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PAPER

Acidic-functionalized ionic liquid as an efficient, green and reusable catalyst for hetero-Michael addition of nitrogen, sulfur and oxygen nucleophiles to α,β-unsaturated ketones†

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A series of acidic-functionalized ionic liquids were synthesized and applied to the hetero-Michael addition of nitrogen, sulfur and oxygen nucleophiles to α,β-unsaturated ketones under solvent-free conditions. Notably, 1-methylimidazolium *p*-toluenesulfonic ([Hmim]OTs) was found to be the most efficient catalyst and could realize "homogeneous catalysis, two-phase separation". Additionally, the catalytic system has wide substrate scope and good to excellent yields (up to 99%) could be obtained at room temperature.

Introduction

Ionic liquids (ILs) are salts being composed of distinct cations and anions that are capable of facilely tuning, whereby they can be designed for task-specific applications through smart choice of the respective cation and/or anion. In addition, ILs also have some favorable properties, such as negligible vapor pressure, non-flammability, high thermal and chemical stability, and adjustable solvent power for organic and inorganic substances.[1] Based on the above attractive properties, various ILs have been extensively investigated. Especially, some functionalized ILs, such as acidic, basic and other ionic liquids have been synthesized and used to catalyze various chemical reactions.[2]

Michael and hetero-Michael addition are powerful reactions for the formation of carbon–carbon and carbon–hetero atom bonds.[3] Moreover, the addition products such as β-amino, β-thio and β-oxy ketone functionalities are important synthetic intermediates.[4] Normally, either the donor or the acceptor component needs to be activated in hetero-Michael addition reactions. The classical method to achieve this has been deprotonation of the nucleophile with strong bases.[5] And important advances have been made with Lewis acid catalysts, which activate the acceptor components and allow hetero-Michael addition to proceed under much milder conditions. In this respect, numerous homogeneous catalysts have currently been developed, such as bismuth nitrate,[6] bis(trifluoromethanesulfon)imide,[7] $[Pd(CH_3CN)_2Cl_2]$ over noble metal chlorides,[8] phosphines and their derivatives,[9] Me_4NF,[10] $BF_3{\cdot}OEt_2$,[11] borax,[12] $VO(OTf)_2$[13] and so on. On the other hand, silica@copper (SiO_2@Cu) core–shell nanoparticles,[14] nafion® SAC-13 perfluorinated resin sulfonic acid,[15] KF/Al_2O_3,[16] various cation-exchanged faujasite zeolites with different Si/Al ratios,[17] Amberlyst-15,[18] perchloric acid adsorbed on silica gel ($HClO_4$–SiO_2)[19] as numerous heterogeneous catalysts were also exploited. Both homogeneous catalysis and heterogeneous catalysis have their own advantages and disadvantages. To preserve the benefits of a homogeneous catalyst while co-opting the primary benefits of a heterogeneous catalyst, one strategy is to use functionalized ionic liquids as the catalyst, whereby the system could realize "homogeneous catalysis, two-phase separation".

Although several kinds of ionic liquids have been used for the transformation,[20] most are non-functionalized ILs and the ILs were usually used as solvents or their usage amount was too large for the catalytic system. Moreover, rarely reported catalysts were applied to investigate three different types of nucleophiles in detail. The success of conjugate addition reactions lies in the use of either acidic or basic conditions which, if not selected judiciously, can be detrimental to the desired synthesis allowing unwanted side-reactions to contaminate the product. In addition, the possibility of poisoning metal-based catalysts with thiols, alkyl- or arylamines cannot be completely ruled out. Moreover, weak nucleophiles such as carbamates and alcohols usually show low activity. Therefore, a milder, environmentally benign catalyst system that can tolerate more nucleophile classes for functionalized Michael acceptors still remains to be explored.

In our continuing effort on developing an efficient catalytic system for this reaction,[9,15,21] we synthesized and applied a series of acidic-functionalized ionic liquids (Fig. 1) as metal-free, recyclable and efficient catalysts for the hetero-Michael reaction of N-containing substrates, thiols, and alcohols as nucleophiles with α,β-unsaturated ketones at room temperature (Scheme 1). Notably, 1-methylimidazolium *p*-toluenesulfonic ([Hmim]OTs) was

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† Electronic supplementary information (ESI) available. CCDC reference numbers 836789, 836790. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c1ob06346d

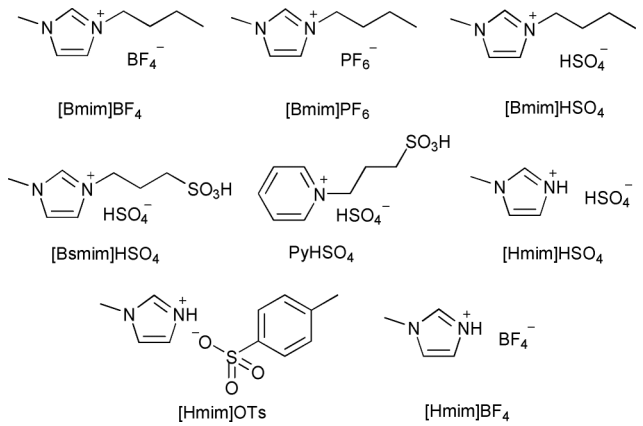
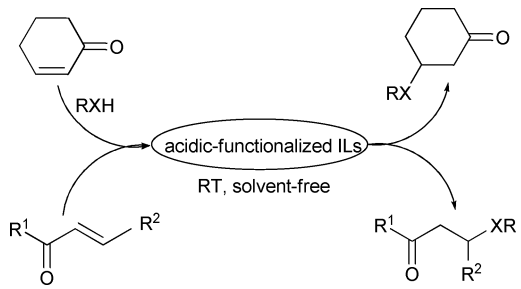


Fig. 1 Acidic-functionalized ionic liquids used in the hetero-Michael reaction.



Scheme 1 Hetero-Michael reactions of nitrogen, sulfur, oxygen nucleophiles with α,β-unsaturated enones.

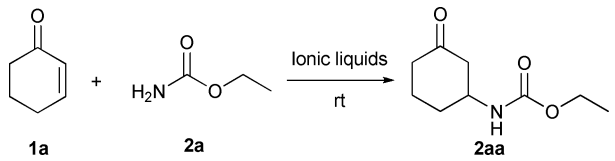
found to be the most efficient catalyst and the catalytic system successfully realized "homogeneous catalysis, two-phase separation".

