2 H, -NH), 7.57–7.12 (m, 9 H, Ar-H); 6.32 (s, 1H, -CH); MS ($C_{17}H_{12}N_2O_3$) = 292.

*4-(4-Chlorophenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2b**)*
White solid, M.P.: 163–173 °C; IR (KBr) ν = 3388 (NH), 1672 (C = O), 1614 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6): δ_H = 7.85 (d, *J* = 7.4 Hz 2 H, NH), 7.39–7.17 (m, 8 H, Ar-H), 6.28 (s, 1H, -CH); MS ($C_{17}H_{11}ClN_2O_3$) = 326.

*4-(3,4-Dimethoxyphenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2c**)*
Cream solid, M.P.: 270–276 °C; IR (KBr) ν = 3083 (NH), 1666 (C = O), 1615 (C = C) cm^{-1}; ^{1}H-NMR (250 MHz, DMSO-d_6): δ_H = 7.87 (d, *J* = 7.8 Hz, 2 H, NH), 7.54 (d, *J* = 7.6 Hz, 2 H, Ar-H), 7.30 (dd, *J* = 12.2, 7.8 Hz, 6 H, Ar-H), 6.25 (s, 1H, CH), 3.69 (s, 6 H, OCH_3); MS ($C_{19}H_{16}N_2O_5$) = 352.

Entry	Catalyst (mmol)	Temp. (°C)	Solvent	Yield (%)
1	0.25	60	-	65
2	0.50	60	-	75
3	0.75	60	-	80
4	1.25	60	-	88
5	1.5	60	-	83
6	1.75	60	-	87
7	1.0	70	-	91
8	1.0	80	-	89
9	1.0	90	-	85
10	1.0	100	-	82
11	1.0	Reflux	EtOH	85
12	1.0	Reflux	H_2O	88
13	1.0	Reflux	DMF	89
14	1.0	Reflux	Acetonitrile	90
15	1.0	Reflux	Toluene	78
16	**1.0**	**60**	-	**95**

Table 1. Optimization of the reaction conditions.

*4-(3-Nitrophenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2d**)*
White solid, M.P.: 180–197 °C; IR (KBr), ν = 3430 (NH), 1663 (C = O), 1616 (C = C) cm^{-1}; ^{1}H-NMR (250 MHz, DMSO-d_6): δ_H = 8.11 (d, *J* = 25.9 Hz 2 H, NH), 7.50–7.06 (m, 8 H, Ar-H), 6.36 (s, 1H, CH); MS ($C_{17}H_{11}N_3O_5$) = 337.

*4-(4-Nitrophenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2e**)*
White solid, M.P.: 180–197 °C; IR (KBr), ν = 3430 (NH), 1663 (C = O), 1616 (C = C) cm^{-1}; ^{1}H-NMR (250 MHz, DMSO-d_6): δ_H = 8.11 (d, *J* = 25.9 Hz 2 H, NH), 7.50–7.06 (m, 8 H, Ar-H), 6.36 (s, 1H, CH); MS ($C_{17}H_{11}N_3O_5$) = 337.

*4-(4-Hydroxyphenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2f**)*
Yellow solid, M.P.: 179–181 °C; IR (KBr) ν = 3318 (NH), 1678 (C = O), 1625 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6): δ_H = 9.97 (s, 1H, OH) 8.02 (d, *J* = 7.7 Hz, 2 H, NH), 7.56 (ddt, *J* = 20.8, 13.0, 7.7 Hz, 8 H, Ar-H),6.40 (s, 1H, CH); MS ($C_{17}H_{12}N_2O_4$) = 308.

*4-(4-Bromophenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2 g**)*
White solid, M.P.: 185–235 °C; IR (KBr) ν = 3380 (NH), 1671 (C = O), 1612 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6) δ_H = 7.86 (s, 2 H, NH), 7.63 (s, 1H, Ar-H), 7.51 (s, 1H, Ar-H), 7.30 (d, *J* = 7.8 Hz 4 H, Ar-H), 7.07 (d, *J* = 8.4 Hz, 2 H, Ar-H), 6.24 (s, 1H, CH); MS ($C_{17}H_{11}BrN_2O_3$) = 371.

