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Supplementary Information

Unexpected Solvation-stabilization of Ions in Protic Ionic Liquid: Insights Disclosed by Bond Energetic Study

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Table of Contents

1. Experimental

1.1 Materials and instrumentations.

DBU (1,8-diazabicyclo[5.4.0]undec-7-ene), trimethylamine hydrochloride ($Et_3N\cdot HCl$), trifluoromethanesulfonic acid (HOTf) and the substrates involved in the acidity measurements described in Table 1 and Table S1 were purchased from commercial sources and purified from distillation or recrystallization at least 3 times before used as the reactants for the preparation of [DBUH][OTf]. Other chemicals, solvents and inert gases were also from commercial available sources with analytical or HPLC grade and used as received unless otherwise noted.

The IR spectra were obtained on a Bruker Tensor II FT-IR instrument; UV-Vis spectra were recorded on an Agilent Cary 100 machine; NMR spectra were recorded on a Bruker AVANCE III HD 400 MHz spectrometer; HRMS spectra were recorded on a Thermo-Scientific™ Q-Exactive™ Quadrupole-Orbitrap mass spectrometer.

1.2 Synthesis of [DBUH][OTf].

NOTE: We found that [DBUH][OTf] prepared from direct equimolar neutralisation[1] between DBU and HOTf is *not suitable* for the pK_a measurement due to a persistent presence of yellowish colour, which could not be removed even after using active carbon in order to decolour the PIL. Therefore, alternatively, ultra-pure colourless [DBUH][OTf] that is suitable for spectroscopic experiments was prepared from ion exchange reaction between [DBUH][Cl] and NaOTf. The synthetic details are described as follow:

A. Preparation of NaOTf aqueous solution.

The NaOTf was synthesized through stoichiometric reaction between HOTf (99%) and NaOH, (semiconductor grade, 99.99%) in water, the pH of the aqueous mixture then adjusted to 5-6. The solution was used directly to the ion exchange reaction.

B. Synthesis of [DBUH][Cl].

137.7g (1.0 mol) triethylamine hydrochloride (>99%) was dissolved in 500 ml methanol (HPLC grade) under an ice-bath, 182.7g (1.2 mol) DBU was slowly added in several portions with vigorous agitation, the reaction temperature was kept at 0 ^{o}C for 1 hour after the addition of DBU, then reaction temperature was allowed to raise to room temperature and the reaction mixture was further agitated at this temperature for 12 hrs. The organic solvent was then removed under vacuum and the resulting solid was recrystallized from dichloromethane (DCM, HPLC) and ethyl acetate (EA, HPLC) at least 5 times. 126.0 g [DBUH][Cl] was obtained as white solid (yield 67.0%) after recrystallizations and dried at 60 ^{o}C under vacuum for 12 hrs.

^{1}H NMR (400 MHz, DMSO) δ 10.49 (s, 1H), 3.60–3.51 (m, 2H), 3.47 (t, *J* = 5.8 Hz, 2H), 3.22 (t, *J* = 5.7 Hz, 2H), 2.89–2.69 (m, 2H), 1.99–1.79 (m, 2H), 1.76–1.43 (m, 6H); ^{13}C NMR (101 MHz, DMSO) δ 165.3, 53.3, 47.8, 37.4, 31.3, 28.2, 25.9, 23.4, 18.9; IR (neat): 3199, 3039, 2921, 2861, 1639, 1588 cm^{-1}; HRMS (ESI$^+$): Calcd. for $[C_9H_{17}N_2]^+$ 153.13862, found 153.13823.

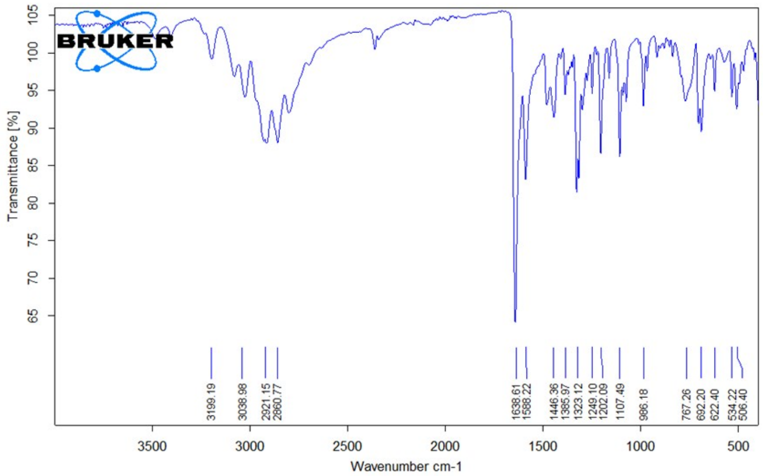


Figure S1 IR spectrum of [DBUH][Cl]

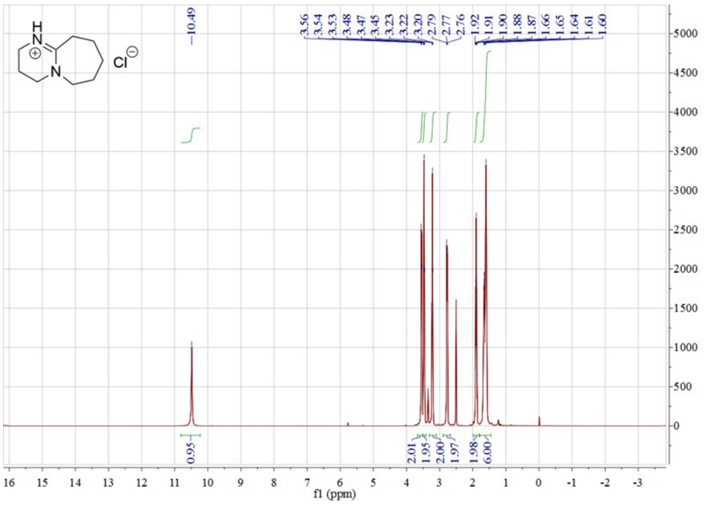


Figure S2 ^{1}H spectrum of [DBUH][Cl]