Results and discussion

Initial studies were carried out using cyclohexenone (**1a**) and ethyl carbamate (**2a**) as a model partner catalyzed by a series of ionic liquids derived from 1-methylimidazolium, pyridine and the results were summarized in Table 1. Obviously, the reaction could not occur without any catalyst (Table 1, entry 1). Neutral ionic liquids such as [Bmim]BF_4 and [Bmim]PF_6 were also found to be inactive for the reaction (entries 2 and 3). Subsequently, the activities were compared with ionic liquids employing HSO_4^- as the anion and [Bmim]$^+$, [Bsmim]$^+$, Py$^+$ or [Hmim]$^+$ as cations (entries 4–7). As a result, the catalytic efficiency increased in the order of Py$^+$ < [Bmim]$^+$ < [Bsmim]$^+$ < [Hmim]$^+$. Then the anion's effects on the reaction of a series of acidic-functionalized ionic liquids based on 1-methylimidazolium were examined (entries 7–9). Interestingly, the acidic-functionalized IL with OTs^- showed excellent performance to give 89% yield (entry 8). Therefore, [Hmim]OTs was chosen as the model catalyst for further investigation.

Subsequently, the influence of the amount of the catalyst on the reaction was also evaluated under identical reaction conditions, as listed in Fig. 2. The yield of the product was just 57% in the presence of 10 mmol% [Hmim]OTs and the yield markedly increased to 82% with 30 mmol% catalyst present. However, the yield changed only slightly when further increasing the amount of [Hmim]OTs from 30 mmol% to 100 mmol%. Therefore, 30 mmol% was the optimal amount for the reaction from an economical standpoint.

Table 1 Screening the activities of the ionic liquids[a]



Entry	Ionic liquid	Yield (%)[b]
1	—	NR[c]
2	[Bmim]BF_4	NR[c]
3	[Bmim]PF_6	NR[c]
4	[Bmim]HSO_4	53
5	[Bsmim]HSO_4	62
6	$PyHSO_4$	50
7	[Hmim]HSO_4	70
8	[Hmim]OTs	89
9	[Hmim]BF_4	71

[a] Reaction conditions: cyclohexenone 0.5 mmol, ethyl carbamate 0.6 mmol, ionic liquid 1 mL, rt, t = 24 h. [b] GC yield using n-decane as internal standard. [c] No reaction occurred.

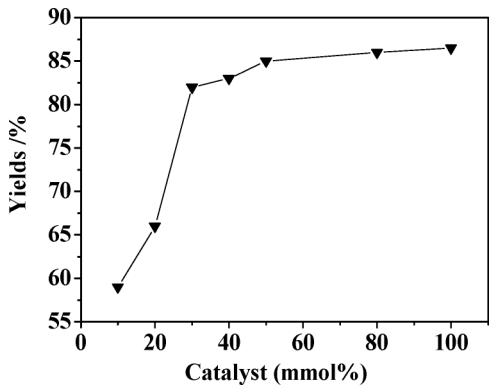
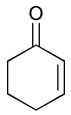
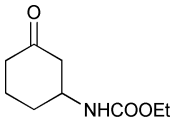
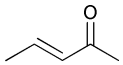
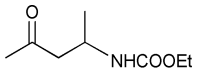
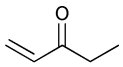
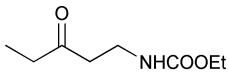
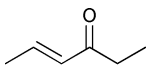
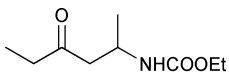
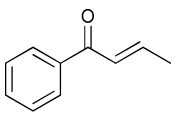
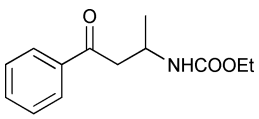
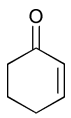
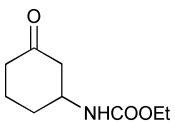
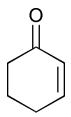
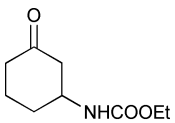
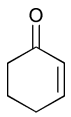
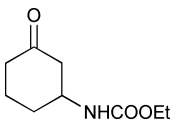


Fig. 2 The influence of the catalyst amount on the reaction. Reaction conditions: cyclohexenone 0.5 mmol, ethyl carbamate 0.6 mmol, rt, 24 h, cat. [Hmim]OTs.

To examine the utility and generality of this methodology for hetero-Michael addition, we applied the present catalyst system to a series of α,β-unsaturated ketones with nitrogen, sulfur and oxygen nucleophiles (Tables 2–5). Firstly, hetero-Michael addition of α,β-unsaturated ketones with nitrogen nucleophiles catalyzed by [Hmim]OTs was examined. Using ethyl carbamate as the nitrogen nucleophile, cyclohexenone and all kinds of linear enones could react smoothly to obtain above 80% yields except **1e** (Table 2, entries 1–5). Additionally, some control experiments were done to compare the catalytic activities between traditional acids and [Hmim]OTs possessing similar pK_a under an analogical determination method (see ESI†). To our delight, [Hmim]OTs exhibited the best activity (entries 6–8).

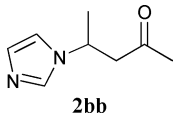
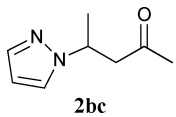
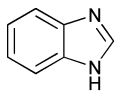
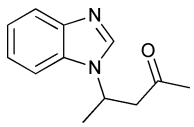
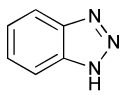
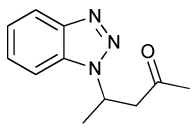
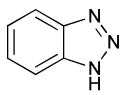
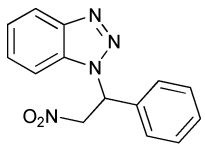
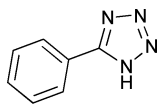
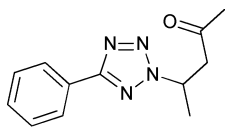
Then all kinds of nitrogen nucleophiles were also investigated using pent-3-en-2-one as the acceptor and the results were summarized in Table 3. As we know, imidazoles unsubstituted in the 1-position are weak acids. The pK_a values of imidazole, pyrazole, benzimidazole, benzotriazole and 5-phenyl-1H-tetrazole are respectively 14.52, 14.21, 12.75, <9.3 and <4.89.[22] That's to say, the N–H acidity becomes stronger with the increase of the number of N atoms. The results revealed that the reactivity decreased in the order of 5-phenyl-2H-tetrazole > 1H-benzo[1,2,3]triazole

Table 2 Hetero-Michael addition of α,β-unsaturated ketones with ethyl carbamate (**2a**) catalyzed by [Hmim]OTs[a]

Entry	Enone	Product	*t* (h)	Yield (%)[b]
1	 **1a**	 **2aa**	24	82
2	 **1b**	 **2ba**	16	98
3	 **1c**	 **2ca**	16	95
4	 **1d**	 **2da**	24	87
5	 **1e**	 **2ea**	24	56
6[c]	 **1a**	 **2aa**	24	86
7[d]	 **1a**	 **2aa**	24	80
8[e]	 **1a**	 **2aa**	24	76

[a] Reaction conditions: α,β-unsaturated ketones 0.5 mmol, ethyl carbamate 0.6 mmol, cat. = [Hmim]OTs, 30 mmol%, rt. [b] Isolated yield. [c] 2 mL DMSO. [d] cat. HCl 30 mmol%, 2 mL DMSO. [e] cat. H_2SO_4 30 mmol%, 2 mL DMSO.