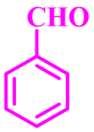
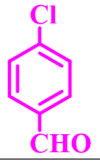
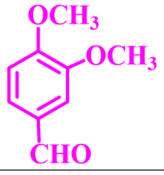
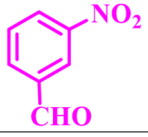
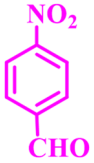
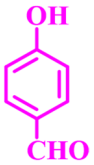
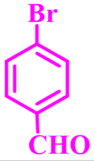
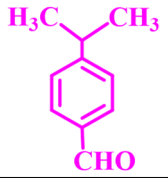
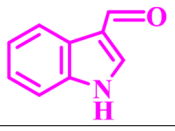
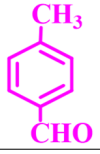
*4-(4-Isopropylphenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2 h**)*
White solid, M.P.: 175–185 °C; IR (KBr) ν = 3384 (NH), 1703 (C = O), 1683 (C = C) cm^{-1}. ^{1}H NMR (250 MHz, DMSO-d_6) δ_H = 7.85 (d, *J* = 9.8 Hz, 2 H, NH), 7.72–6.63 (m, 8 H, Ar-H), 6.28 (s, 1H, CH), 2.80 (dq, *J* = 12.9, 6.9 Hz, 1H, CH), 1.21 (s, 6 H, CH_3); MS ($C_{20}H_{18}N_2O_3$) = 334.

*4-(1H-Indol-3-yl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2i**)*
Orange solid, M.P.: 215–220 °C; IR (KBr) ν = 3345 (NH), 1691 (C = O), 1640 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6): δ_H = 8.95 (d, *J* = 44.7 Hz, 2 H, NH), 7.94 (s, 1H, NH of indole), 7.74–7.09 (m, 9 H, Ar-H), 4.00 (s, 1H, CH); MS ($C_{19}H_{13}N_3O_3$) = 331.

*4-(p-Tolyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2j**)*
White solid, M.P.: 180–185 °C; IR (KBr) ν = 3075 (NH), 1671 (C = O), 1618 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6) δ_H = 7.84 (d, *J* = 7.6 Hz, 2 H, NH) 7.61–7.11 (m, 8 H, Ar-H), 6.26 (s, 1H, CH), 2.28 (s, 3 H, CH_3); MS ($C_{18}H_{14}N_2O_3$) = 306.

*4-(4-Methoxyphenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2k**)*
White solid, M.P.: 281–283 °C; IR (KBr) ν = 3377 (NH), 1672 (C = O), 1642 (C = C) cm^{-1}; ^{1}H NMR (250 MHz, DMSO-d_6): δ_H = 7.85 (s, 2 H, NH) 7.53 (s, 4 H, Ar-H), 7.01 (s, 4 H, Ar-H), 6.24 (s, 1H, CH), 3.68 (s, 3 H, OCH_3); MS ($C_{18}H_{14}N_2O_4$) = 322.

*4-(2,4-Dichlorophenyl)-3,4-dihydro-2H-chromeno[4,3-d]pyrimidine-2,5(1H)-dione (**2 L**)*
White solid, M.P.: 160–167 °C; IR (KBr) ν = 3367 (NH), 1674 (C = O), 1611 (C = C) cm^{-1}; ; ^{1}H NMR (250 MHz, DMSO-d_6) δ_H = 8.01 (d, *J* = 7.7 HZ, 2 H, NH) 7.38 (ddd, *J* = 14.1, 6.6, 4.4 HZ, 8 H, Ar-H), 6.31 (s, 1H, CH); MS ($C_{17}H_{11}Cl_2N_2O_3$) = 361.