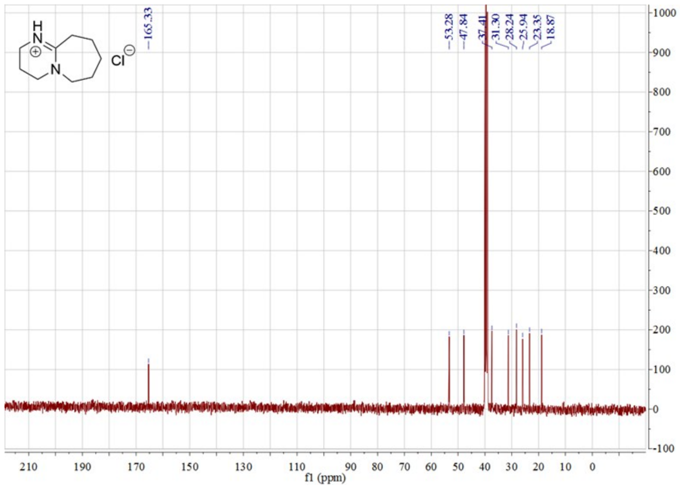


Figure S3 ^{13}C NMR spectrum of [DBUH][Cl]

C. Synthesis of [DBUH][OTf] through ion exchange reaction.

Under argon protection, 200 ml aqueous solution of NaOTf which was prepared according the procedure described above was added 300 ml DCM (HPLC), then 188.7g (1 mol) [DBUH][Cl] was added in portions carefully, the reaction mixture then kept at room temperature for 24 hrs. After the separation, the aqueous layer then was extracted by DCM 3 times and the organic layer was combined and washed with ultrapure water until no white precipitation by mixing 0.1 M $AgNO_3$ stock solution with the aqueous layer. Then the organic layer was dried with anhydrous $MgSO_4$ and removed under vacuum after filtration. The crude [DBUH][OTf] was further washed with freshly distilled diethyl ether 3 times, and dried at 60 ^{o}C under vacuum for 12 hrs to give 241.8 g (yield 80.0%) colourless liquid. The water content was about 100 ppm (the average of 3 independent measurements after dried under vacuum and 60 ^{o}C for 12 hrs), which was monitored by conventional Karl-Fisher titration method. The PIL was flushed with argon and stored in a glove-box.

It is worth noting that the water content of [DBUH][OTf] prepared by us is among the best achievable so far for the acidity investigation or physical parameters measurement purpose,[2] which normally requires a much more stringent criterion on the purity of solvents involved, compared with for synthetic purpose. In addition, we found that a small amount of water in [DBUH][OTf] has no or negligible effect on the acid-base equilibria, for example, we deliberately measured the pK_a of the same compound in a [DBUH][OTf] solvent with higher water content, i.e. 200 ppm, identical pK_a value for the acid was found as measured in the [DBUH][OTf] with 100 ppm water content.

^{1}H NMR (400 MHz, $CDCl_3$) δ 8.78 (br, 1H), 3.60–3.43 (m, 4H), 3.34 (dd, J = 7.9, 6.0 Hz, 2H), 2.75–2.57 (m, 2H), 2.10–1.93 (m, 2H), 1.81–1.55 (m, 6H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.3, 120.6 (q, J = 320.0 Hz), 54.7, 48.7, 38.3, 32.9, 28.8, 26.5, 23.8, 19.3; IR (neat): 3277, 3145, 2938, 1647, 1591 cm^{-1}; HRMS (ESI$^+$): Calcd. for $[C_9H_{17}N_2]^+$ 153.13862, found 153.13823. HRMS (ESI$^-$): Calcd. for $[CF_3O_3S]^-$ 148.95257, found 148.95111.

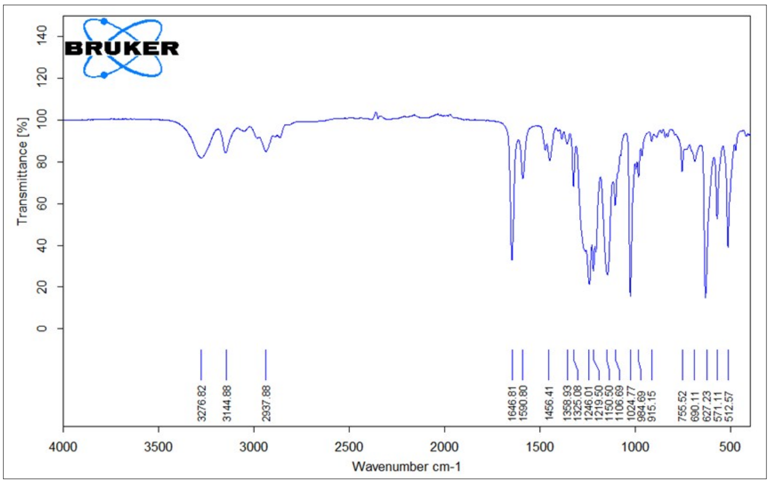


Figure S4 IR spectrum of [DBUH][OTf]

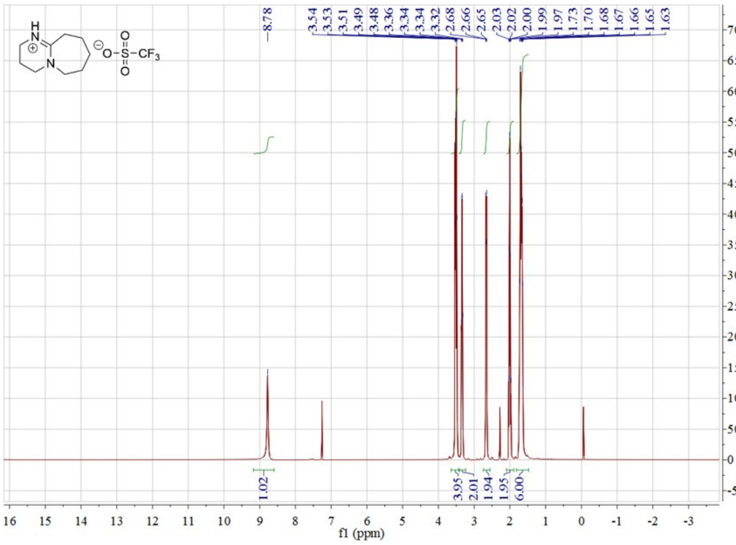


Figure S5 ^{1}H NMR spectrum of [DBUH][OTf]

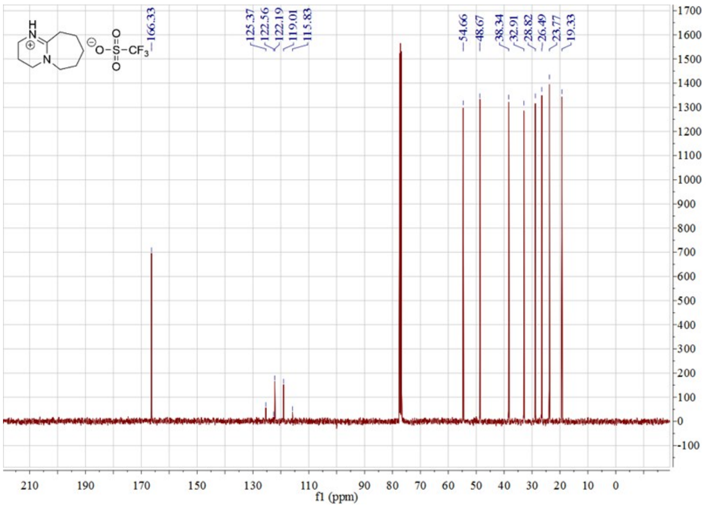


Figure S6 ^{13}C NMR spectrum of [DBUH][OTf]

1.3 Synthesis of protic amine salts.

The general synthetic procedure and the characterizations for these amine salts introduced in Table 1 (**2a-2f**) were reported previously.[3a,3b] Here we only report the characterizations of 2 new compounds.