Table 3 Hetero-Michael addition of α,β-unsaturated substrates with nitrogen-containing heterocycles catalyzed by [Hmim]OTs[a]

Entry	Nucleophile	Product	*t* (h)	Yield (%)[b]
1	 **2b**	 **2bb**	24	65
2	 **2c**	 **2bc**	24	76
3[c]	 **2d**	 **2bd**	24	79
4[c]	 **2e**	 **2be**	3	92
5[c,d]	 **2e**	 **2ke**	12	82
6[c]	 **2f**	 **2bf**	1	95

[a] Reaction conditions: pent-3-en-2-one 0.5 mmol, nitrogen-containing heterocycle 0.6 mmol, cat. = [Hmim]OTs, 30 mmol%, rt. [b] Isolated yield. [c] 2 mL CH_2Cl_2 was added. [d] (*E*)-(2-nitrovinyl)benzene (**1k**) as the substrate, 60 °C, 12 h.

> 1*H*-benzo-imidazole > 1*H*-pyrazole > 1*H*-imidazole (Table 3, entries 1–5), which was occasional in accordance with the order of the acidity.[22] Notably, using 5-phenyl-2*H*-tetrazole as the nitrogen nucleophile, a nearly quantitative yield could be obtained within 1 h (entry 6). In addition, the activities of several nitrogen nucleophiles were also examined employing 1-phenylbut-2-en-1-one as the acceptor and the results were summarized in Table S1†. And X-ray analysis has been used to establish some crystal structures and prove the *N*-substituted position (see ESI†). Besides, several other α,β-unsaturated electrophiles such as methyl acrylate, acrylamide, acrylonitrile and (*E*)-(2-nitrovinyl)benzene were also tested using ethyl carbamate or 1*H*-benzo[1,2,3]triazole as the acceptor respectively. Unfortunately, the reactions did not work at room temperature in most cases (see ESI†, Table S2, entries 1–8). Only an 82% yield could be obtained employing 1*H*-benzo[1,2,3]triazole and (*E*)-(2-nitrovinyl)benzene as the substrates by improving the temperature to 60 °C (Table 3, entry 5).

As we know, thiols are notoriously difficult to use in the presence of Lewis acidic metals due to their strong tendency to poison these catalysts, although recent advances have been made.[23] Therefore, developing a more efficient catalytic system for addition of thiols with α,β-unsaturated ketones would be important. Fortunately, further experiments revealed that [Hmim]OTs could be applied successfully to thiols (Table 4). Benzenethiol and cyclohex-2-en-1-one could afford almost quantitative yield within 18 h. In addition, the results indicated that the yield was lower than using benzenethiol as the sulfur nucleophiles, either benzenethiol with withdrawing substitute or with donating substitute (Table 4, entries 1, 2, 4–6). Moreover, the steric hindrance of the substitute

Table 4 Hetero-Michael addition of α,β-unsaturated substrates with sulfur nucleophiles catalyzed by [Hmim]OTs[a]

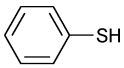
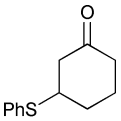
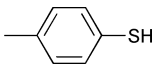
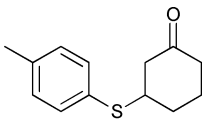
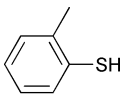
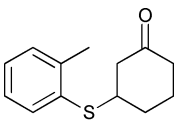
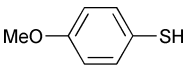
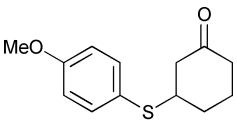
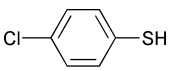
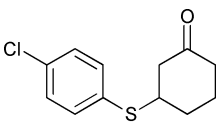
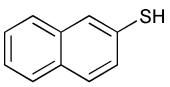
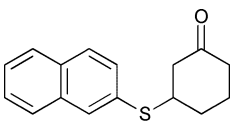
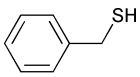
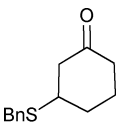
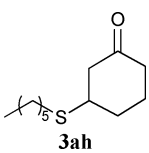
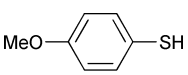
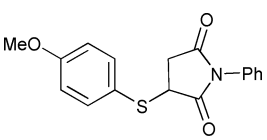
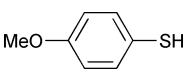
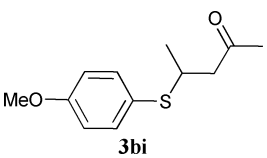
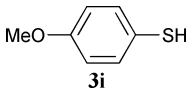
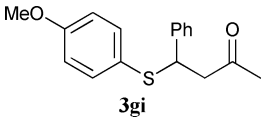
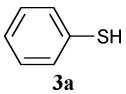
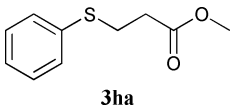
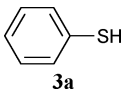
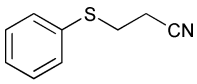
Entry	Nucleophile	Product	*t* (h)	Yield (%)[b]
1	 **3a**	 **3aa**	12/18	87/97
2[c]	 **3b**	 **3ab**	24	86
3	 **3c**	 **3ac**	32	93
4	 **3d**	 **3ad**	24	92
5[c]	 **3e**	 **3ae**	28	93
6[c]	 **3f**	 **3af**	24	82
7	 **3g**	 **3ag**	24	69
8	 **3h**	 **3ah**	24	61
9[c]	 **3i**	 **3fi**	4	91
10	 **3i**	 **3bi**	4	99

Table 4 (*Contd.*)

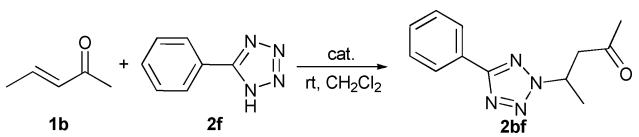
Entry	Nucleophile	Product	*t* (h)	Yield (%)[b]
11	 **3i**	 **3gi**	6	78
12[d]	 **3a**	 **3ha**	4	85
13[e]	 **3a**	 **3ja**	4	89

[a] Reaction conditions: substrate 0.5 mmol, thiophenol 0.6 mmol, cat. [Hmim]OTs 30 mmol%, rt. [b] Isolated yield. [c] 2 mL CH_2Cl_2 was added. [d] methyl acrylate (**1h**) as the substrate. [e] acrylonitrile (**1j**) as the substrate.