Entry	Aldehyde	Product	Time (min)	Yield (%)	M.P. °C Found	M.P. °C literature	TON [a]	TOF [(b]
1		2a	25	90	155–165	160-162[25]	90	3.6
2		2b	30	95	163–173	195-197[25]	95	3.16
3		**2c**	35	83	270–276	268-270[31]	83	2.37
4		**2d**	20	85	180–197	172-174[25]	85	4.25
5		**2e**	25	95	199–220	242-245[32]	95	3.8
6		**2f**	30	86	179–181	180-182[27]	86	2.86
7		**2 g**	20	87	185–235	248-250[33]	87	4.35
8		**2 h**	35	88	175–185	NEW	88	2.51
9		**2i**	20	90	215–220	210-212[34]	90	4.5
10		**2j**	20	95	180–185	260-262[35]	95	4.75

Continued

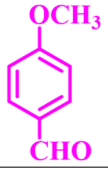
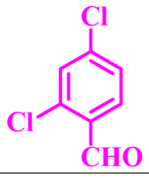
Entry	Aldehyde	Product	Time (min)	Yield (%)	M.P. °C Found	M.P. °C literature	TON [a]	TOF [(b]
11		**2k**	15	96	281–283	285-287[27]	96	6.4
12		**2 L**	20	95	160–167	170-171[27]	95	4.75

Table 2. Synthesis of **2(a-l)** by ChCl/HCA-DES. [a]: TON = moles of catalyst/moles of product. [b]: TOF = TON/time.