Aniline·HOTf ($PhNH_3^+OTf^-$, **2a**):

White solid. ^{1}H NMR (400 MHz, D_2O) δ 7.63–7.47 (m, 3H), 7.48–7.32 (m, 2H); ^{13}C NMR (100 MHz, D_2O) δ 130.1 (s),129.9 (s), 129.1 (s), 122.8 (s), 119.6 (d, $J_{C\text{-}F}$ = 317.2 Hz); HRMS (ESI$^+$): Calcd. for $[C_6H_8N]^+$ 94.0651, found 94.0654, HRMS (ESI$^-$): Calcd. for $[CF_3O_3S]^-$ 148.95257, found 148.95111.

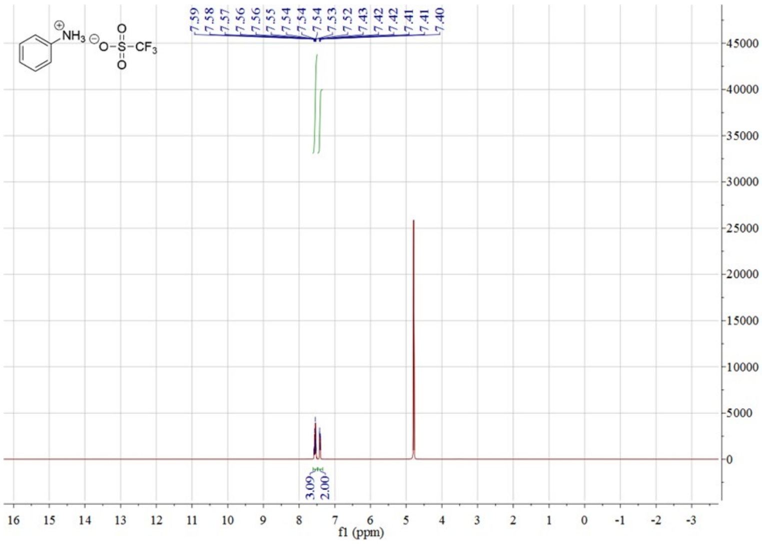


Figure S7 ^{1}H NMR spectrum of aniline·HOTf (**2a**)

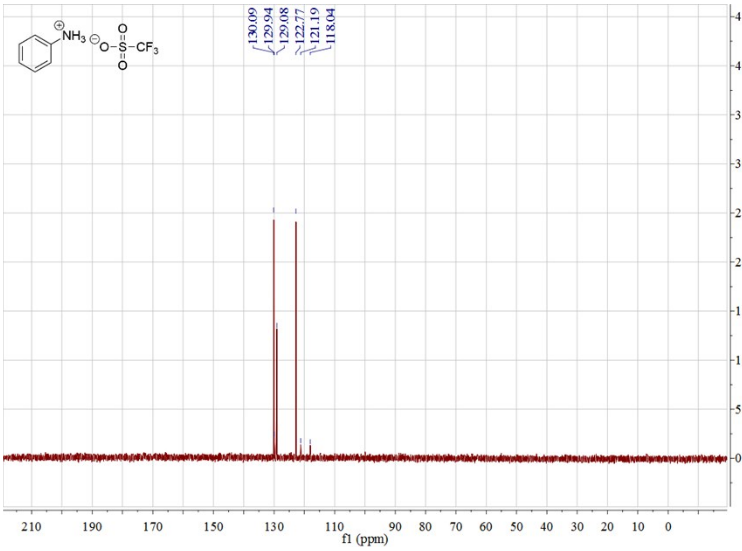


Figure S8 ^{13}C NMR spectrum of aniline·HOTf (**2a**)

Pyridine·HOTf (PyH$^+$OTf$^-$, **2d**):

White solid. ^{1}H NMR (400 MHz, D_2O) δ 8.79 (d, *J* = 5.7 Hz, 2H), 8.64 (t, *J* = 7.9 Hz, 1H), 8.10 (t, *J* = 6.9 Hz, 2H); ^{13}C NMR (101 MHz, D_2O) δ 147.2, 141.1, 127.4, 119.6 (q, *J* = 317.3 Hz); HRMS (ESI$^+$): Calcd. for $[C_5H_6N]^+$ 80.0495, found 80.0500. HRMS (ESI$^-$): Calcd. for $[CF_3O_3S]^-$ 148.95257, found 148.95111.

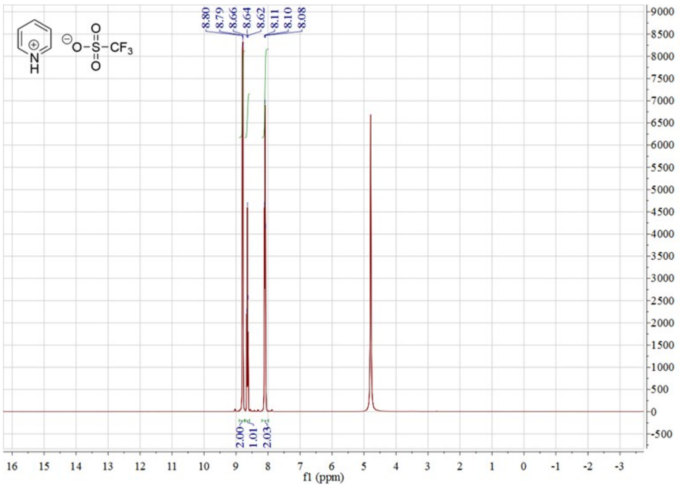


Figure S9 ^{1}H NMR spectrum of pyridine·HOTf (**2d**)