also has some influence on the reaction. However, a good yield could also be obtained by prolonging the reaction time when using *o*-methyl benzenethiol (**3c**) as the sulfur nucleophile (entry 3). Besides, aliphatic thiols were also active for the addition, acquiring moderate yield within 24 h (entries 7 and 8). Then several kinds of α,β-unsaturated substrates were examined employing *p*-CH_3O benzenethiol as the corresponding sulfur nucleophile (entries 4, 9, 10, 11). Interestingly, above 90% yield could be obtained within 4 h when *N*-phenylmaleimide or pent-3-en-2-one was used (entries 9 and 10). However, when using 4-phenylbut-3-en-2-one as the acceptor, only good yield (78%) was obtained by prolonging the reaction time to 6 h and the phenomena may be ascribed to the steric hindrance effect (entry 11). Fortunately, the reactions of benzenethiol with methyl acrylate and acrylonitrile could smoothly occur and obtain excellent yields (85% and 89% respectively) within 4 h (entries 12, 13). Trace or no product could be acquired using acrylamide or (*E*)-(2-nitrovinyl)benzene as the electrophile (Table S2, entries 9, 10†).

Generally, alcohols are less reactive than the above nucleophiles for the hetero-Michael addition, only acquiring poor yields with α,β-unsaturated substrates. Gratifyingly, we found the ionic liquid [Hmim]OTs was also a good catalyst for oxa-Michael addition and the results were summarized in Table 5. Simple alcohols such as methanol, alcohol and so on were suitable nucleophiles with above 60% yields (Table 5, entries 1–4). Fortunately, aromatic alcohols usually exhibiting competitive interference of Friedel–Crafts-type reactions reacted with pent-3-en-2-one to give 60% yield of the Michael product by prolonging the reaction time to 48 h (entry 5). Besides, other α,β-unsaturated ketones with the phenyl ring of the carbonyl side such as 1-phenyl-but-2-en-1-one furnished the addition product in 78% yield (entry 6). And the reaction of methanol and *N*-phenylmaleimide was very slow and just 23% yield could be acquired at the same conditions. However, improving the temperature to 60 °C led to 65% yield just after 12 h.

It is well-known that the stability and reusability of a catalyst system are the two key factors that identify whether it finds potentially application in industry. To test the catalyst reusability, the reaction was carried out in the presence of a catalytic amount of [Hmim]OTs under the optimal reaction conditions with pent-3-en-2-one and 5-phenyl-1*H*-tetrazole as the substrates (Scheme 2). When the reaction was completed, the reaction mixture was extracted with ethyl acetate, the ionic liquid left in the reaction vessel was rinsed with ethyl acetate and dried under vacuum at 90 °C for 8 h to eliminate any water trapped from moisture and reused for subsequent reactions. The results shown in Fig. 3 indicated that the isolated yield of the product **2bf** was almost consistent after five runs and [Hmim]OTs could be reused at least five times.



Scheme 2 The reaction used for testing the recyclability of the acidic–functionalized ionic liquid.

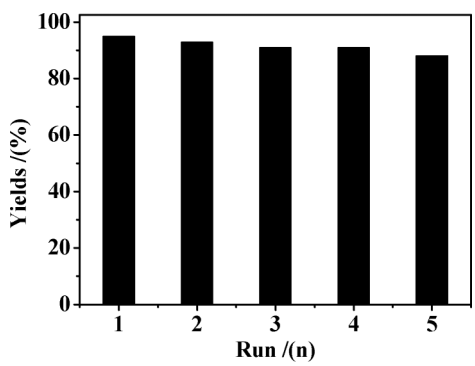
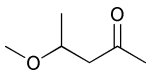
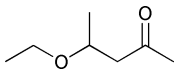
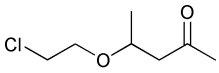
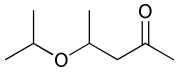
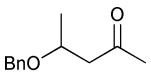
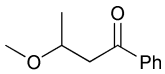
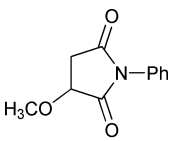
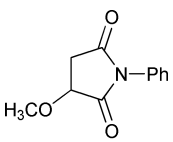


Fig. 3 Recyclability of the catalyst. Reaction conditions: pent-3-en-2-one 0.5 mmol, 5-phenyl-1*H*-tetrazole 0.6 mmol, *t* = 1 h, [Hmim]OTs 30 mmol%.

Conclusions

In conclusion, three kinds of hetero-Michael addition including nitrogen, sulfur and oxygen nucleophiles with α,β-unsaturated substrates have been successfully realized using the synthesized

Table 5 Hetero-Michael addition of α,β-unsaturated ketones with oxygen nucleophiles catalyzed by [Hmim]OTs[a]

Entry	Nucleophile	Product	*t* (h)	Yield (%)[b]
1	CH_3OH **4a**	 **4ba**	12	85
2	CH_3CH_2OH **4b**	 **4bb**	12	76
3	$ClCH_2CH_2OH$ **4c**	 **4bc**	12	61
4	 **4d**	 **4bd**	12	66
5	$PhCH_2OH$ **4e**	 **4be**	48	60
6[c]	CH_3OH **4a**	 **4ea**	48	78
7	CH_3OH **4a**	 **4fa**	48	23
8[c]	CH_3OH **4a**	 **4fa**	12	65

[a] Reaction conditions: substrate 0.5 mmol, alcohol 2.0 mmol, Cat. = [Hmim]OTs, 30 mmol%, rt. [b] Isolated yield. [c] $T = 60$ °C.

acidic-functionalized ionic liquids under metal-free and solvent-free conditions. Notably, 1-methylimidazolium *p*-toluenesulfonic was found to be the most efficient catalyst. Additionally, the catalytic system successfully realized "homogeneous catalysis, two-phase separation" and has wide substrate scope including aromatic and aliphatic nucleophiles. Moreover, good to excellent yields (up to 99%) could be obtained for the three kinds of hetero-Michael addition reactions at room temperature. This process thus represents a greener pathway for the hetero-Michael reactions. Developing a new catalytic system for the reaction or applying the catalytic system for new reactions are in progress in our laboratory.

Experimental

General

NMR spectra were recorded on BRUKER DRX 400 spectrometers. ^{1}H NMR (400 MHz) and ^{13}C NMR (100 MHz) spectra were obtained as solutions in either $CDCl_3$ or D_2O. Chemical shifts were reported in parts per million (ppm, δ) and referenced to $CHCl_3$ (δ 7.27) or D_2O (δ 4.88). Gas chromatographic analyses were performed using an Agilent 6850 system (FID). Silica gel (200–300 microns) was used for all chromatographic separations. Anhydrous organic solvents were dried and stored under nitrogen. All other chemicals used for synthetic procedures were reagent grade or better. Solutions were concentrated *in vacuo* with a rotary evaporator and the residue was purified using a silica gel column unless specified otherwise. All reactions were monitored by TLC with silica gel-coated plates. Detection was conducted by UV absorption (254 nm) and fuming with iodine in a jar.