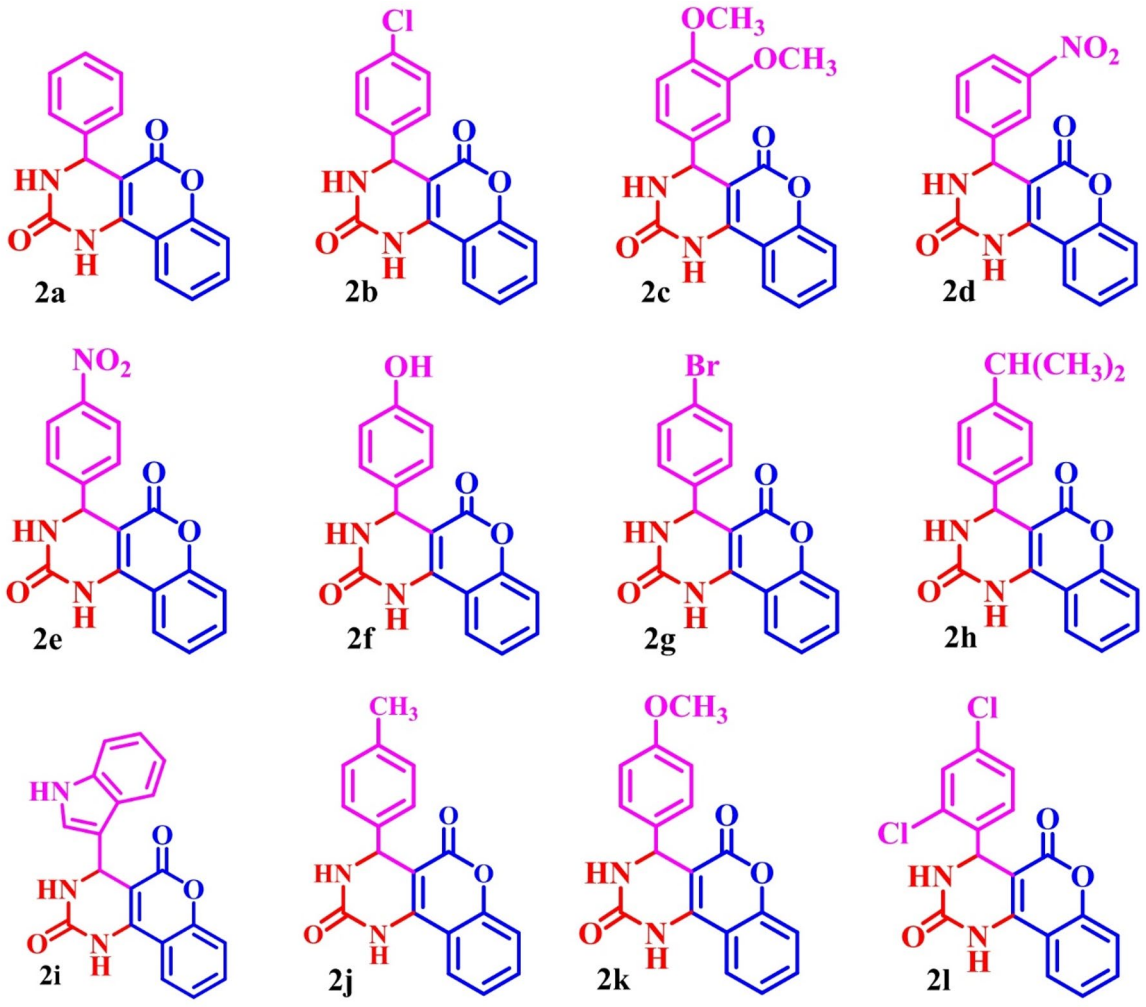
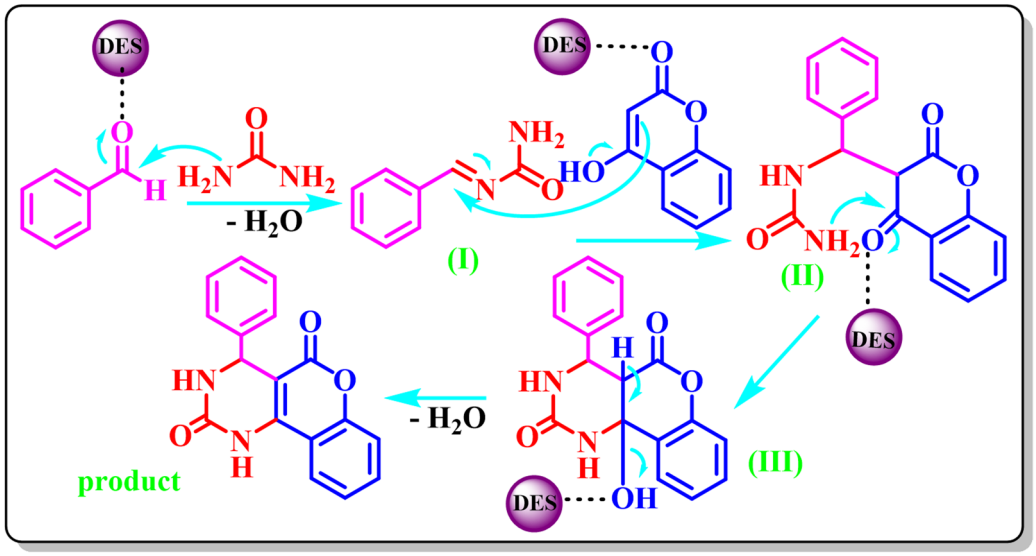


Fig. 4. Synthesis of diverse **2(a-l)**.

Proposed mechanism for the synthesis of 2(a-l)

A proposed mechanism is presented below (Scheme 3). The aldehyde carbonyl group is activated by ChCl/HCA-DES, which is then attacked by urea, forming intermediate I with simultaneous elimination of water. Then, 4-hydroxycoumarin adds to intermediate **I**, forming intermediate **II**. Finally, intramolecular ring closure (intermediate **III**) with elimination of water affords the final product[25–27].



Scheme 3. Proposed mechanism for the synthesis of **2(a-l)**.