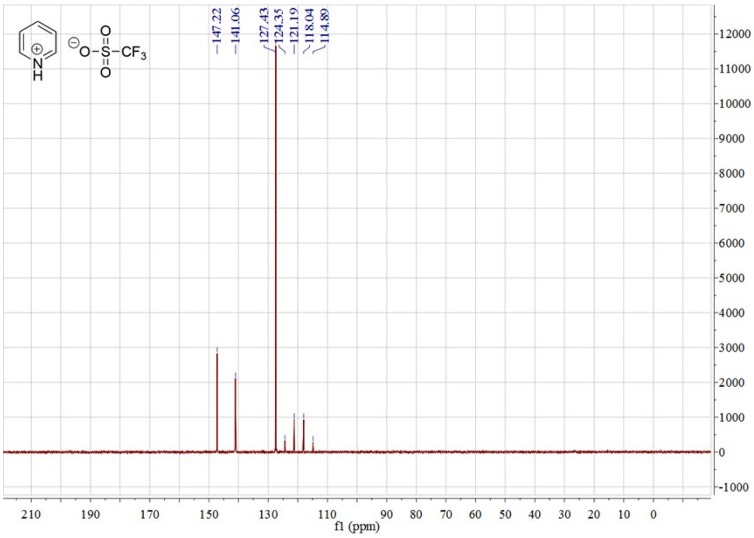


Figure S10 ^{13}C NMR spectrum of pyridine·HOTf (**2d**)

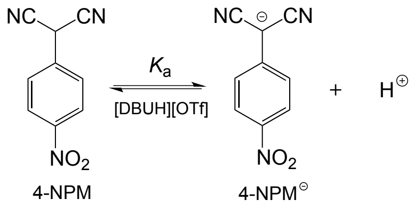
1.4 Determination of pK_a in [DBUH][OTf].

A. General Information:

The specially made UV-cells for the pK_a determinations are similar to previous described in details.[3] The principle of UV-Vis spectroscopic method used in this work is the same as previously reported indicator overlapping approach.[3][4] Prepared ultra-pure [DBUH][OTf] was stored in a glove box, in addition, the water content was monitored each time before using as the solvent for pK_a determination. All the organic acids involved in this work, if possible, were strictly purified through distillation or recrystallization, depending on the nature of these acids, and were stored in a glove-box or a vacuum desiccator.

B. Building up the acidity ladder in [DBUH][OTf].

a. Anchor point pK_a by self-dissociation of 4-nitrophenylmalononitrile (4-NPM).



$$K_a = \frac{[\text{4-NPM}^{\ominus}][\text{H}^{\oplus}]}{[\text{4-NPM}]}$$

Scheme S1. Self-dissociation of 4-NPM in [DBUH][OTf] at 25°C

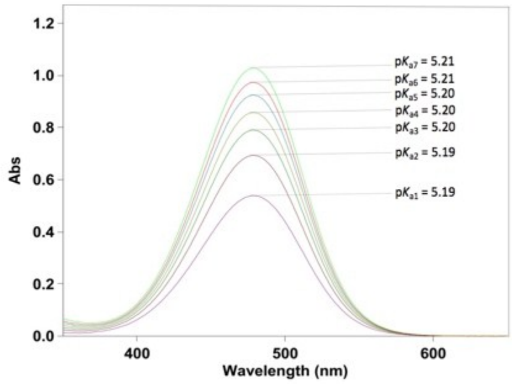
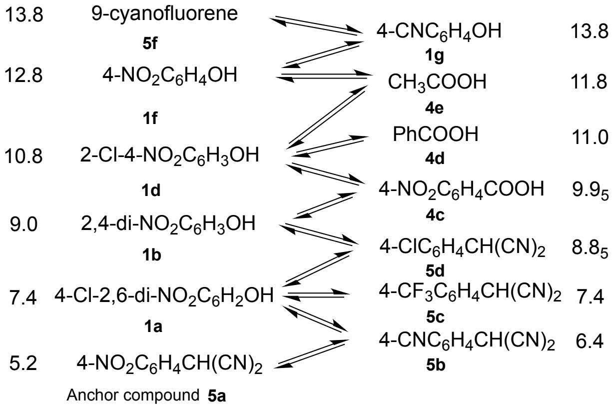


Figure S11 UV-Spectrum of Self-dissociation of 4-NPM in [DBUH][OTf] at 25°C, the pK_a of anchor compound 4-NPM was the average value of at least 3 parallel experiments, and at least 6-7 pK_a data can be obtained in each experiment.

As showed in Scheme S1 and Figure S11, in the specially made UV-cell described above, ~1 ml neat [DBUH][OTf] was added under stringent air and water free operation, the exact amount of the PIL was calculated from the weight and density of [DBUH][OTf].[5] The stock solution of appropriate amount of 4-NPM dissolved in neat [DBUH][OTf] was then added dropwise into the cell under positive pressure by a 1 ml Hamilton™ syringe with a long needle, the UV-Vis spectrum and the weight of solution added were recorded accordingly. The experiments were performed at 25°C with a thermostat control unit within the UV machine. The extinction coefficient of 4-NPM was obtained by adding base DBU into the stock [DBUH][OTf] solution of 4-NPM by following the increasing of absorbance at 480 nm (Fig. S11). The extinction coefficient of 4-NPM was calculated as $\varepsilon_{max}^{480nm} = 27350$ L mol^{-1} cm^{-1}. Then self-dissociation constant (K_a) was calculated from the extinction coefficient of 4-NPM anion and the concentration of 4-NPM added each time, and the anchor acidity value for 4-NPM (pK_a = 5.20) was the average of 3 parallel experiments (using different batch of [DBUH][OTf] prepared, each experiment contains 6-7 pK_a data), the standard deviation (SD) was less than 0.02 pK unit.

b. Acidity ladder.

With the acidity of anchor compound (pK_a = 5.20), the acidity ladder in neat [DBUH][OTf] then established by UV-Vis indicator approach which has been used in our previous acidity measurement work in ILs.[3][4] Due to the levelling effect, the base used for deprotonation of the indicators was the strongest base in [DBUH][OTf], i.e. DBU itself.



Scheme S2 The acidity ladder in [DBUH][OTf], SD ≤ ± 0.05 p*K* unit

c. The acidity determination of the substrates involved in this work.