The synthetic procedure for 1-methylimidazolium *p*-toluenesulfonic ([Hmim]OTs)

1-Methylimidazole (6.15 g, 0.075 mol) was placed in a three necked flask, which was provided with a stirrer and cooled to 0 °C. Then *p*-toluenesulfonic acid (0.075 mol, 12.9 g; 40% solution in water, 33 mL) was added slowly over a period of 30 min while stirring and cooling to maintain the temperature at 0–5 °C. After that, the reaction mixture was stirred for an additional period of 2 h. Water was removed in vacuum to give the product as a colorless liquid, which solidified on cooling. 1-Methylimidazolium *p*-toluenesulfonic (19.0 g, 98% yield) was obtained after drying *in vacuo* for 24 h.

IR: 3417, 3149, 2659, 2855, 2642, 2072, 1924, 1628, 1587, 1552, 1495, 1451, 1392, 1311, 1281, 1192, 1126, 1038, 1011, 904, 819, 757, 688, 626, 567. ^{1}H NMR (400 MHz, D_2O) δ = 2.21 (s, 3H), 3.71 (s, 3H), 7.15–7.23 (m, 4H), 7.50 (s, 1H), 7.53 (s, 1H), 8.42 (s, 1H). ^{13}C NMR (100 MHz, D_2O) δ = 20.4, 35.3, 119.4, 122.8, 125.3, 129.3, 134.8, 139.5, 142.3. MS (ESI): $[m/z]^+ = 82.8$, $[m/z]^- = 170.6$.

General procedure for hetero-Michael addition

To a well stirred mixture of nucleophile (0.6 mmol) and catalyst ([Hmim]OTs 30 mol%, 38.1 mg) was added α,β-unsaturated substrate (0.5 mmol) and then the reaction mixture was stirred for the designated reaction time. After completion of the reaction, the mixture was extracted with ethyl acetate (5 mL × 3), the organic layer was washed with brine, dried (Na_2SO_4), evaporated and purified by using column chromatography to obtain the pure product. The products were characterized by measuring melting point, IR, ^{1}H NMR,^{13}C NMR and HRMS.

Characterization of the products

Ethyl 3-oxocyclohexylcarbamate (2aa). 75.9 mg, 82% yield as yellow liquid. IR: 3324, 2949, 2870, 1708, 1534, 1276, 1248, 1219, 1049, 780, 651. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.24 (t, J = 6.8 Hz, 3H), 1.67–1.77 (m, 2H), 1.99–2.03 (m, 1H), 2.08–2.18 (m, 1H), 2.27–2.40 (m, 3H), 2.27–2.40 (m, 1H), 2.70 (dd, J = 4.8, 14.0 Hz, 1H), 3.97 (s, 1H), 4.10 (t, J = 2.0 Hz, 2H), 5.09 (d, J = 7.2 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 14.6, 22.0, 31.2, 40.8, 48.0, 50.1, 60.8, 155.7, 209.0. HRMS-ESI: Calcd. For $C_9H_{15}NNaO_3$: 208.0944. Found: 208.0936.

Ethyl 4-oxopentan-2-ylcarbamate (2ba). 84.8 mg, 98% yield as yellow liquid. IR: 3330, 2967, 2934, 1716, 1533, 1369, 1259, 1098,

1073, 1018, 799. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.16 (t, *J* = 6.4 Hz, 6H), 2.09 (s, 3H), 2.53 (dd, *J* = 6.4, 16.8 Hz, 1H), 2.65 (dd, *J* = 5.2, 16.8 Hz, 1H), 3.98–4.02 (m, 3H), 5.09 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 13.6, 19.6, 29.5, 42.6, 48.3, 59.6, 154.9, 206.6. HRMS-ESI: Calcd. For $C_8H_{15}NNaO_3$: 196.0944. Found: 196.0949.

Ethyl 3-oxopentylcarbamate (2ca). 75.5 mg, 95% yield as yellow liquid. IR: 3551, 2980, 2940, 1710, 1530, 1376, 1254, 111, 1036, 779, 617. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.06 (t, *J* = 7.6 Hz, 3H), 1.22 (t, *J* = 7.2 Hz, 3H), 2.44 (q, *J* = 7.2, Hz, 2H), 2.66 (t, *J* = 5.6 Hz, 2H), 3.41 (q, *J* = 5.6 Hz, 2H), 4.08 (q, *J* = 6.4 Hz, 2H), 5.21 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 7.6, 14.5, 35.5, 36.1, 41.9, 60.6, 156.6, 210.8. HRMS-ESI: Calcd. For $C_8H_{15}NNaO_3$: 196.0944. Found: 196.0944.

Ethyl 4-oxohexan-2-yl carbamate (2da). 80.4 mg, 87% yield as yellow liquid. IR: 3334, 2978, 2938, 1712, 1532, 1254, 1079, 1027, 832. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 0.97 (t, *J* = 7.2 Hz, 3H), 1.14–1.17 (m, 6H), 2.37 (q, *J* = 7.2 Hz, 2H), 2.51 (dd, *J* = 5.2, 16.4 Hz, 1H), 2.63 (dd, *J* = 4.8, 16.4 Hz, 1H), 3.96–4.01 (m, 3H), 5.16 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 6.6, 13.6, 19.6, 35.5, 42.7, 59.6, 154.9, 209.3. HRMS-ESI: Calcd. For $C_9H_{17}NNaO_3$: 210.1101. Found: 210.1093.

Ethyl (1-methyl-3-oxo-3-phenylpropyl)carbamate (2ea). 65.8 mg, 56% yield as light yellow liquid. IR: 2977, 2925, 1741, 1680, 1425, 1256, 1057, 1030, 760, 694. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.23 (t, *J* = 7.2 Hz, 3H), 1.30 (d, *J* = 6.8 Hz, 3H), 3.06 (dd, *J* = 6.4, 16.8 Hz, 1H), 3.38 (d, *J* = 14.0 Hz, 1H), 4.10 (q, *J* = 7.2 Hz, 2H), 4.19–4.26 (m, 1H), 5.21 (s, 1H), 7.47 (t, *J* = 7.2 Hz, 2H), 7.58 (t, *J* = 7.6 Hz, 1H), 7.97 (d, *J* = 7.2 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 14.6, 20.4, 44.2, 44.3, 60.7, 128.1, 128.7, 133.3, 136.9, 155.9, 198.8. HRMS-ESI: Calcd. For $C_{13}H_{17}NNaO_3$: 258.1101. Found: 258.1105.