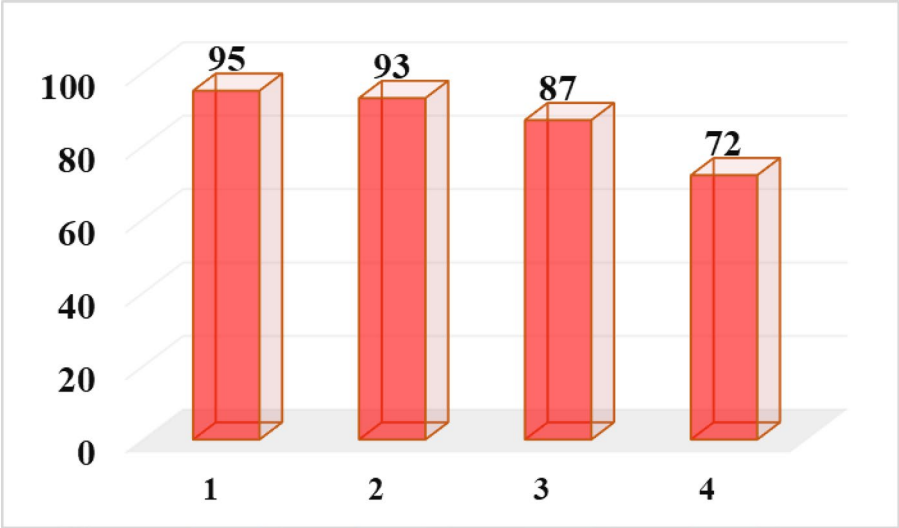


Fig. 5. Reusability of ChCl/HCA-DES.

Reusability of DES catalyst in the synthesis of 2(a-l)

Figure 5 shows the recyclability of the ChCl/HCA-DES catalyst. Since the DES catalyst is soluble in the aqueous phase but insoluble in ethyl acetate, a mixture of water and ethyl acetate (1:1) was used at the end of each reaction run. The ChCl/HCA-DES catalyst was separated from the aqueous phase by liquid–liquid extraction, dried at room temperature, and reused in subsequent reaction cycles. A relatively small decrease in catalytic activity was observed over multiple runs, with yields of 95%, 93%, 87%, and 72% in runs 1–4, respectively.

Comparison of the catalyst activities

Table 3 presents a comparison of various methods for the synthesis of **2(a-l)**. As shown, our proposed method achieves higher yields in shorter reaction times compared to previously reported methods.

Conclusion

ChCl/HCA-DES was successfully synthesized by combining two moles of choline chloride (ChCl) with one mole of hydroquinone carboxylic acid (HCA), as determined from the eutectic point phase diagram. The DES was thoroughly characterized using FT-IR, 1 H NMR, TGA/DTA, densitometry, viscometry, and refractive index measurements.

The ChCl/HCA-DES proved to be an efficient and environmentally friendly catalyst for the solvent-free synthesis of biologically active dihydrochromeno[4,3-*d*]pyrimidinediones **2(a–l)** at 60 °C. This methodology

Entry	Catalyst	Conditions	Time (min)	Yield (%)	Ref.
1	Thr/Mal-DES	solvent-free	30	96	[26]
2	[Caffeine-H][$ClCH_2COO$]	solvent-free	22	78	[27]
3	HCl	EtOH, Reflux	720	74	[28]
4	VCl_3	CH_3CN, Reflux	120	82	[29]
5	K_2CO_3	EtOH/H_2O	420	53	[30]
6	ChCl/HCA-DES	solvent-free	24	91	This work

Table 3. Comparison of the catalyst.

offers several advantages, including high yields, short reaction times, and facile recovery and reuse of the DES catalyst, highlighting its potential as a green and sustainable alternative to previously reported catalytic systems.

Data availability

All data generated or analyzed during this study are available from the corresponding author on reasonable request.

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Author contributions
Zahra Jahaniyan did the lab experiment. Davood Habibi acted as a supervisor. Arezo Monem contributed as a co-supervisor. Elnaz Chegeni contributed as a co-author.

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Declarations

Competing interests
The authors declare no competing interests.

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