The acidities of various substrates were determined by employing appropriate acid indicator(s) described in Scheme S2. The base used for deprotonation of indicators was DBU. The principle of pK_a measurement by UV-Vis indicator method is the same as before [3,4] and briefly introduced as follow:

$$HA + In^- \rightleftharpoons HIn + A^- \quad (Eqn.S1)$$

$$pK_a = pK_{HIn} - logK_{eq} = pK_{HIn} - log\frac{[HIn][A^-]}{[HA][In^-]} \quad (Eqn.S2)$$

where in Eqns. S1 and S2, HIn and HA denotes the indicator and substrate acids respectively. In the measurement process, an indicator acid (HIn) with known pK_a value was firstly deprotonated by a strong base DBU by titration, the absorbance of indicator anion (In^-) increased with the addition of the base until all the indicator acid (HIn) converted to it anion form (In^-), the absorbance now reached a maximum, which depending on the concertation of HIn and extinction coefficient of In^-. Due to the extinction coefficient of these indicator anions are very large (in a range of 2×10^4 to 2.8×10^4 L mol^{-1} cm^{-1} for malononitrile derivatives), the concertation of these indicator acids were in the range of 10^{-4} to 10^{-5} M. Then a [DBUH][OTf] solution of an acid of interest (HA) was added into the system, and the absorbance decreased upon each addition of HA due to the naturalisation of In^- by HA which is illustrated in the above eqn.1. Each addition of HA provides an equilibrium constant (K_{eq}) for the reaction between HA and In^-, and with the knowledge of the acidity of indicator acid (pK_{HIn}) and the amount of HA added each time, the pK_a of HA thus can be derived through Eqn. S2. The reported acidity for each acid in the manuscript was an average value of at least 3 independent experiments.

The following Figures S12-17 show the representative titration diagrams.

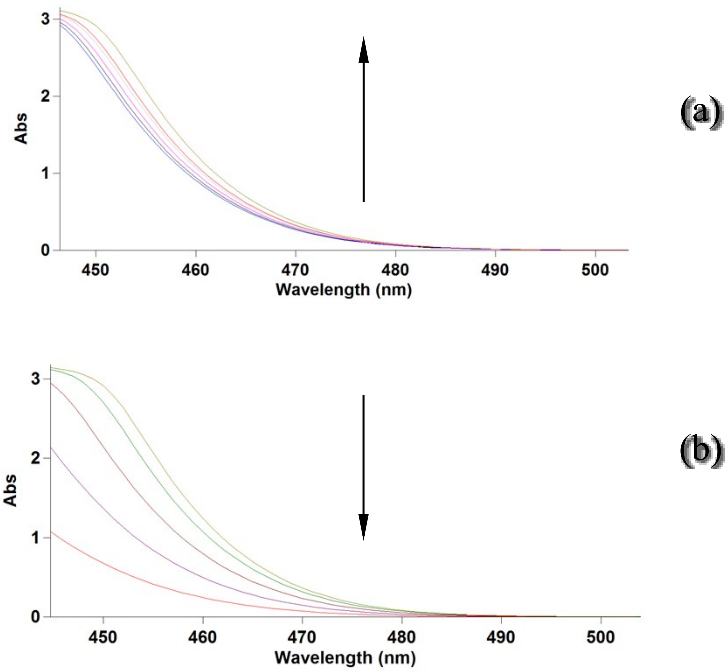


Figure S12 (a) The deprotonation of indicator acid 2-chloro-4-nitrophenol (**1d**) by DBU and (b) titration of 2-chloro-4-nitrophenolate (**1d**$^-$) by acetic acid (**4e**) in [DBUH][OTf] at 25^{o}C

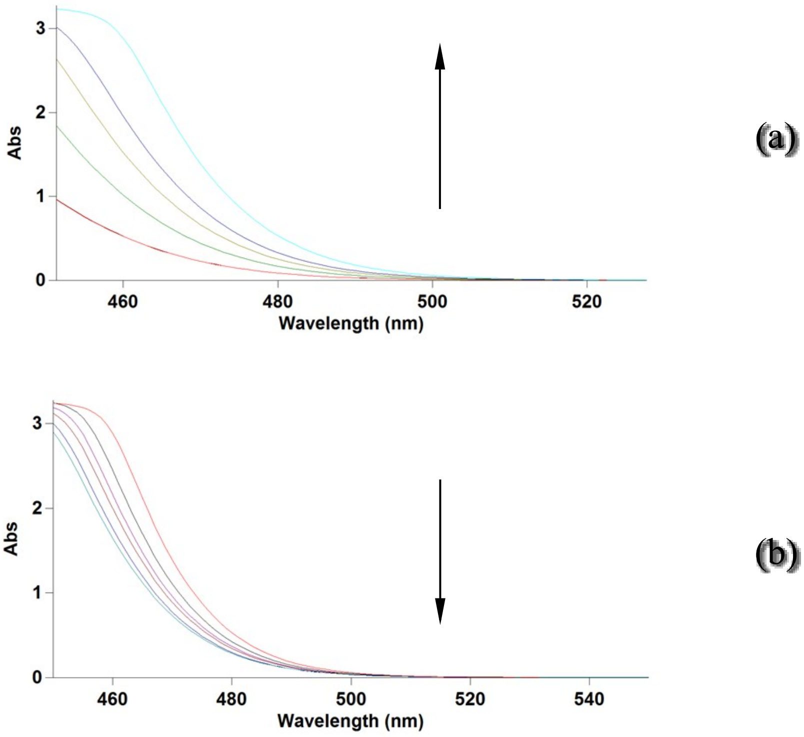


Figure S13 (a) The deprotonation of indicator acid 2,4-dinitrophenol (**1b**) by DBU and (b) titration of 2,4-dinitrophenolate (**1b**$^-$) by 4-ClC$_6$H$_4$CH(CN)$_2$ (**5d**) in [DBUH][OTf] at 25^{o}C

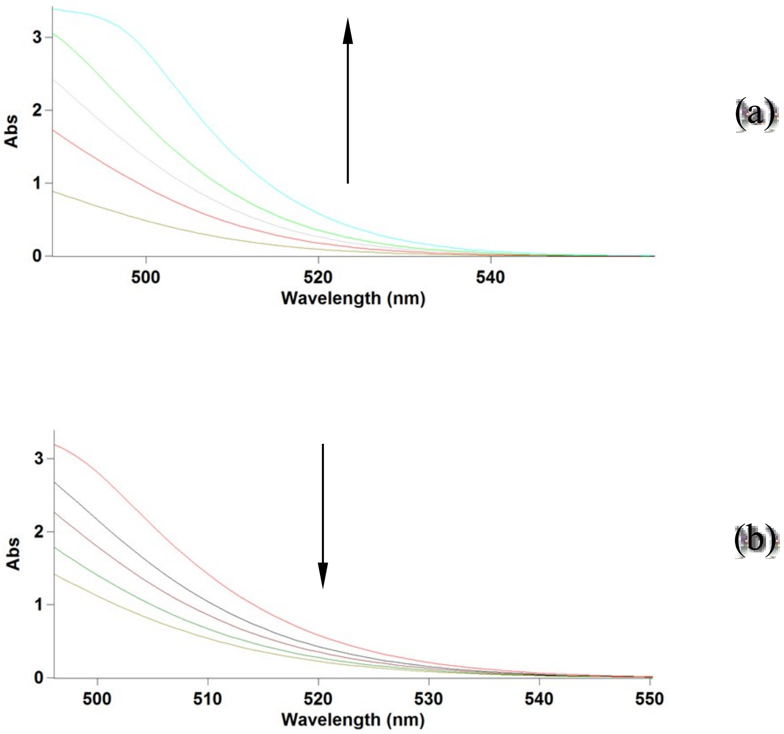


Figure S14 (a) The deprotonation of indicator acid 4-chloro-2,6-dinitrophenol (**1a**) by DBU and (b) titration of 4-chloro-2,6-dinitrophenolate (**1a**⁻) by 4-$CNC_6H_4CH(CN)_2$ (**5b**) in [DBUH][OTf] at 25°C