4-(1*H*-Imidazol-1-yl)pentan-2-one (2bb). 49.4 mg, 65% yield as yellow liquid. IR: 3115, 2960, 2929, 2857, 1719, 1500, 1457, 1413, 1370, 1285, 1077, 745, 665. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.49 (d, *J* = 6.8 Hz, 3H), 2.09 (s, 3H), 2.80 (dd, *J* = 6.4, 17.6 Hz, 1H), 2.93 (dd, *J* = 6.8, 17.6 Hz, 1H), 4.70–4.79 (m, 1H), 6.93 (s, 1H), 7.03 (s, 1H), 7.53 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 21.7, 30.5, 48.7, 51.0, 116.6, 129.4, 135.8, 204.8. HRMS-ESI: Calcd. For $C_8H_{13}N_2O$: 153.1022. Found: 153.1022.

4-(1*H*-Pyrazol-1-yl)pentan-2-one (2bc). 57.8 mg, 76% yield as yellow liquid. IR: 3203, 2982, 1716, 1399, 1366, 757. ^{1}H NMR (400 MHz, $CDCl_3$): *δ* 1.52 (d, *J* = 6.8 Hz, 3H), 2.07 (s, 3H), 2.81 (dd, *J* = 6.0 Hz, 17.2 Hz, 1H), 3.25 (dd, *J* = 7.2 Hz, 17.2 Hz, 1H), 4.88–4.80 (m, 1H), 6.20 (t, *J* = 2.4 Hz, 1H), 7.43 (d, *J* = 2.0 Hz, 1H), 7.53 (d, *J* = 1.6 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): *δ* 21.2, 30.5, 49.8, 53.2, 104.8, 139.3, 206.0. HRMS-ESI: Calcd. For $C_8H_{13}N_2O$: 153.1022. Found: 153.1023.

4-(1*H*-Benzo[d]imidazol-1-yl)pentan-2-one (2bd). 79.8 mg, 79% yield as yellow liquid. IR: 3400, 3087, 2979, 7934, 1716, 1490, 1457, 1364, 1284, 1227, 1169, 1113, 1032, 773, 747. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.66 (d, *J* = 7.2 Hz, 3H), 2.12 (s, 3H), 2.98 (dd, *J* = 7.2, 17.6 Hz, 1H), 3.16 (dd, *J* = 5.6, 18.0 Hz, 1H), 5.01–5.10 (m, 1H), 7.27–7.32 (m, 2H), 7.46 (d, *J* = 6.8 Hz, 1H), 7.81 (d, *J* = 6.4 Hz, 1H), 7.99 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 20.6, 30.5, 47.5, 49.4, 110.2, 122.2, 122.8, 132.7, 141.2, 144.0, 204.8. HRMS-ESI: Calcd. For $C_{12}H_{15}N_2O$: 203.1179. Found: 203.1180.

4-(1*H*-Benzo[d][1,2,3]triazol-1-yl)pentan-2-one (2be). 93.4 mg, 92% yield as yellow liquid. IR: 2982, 2935, 1717, 1369, 1166, 749. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.66 (d, *J* = 7.2 Hz, 3H), 2.12 (s, 3H), 2.98 (dd, *J* = 7.2, 17.6 Hz, 1H), 3.16 (dd, *J* = 5.6, 18.0 Hz, 1H), 5.01–5.10 (m, 1H), 7.27–7.32 (m, 2H), 7.46 (d, *J* = 6.8 Hz, 1H), 7.81 (d, *J* = 6.4 Hz, 1H), 7.99 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 20.6, 30.5, 47.5, 49.4, 110.2, 122.2, 122.8, 132.7, 141.2, 144.0, 204.8. HRMS-ESI: Calcd. For $C_{11}H_{13}N_3NaO$: 226.0951. Found: 226.0945.

1-(2-Nitro-1-phenylethyl)-1*H*-benzo[1,2,3]triazole (2ke). 146.6 mg, 82% yield as light yellow solid. mp: 92–93 °C IR: 1559, 1376, 747, 705. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 5.15 (dd, *J* = 4.8, 14.8 Hz, 1H), 5.95 (q, *J* = 9.6 Hz, 1H), 6.58 (q, *J* = 4.8 Hz, 1H), 7.34–7.47 (m, 8H), 8.08 (d, *J* = 8.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 59.8, 76.6, 109.3, 120.3, 124.6, 126.9, 128.0, 129.6, 129.8, 132.7, 134.0, 146.2. HRMS-ESI: Calcd. For $C_{14}H_{12}N_4NaO_2$: 291.0852. Found: 291.0854.

4-(5-Phenyl-2*H*-tetrazol-2-yl) pentan-2-one (2bf). 109.3 mg, 95% yield as light liquid. IR: 2987, 1720, 1465, 1450, 1363, 1026, 733, 694. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.59 (d, *J* = 6.8 Hz, 3H), 2.13 (s, 3H), 2.96 (dd, *J* = 6.4, 18.0 Hz, 1H), 3.38 (dd, *J* = 7.2, 18.0 Hz, 1H), 5.34–5.42 (m, 1H), 7.36–7.41 (m, 3H), 8.05 (dd, *J* = 2.0, 8.0 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 19.8, 29.3, 47.3, 54.9, 125.8, 126.4, 127.8, 129.2, 163.8, 203.1. HRMS-ESI: Calcd. For $C_{12}H_{14}N_4NaO$: 253.1060. Found: 253.1064.

3-Phenylthiocyclohexan-1-one (3aa). 99.9 mg, 97% yield as yellow liquid. IR: 2943, 2867, 1713, 1581, 1477, 1442, 1314, 1280, 1222, 1097, 1027, 972, 746, 695. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.67–1.79 (m, 2H), 2.11–2.18 (m, 2H), 2.30–2.41 (m, 3H), 2.68 (dd, *J* = 4.4, 14.4 Hz, 1H), 3.39–3.46 (m, 1H), 7.28–7.34 (m, 3H), 7.42 (dd, *J* = 1.6, 7.2 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 24.0, 31.2, 40.8, 46.1, 47.7, 127.8, 129.0, 133.0, 133.2, 208.7. HRMS-ESI: Calcd. For $C_{12}H_{14}NaOS$: 229.0658. Found: 229.0651.

3-(4-Methylphenylthio) cyclohexan-1-one (3ab). 94.6 mg, 86% yield as yellow liquid. IR: 3021, 2940, 2865, 1713. 1491. 1449. 1421. 1342. 1313. 1280. 1220. 1096. 1023. 971. 810. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.57–1.67 (m, 2H), 2.01–2.09 (m, 2H), 2.19–2.29 (m, 6H), 2.57 (dd, *J* = 4.4, 14.0 Hz, 1H), 3.22–3.29 (m, 1H), 7.04 (d, *J* = 8.0 Hz, 2H), 7.05 (d, *J* = 8.0 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 20.1, 23.0, 30.2, 39.8, 45.4, 46.7, 128.1, 128.8, 132.9, 137.1, 207.8. HRMS-ESI: Calcd. For $C_{13}H_{16}NaOS$: 243.0814. Found: 243.0809.