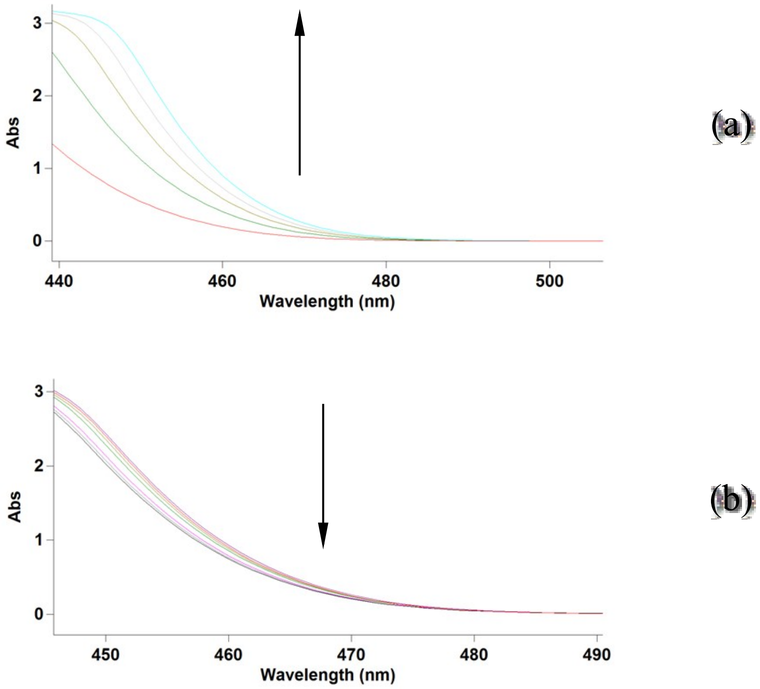


Figure S15 (a) The deprotonation of indicator acid 4-nitrophenol (**1f**) by DBU and (b) titration of 4-chloro-2,6-dinitrophenolate (**1f**⁻) by 4-cyanophenol (**1g**) in [DBUH][OTf] at 25°C

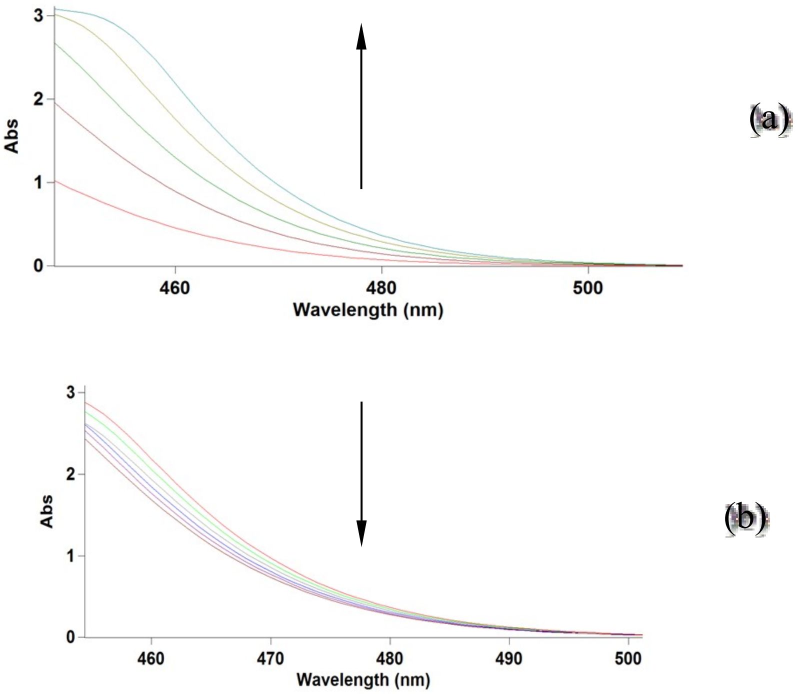


Figure S16 (a) The deprotonation of indicator acid 2,4-dinitrophenol (**1b**) by DBU and (b) titration of 2,4-dinitrophenolate (**1b**⁻) by 5-thiomethyltetrazoles (**3a**) in [DBUH][OTf] at 25°C.

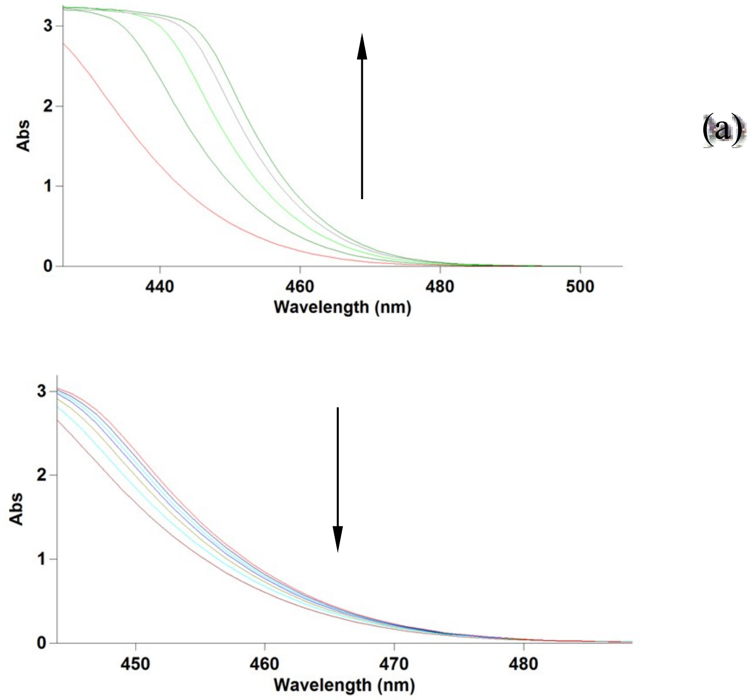


Figure S17 (a) The deprotonation of indicator acid 4-nitrophenol (**1f**) by DBU and (b) titration of 4-chloro-2,6-dinitrophenolate (**1f**⁻) by 5-methyltetrazoles (**3c**) in [DBUH][OTf] at 25°C

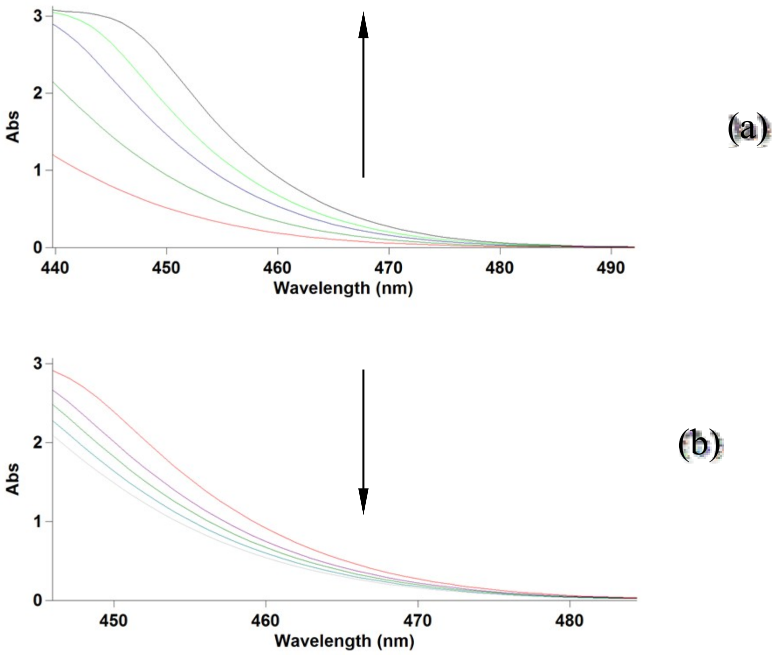


Figure S18 (a) The deprotonation of indicator acid 2-chloro-4-nitrophenol (**1d**) by DBU and (b) titration of acid 2-chloro-4-nitrophenolate (**1d**⁻) by imidazole•HOTf (ImH⁺, **2c**) in [DBUH][OTf] at 25°C

2. Acidities of benzoic acids in [DBUH][OTf].

Table S1 pK_a Values of para-substituted benzoic acids in various solvents

substituent	[DBUH][OTf][a]	[BMIM][OTf][b,c]	DMSO[c]	Water[c]
p-MeO	11.3_5	13.6	11.4	4.5
p-Me	11.2	13.5	11.2	4.3_5
H	11.0	13.3	11.0	4.2
p-F	10.8_5	13.0	10.6	4.1_5
p-Cl	10.6_5	12.8	10.1	4.0
p-CF$_3$	10.3	12.4		3.7
p-CN	10.1	12.2	9.2_5	3.5_5
p-NO$_2$	9.9_5	12.0	9.1	3.4_5

[a] The standard deviation, SD ≤ ± 0.05 pK unit. [b] [BMIM] = 1-butyl-3-methylimidazolium, and the homoassociation constants (K_{homo}) for the dissociation of these carboxylic acids in [BMIM][OTf] are in an order of 10^3 M^{-1}. [c] The pK_a data from Ref. [6]

Table S2. Homoassociation effects was found during the pK_a measurement of benzoic acid in an aprotic IL [BMIM][NTf$_2$] but not in the protic IL [DBUH][OTf], as evidenced by the decreasing of calculated pK_a value upon adding the benzoic acid dropwise in [BMIM][NTf$_2$], but not in [DBUH][OTf]. (SD ≤ ± 0.03 pK unit)

ILs / drop	1	2	3	4	5	6	7	8
[BMIM][NTf$_2$]	15.1	15.00	15.0	14.9	14.8	14.8	14.7	14.6
[DBUH][OTf]	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0

3. Regression analyses.

3.1 Correlations of acidities between [DBUH][OTf] and [BMIM][OTf].

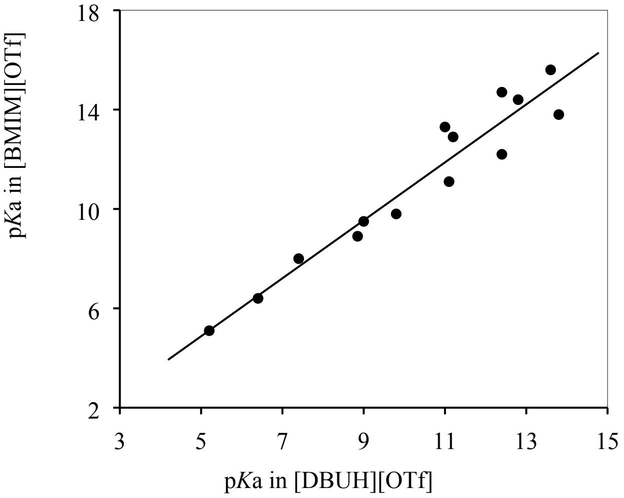


Figure S19 The correlation between acidities of **1a**-**5g** in [DBUH][OTf] and [BMIM][OTf] (with these available data in the latter)

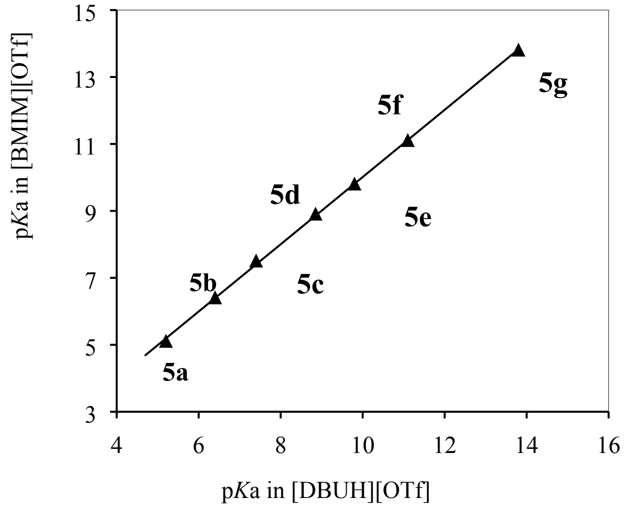


Figure S20 The correlation between acidities of **5a**-**5g** in [DBUH][OTf] and [BMIM][OTf]