3-(*o*-Tolylthio)cyclohexanone (3ac). 102.3 mg, 93% yield as yellow liquid. IR: 2942, 1713, 1588, 1464, 1451, 1219, 1178, 1062, 751, 601. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.69–1.82 (m, 2H), 2.11–2.17 (m, 2H), 2.32–2.40 (m, 3H), 2.43 (s, 3H), 2.68 (dd, *J* = 4.4, 14.0 Hz, 1H), 3.39–3.45 (m, 1H), 7.14–7.23 (m, 3H), 7.39 (dd, *J* = 1.6, 7.2 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 20.9, 24.1, 31.3, 40.9, 45.6, 47.7, 126.5, 127.7, 130.5, 132.6, 133.2, 140.5, 208.7. HRMS-ESI: Calcd. For $C_{13}H_{16}NaOS$: 243.0814. Found: 243.0816.

3-(4-Methoxyphenylthio)cyclohexanone (3ad). 108.6 mg, 92% yield as white solid. mp: 47–48 °C. IR: 2942, 2938, 1709, 1592,

1494, 1447, 1284, 1247, 1177, 1099, 1030, 832, 805, 640, 531. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.64–1.69 (m, 2H), 2.09–2.15 (m, 2H), 2,24–2.34 (m, 3H), 2.61 (dd, *J* = 4.4, 14.4 Hz, 1H), 3.19–3.25 (m, 1H), 3.78 (s, 3H), 6.84 (d, *J* = 8.8 Hz, 2H), 7.38 (d, *J* = 8.8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 24.0, 31.1, 40.7, 46.9, 47.7, 55.2, 114.5, 122.8, 136.4, 159.9, 209.0. HRMS-ESI: Calcd. For $C_{13}H_{16}NaO_2S$: 259.0763. Found: 259.0768.

3-(4-Chlorophenylthio)cyclohexanone (3ae). 111.6 mg, 93% yield as white solid. mp: 65–66 °C. IR: 2954, 2880, 826, 743. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.63–1.78 (m, 2H), 2.12–2.17 (m, 2H), 2.31–2.39 (m, 3H), 2.67 (dd, *J* = 4.4, 14.4 Hz, 1H), 3.37–3.44 (m, 1H), 7.29 (d, *J* = 8.4 Hz, 2H), 7.36 (d, *J* = 8.4 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 24.0, 31.1, 40.8, 46.4, 47.6, 129.3, 131.5, 134.1, 134.6, 208.4. HRMS-ESI: Calcd. For $C_{12}H_{13}ClNaOS$: 263.0268. Found: 263.0264.

3-(Naphthalen-2-ylthio)cyclohexanone (3af). 105.0 mg, 82% yield as white solid. mp: 48 °C IR: 2934, 2859, 1713, 821, 748. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.64–1.81 (m, 2H), 2.08–2.20 (m, 2H), 2.24–2.44 (m, 3H), 2.69–2.74 (m, 1H), 3.49–3.56 (m, 1H), 7.44–7.50 (m, 3H), 7.75–7.81 (m, 3H), 7.89 (d, *J* = 0.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 30.3, 39.8, 45.1, 46.7, 125.4, 125.6, 126.4, 126.7, 127.6, 129.2, 129.4, 131.1, 131.5, 132.6, 207.6. HRMS-ESI: Calcd. For $C_{16}H_{16}NaOS$: 279.0814. Found: 279.0814.

3-Benzylthio-cyclohexan-1-one (3ag). 75.9 mg, 69% yield as yellow liquid. IR: 2941, 2867, 1711, 1454, 1421, 1315, 1282, 1223, 767, 704, 510. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.62–1.74 (m, 2H), 2.06–2.10 (m, 2H), 2.29–2.34 (m, 2H), 2.37 (t, *J* = 4.0 Hz, 1H), 2.66 (dd, *J* = 4.4, 14.4 Hz, 1H), 2.89–2.96 (m, 1H), 3.75 (d, *J* = 2.0 Hz, 1H), 7.22–7.25 (m, 1H), 7.30 (d, *J* = 4.4 Hz, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 24.0, 31.2, 34.8, 40.8, 41.8, 47.7, 127.0, 128.5, 128.6, 137.8, 208.5. HRMS-ESI: Calcd. For $C_{13}H_{16}NaOS$: 243.0814. Found: 243.0806.

3-(Hexylsulfanyl)cyclohexanone (3ah). 65.3 mg, 61% yield as yellow liquid. IR: 2928. 2857, 1714, 1451, 1314, 1221. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 0.84 (t, *J* = 6.8 Hz, 3H), 1.21–1.27 (m, 4H), 1.29–1.37 (m, 2H), 1.49–1.56 (m, 2H), 1.64–1.72 (m, 2H), 2.07–2.14 (m, 2H), 2.27–2.37 (m, 3H), 2.50 (t, *J* = 7.2 Hz, 2H), 2.66 (dd, *J* = 4.4, 14.0 Hz, 1H), 2.99–3.04 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 13.9, 22.4, 24.2, 28.5, 29.6, 30.4, 31.3, 31.6, 40.9, 42.7, 48.1, 208.8. HRMS-ESI: Calcd. For $C_{12}H_{22}NaOS$: 237.1284. Found: 237.1274.

4-(4-Methoxyphenylthio) pentan-2-one (3bi). 110.9 mg, 91% yield as light yellow liquid. IR: 2964, 17144, 1592, 1493, 1246, 1031, 830. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.24 (d, *J* = 6.8 Hz, 3H), 2.12 (s, 3H), 2.51 (dd, *J* = 8.4, 16.8 Hz, 1H), 2.71 (dd, *J* = 5.2, 17.2 Hz, 1H), 3.46–3.55 (m, 1H), 3.80 (m, 3H), 6.85 (d, *J* = 8.4 Hz, 2H), 7.39 (d, *J* = 8.8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 21.0, 30.5, 39.4, 50.4, 55.3, 114.5, 124.0, 136.0, 159.7, 206.7 HRMS-ESI: Calcd. For $C_{12}H_{16}NaO_2S$: 247.0763. Found: 247.0756.

4-(4-Methoxyphenylthio)-4-phenylbutan-2-one (3gi). 111.5 mg, 78% yield as white solid. mp: 76 °C. IR: 3409, 2961, 1711, 1591, 1472, 1287, 1271, 1175, 1027, 829, 699. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 2.07 (s, 3H), 3.03 (dd, *J* = 2.0, 7.6 Hz, 2H), 3.77 (s, 3H), 4.53 (t, *J* = 7.6 Hz, 1H), 6.76 (d, *J* = 8.8 Hz, 2H), 7.17–7.25 (m, 7H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 30.7, 49.1, 55.3, 114.3, 124.0, 127.3, 127.7, 128.4, 136.3, 141.2, 159.9, 205.7. HRMS-ESI: Calcd. For $C_{17}H_{18}NaO_2S$: 309.0920. Found: 309.0920.

Methyl 3-(phenylthio)propanoate (3ha). 102.8 mg, 85% yield as yellow liquid. IR: 2950, 1738, 1438, 1245, 743, 694. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 3.14 (d, *J* = 6.4 Hz, 1H), 3.27 (dd, *J* = 5.6, 14.4 Hz, 1H), 3.39 (dd, *J* = 4.0, 14.0 Hz, 1H), 3.61 (s, 3H), 4.39–4.43 (m, 1H), 7.20–7.24 (m, 1H), 7.28–7.31 (m, 2H), 7.43 (d, *J* = 7.2 Hz, 2H). ^{13}C NMR (100 MHz, CDCl3) δ = 39.1, 52.5, 69.3, 126.9, 129.0, 130.7, 134.8, 173.1. EI-MS (*m*/*z*): 191.27.

3-(Phenylthio)propanenitrile (3ja). 72.6 mg, 89% yield as yellow liquid. IR: 3057, 2932, 2250, 1581, 1478, 1436, 744, 694. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 2.58 (t, *J* = 7.2 Hz, 2H), 3.12 (t, *J* = 7.2 Hz, 2H), 7.28–7.36 (m, 3H), 7.42 (dd, *J* = 0.8, 8.8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 18.1, 30.1, 117.9, 127.6, 129.3, 131.3, 133.1. EI-MS (*m*/*z*): 163.24.

4-Methoxypentan-2-one (4ba). 49.3 mg, 85% yield as yellow liquid. IR: 1637, 1369, 1236, 664. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.15 (d, *J* = 6.4 Hz, 3H), 2.15 (s, 3H), 2.41 (dd, *J* = 5.6 Hz, 16.0 Hz, 1H), 2.70 (dd, *J* = 7.2 Hz, 16 Hz, 1H), 3.29 (s, 3H), 3.73–3.81 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.1, 30.9, 50.5, 56.2, 73.1, 207.4. EI-MS (*m*/*z*): 116.16.

4-Ethoxypentan-2-one (4bb). 49.4 mg, 76% yield as yellow liquid. IR: 3587, 3004, 2967, 2929, 2252, 1712, 1422, 1092, 919, 735, 531. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.12–1.15 (m, 6H), 2.15 (s, 3H), 3.34–3.41 (m, 1H), 3.49–3.57 (m, 1H), 3.29 (s, 3H), 3.82–3.89 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.4, 19.9, 31.0, 50.7, 63.9, 71.5, 207.6 EI-MS (*m*/*z*): 130.18.

4-(2-Chloroethoxy)pentan-2-one (4bc). 50.0 mg, 61% yield as yellow liquid. IR: 2970, 2930, 1715, 1372, 1136, 1111, 666. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.15 (d, *J* = 6.0 Hz, 3H), 2.13 (s, 3H), 2.40 (dd, *J* = 5.2, 16.4 Hz, 1H), 2.71 (dd, *J* = 7.6, 16 Hz, 1H), 3.51–3.61 (m, 3H), 3.68–3.74 (m, 1H), 3.87–3.95 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 19.7, 31.1, 43.1, 50.5, 68.9, 72.3, 207.2. HRMS-ESI: Calcd. For $C_7H_{13}ClNaO_2$: 187.0496. Found: 187.0483.

4-Isopropoxypentan-2-one (4bd). 47.5 mg, 66% yield as yellow liquid. IR: 2929, 1715, 1371, 1773. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.07–1.15 (m, 9H), 2.16 (s, 3H), 2.39 (dd, *J* = 5.6 Hz, 15.6 Hz, 1H), 2.68 (dd, *J* = 7.2 Hz, 15.2 Hz, 1H), 3.60–3.66 (m, 1H), 3.90–3.98 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.9, 22.2, 23.2, 31.3, 51.2, 69.2, 69.4, 207.9. HRMS-ESI: Calcd. For $C_8H_{16}NaO_2$: 167.1043. Found: 167.1045.

4-(Benzyloxy)pentan-2-one (4be). 57.6 mg, 60% yield as yellow liquid. IR: 3451, 2971, 2929, 2872, 1715, 1453, 1371, 1092, 740, 699. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.22 (d, *J* = 6.0 Hz, 3H), 2.13 (s, 3H), 2.46 (dd, *J* = 5.6, 16.0 Hz, 1H), 2.77 (dd, *J* = 7.2, 16.0 Hz, 1H), 3.98–4.06 (m, 1H), 4.43 (d, 1H), 4.55 (d, 1H), 7.24–7.28 (m, 1H), 7.30–7.34 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 19.8, 31.0, 50.8, 65.1, 70.8, 71.6, 127.7, 128.4, 138.5, 207.5. HRMS-ESI: Calcd. For $C_{12}H_{16}NaO_2$: 215.1043. Found: 215.1035.

3-Methoxy-1-phenylbutan-1-one (4ea). 69.4 mg, 78% yield as white solid. mp: 120–121 °C. IR: 1370, 1300, 1217, 1187, 1356, 1093, 998, 755, 693. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 1.26 (d, *J* = 6.4 Hz, 3H), 2.92 (dd, *J* = 6.0, 16.4 Hz, 1H), 3.34 (s, 3H), 3.34(dd, *J* = 6.8, 16.4 Hz, 1H), 3.96–4.04 (m, 1H), 7.46 (t,

J = 7.6 Hz, 2H), 7.56 (t, J = 7.6 Hz, 1H), 7.97 (d, J = 7.2 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ = 19.5, 45.4, 56.4, 73.5, 128.1, 128.5, 133.0, 137.2, 198.6. HRMS-ESI: Calcd. For $C_{11}H_{14}NaO_2$: 201.0886. Found: 201.0888.

3-Methoxy-1-phenylpyrrolidine-2,5-dione (4fa). 66.6 mg, 65% yield as white solid. mp: 80–81 °C. IR: 3287, 3135, 3054, 1730, 1668, 1631, 1560, 1546, 1441, 1320, 1172, 756, 693. ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.95 (s, 3H), 6.22 (d, J = 13.2 Hz, 1H), 6.44 (d, J = 13.6 Hz, 1H), 7.13 (t, J = 7.6 Hz, 1H), 7.34 (t, J = 8.4 Hz, 2H), 7.67 (d, J = 7.6 Hz, 2H), 10.83 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 52.8, 120.1, 124.6, 124.9, 129.0, 137.8, 140.3, 161.4, 167.2. HRMS-ESI: Calcd. For $C_{11}H_{11}NNaO_3$: 228.0631. Found: 228.0637.

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