3.2 Correlations of acidities between [DBUH][OTf] and DMSO.

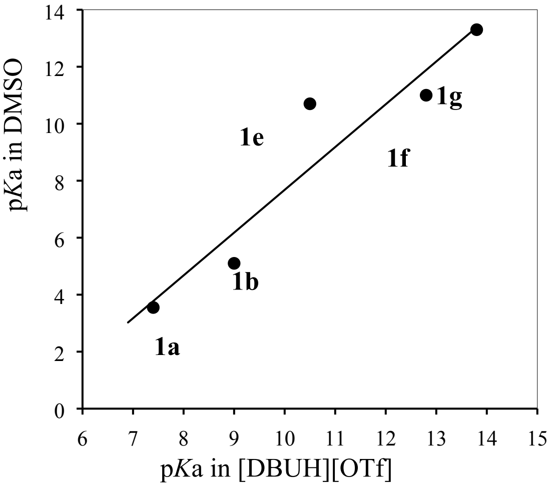


Figure S21 The correlation between pK_as of O-H acids (**1a**-**1g**) in [DBUH][OTf] and DMSO

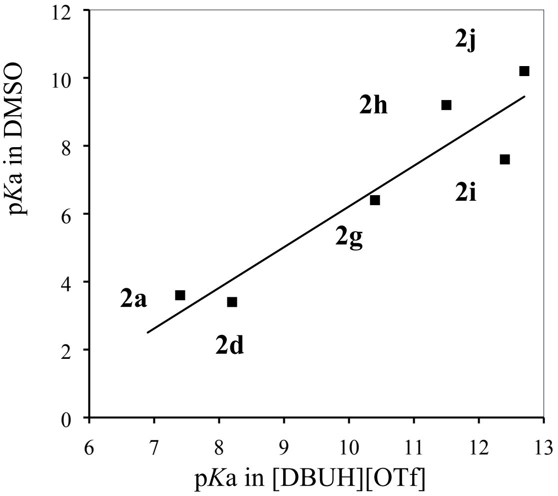


Figure S22 The correlation between pK_as of N^+-H (**2a**-**2j**) acids in [DBUH][OTf] and DMSO

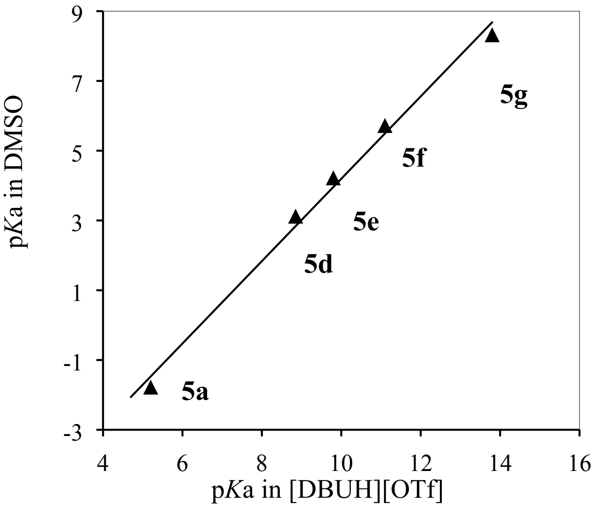


Figure S23 The correlation between pK_as of C-H acids (**5a-5g**) in [DBUH][OTf] and DMSO

3.3 Correlations of acidities between PIL and water.

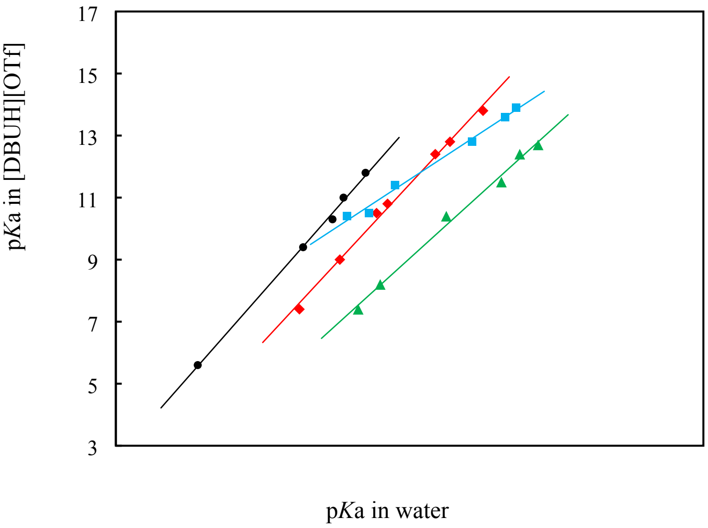


Figure S24 Correlations between pK_as of N-H (■), N$^+$-H (▲), O-H (◆), and carboxylic (RCOOH, ●) acids in [DBUH][OTf] and those in water. (A detailed version of Figure 3)

For N$^+$-H type acids: pK_a ([DBUH][OTf]) = 1.07 pK_a (water) + 2.60 Eqn.S3

For N-H type acids: pK_a ([DBUH][OTf]) = 0.775 pK_a (water) + 6.93 Eqn. S4

For O-H type acids: pK_a ([DBUH][OTf]) = 1.28 pK_a (water) + 3.78 Eqn. S5

For COOH type acids: pK_a ([DBUH][OTf]) = 1.34 pK_a (water) + 5.26 Eqn. S6

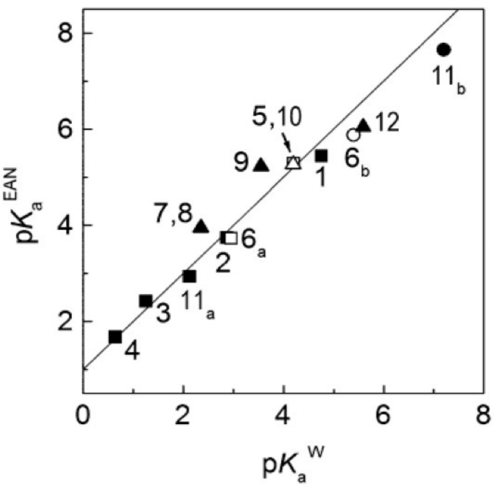


Figure S25 Correlation between pK_as of carboxylic acids (1-6), amino acids (7-10), phosphoric acid (11a, 11b) and trifluoroethylamine (12) in EAN and those in water ($R^2 = 0.911$, Copyright 2016 John Wiley and Sons). [7]

4. References.

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[5] The density of [DBUH][OTf] = 1.345 g/cm^3 at 25 ^{o}C, which is calculated from the linear density-temperature dependence relationship reported previously, for details, see: Miran, M. S.; Kinoshita, H.; Yasuda, T.; Md. Susan, A. B. H.; Watanabe, M. *Phys. Chem. Chem. Phys*. **2012**, *14*, 5178.

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