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Preparation of a novel silica gel-adsorbed Brønsted acid catalyst for the solvent-free esterification of bromoacetic acid with benzyl alcohol

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ABSTRACT

A new bifunctional Brønsted acid catalyst that contains two sulfo groups was prepared. The adsorption of this new bifunctional Brønsted acid catalyst on silica gel made it possible to be reused 10 times without a loss of catalytic activity in the solvent-free esterification of bromoacetic acid with an equiv. of benzyl alcohol without the formation of dibenzyl ether.

1. Introduction

Carboxylic acid esters as important intermediates for the synthesis of dopes, adhesives, plasticizers, flavors, and pharmaceuticals, have attracted much attention. Typically, they are synthesized by Fischer esterification of carboxylic acids and alcohols. In this method, the esterification of carboxylic acids normally requires a large amount of volatile alcohol or a small amount of alcohol in a volatile solvent, such as toluene or cyclohexane [1]. Especially, with benzyl alcohol derivatives, dibenzyl ether derivatives are obtained as the main by-products, much more so than with aliphatic alcohols. Therefore, the use of over 2 equiv. of an acid [2], solvent [3] or microwave [2c] is required to obtain the corresponding benzyl esters in high yields.

On the other hand, immobilizing homogeneous catalysts on solid support has attracted a great deal of interest in industry, since the immobilized catalysts provide great advantages over their unsupported counterparts in terms of separation, reusability, and particularly to give practical conveniences in a continuous system. In these circumstances, we have developed a new type of bifunctional Brønsted acid. The adsorption of this new Brønsted acid onto amorphous silica gel [4] enabled us to *completely suppress the formation of dibenzyl ether*, and α-bromoacetic acid benzyl ester can be obtained in good yields with the use of only *a stoichiometric amount of benzyl alcohol, even without a solvent*. The catalyst could be reused in the esterification 10 times without a loss of catalytic activity.

In this paper, we describe the details of not only the preparation of this new silica gel-adsorbed bifunctional Brønsted acid catalyst which contains two sulfoalkyl groups, but also its use for the esterification of α-bromocarboxylic acids, which are essential compounds for the Reformatsky reaction [5] and important intermediates [6], under environment-friendly conditions.

2. Experimental

2.1. General

^{1}H (400 MHz) or ^{13}C (100 MHz) NMR spectra were measured with a JEOL α-400 FT-NMR spectrometer with tetramethylsilane (Me_4Si) as an internal standard. Melting points were obtained on a Yanagimoto MP-S2 micro melting point apparatus and are uncorrected. IR spectra were measured on a SHIMADZU IR Affinity-1 spectrometer. HRMS were measured on a JEOL JMS-700 mass spectrometer. Enantiomer ratios were measured on a SHIMADZU GC-2010 gas chromatograph using GL Sciences CP-CHIRALCEL-DEX CB (VARIAN, 0.25 mm × 25 m, DF = 0.25) capillary column. The pure products were isolated by column chromatography using silica gel (Wakogel C-200, 100–200 mesh, Wako Pure Chemical Ind., Ltd.). All chemicals were of reagent grade and, if necessary, purified in the usual manner prior to use.

2.1.1. Preparation of 1,3-bis(3-sulfopropyl)-1H-imidazol-3-ium trifluoromethanesulfonate (**2**)

To imidazole (0.683 g, 10.04 mmol) in ethanol (18 mL) was added sodium ethanolate (0.690 g, 10.14 mmol), and the

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mixture was stirred at room temperature for 4 h. Propanesultone (3.175 g, 25.99 mmol) was then added and the mixture was stirred at the same temperature for 2 h. After the solvent was removed under reduced pressure, the obtained compounds were repeatedly washed with ethanol, and subjected to evaporation under vacuum at 60 °C. The obtained solid was washed with methanol and subjected to evaporation under vacuum at room temperature to give sodium 3,3′-(1*H*-imidazole-3-ium-1,3-diyl)dipropane-1-sulfonate (**1**) (2.737 g, 82%).

*2.1.2. Sodium 3,3′-(1H-imidazole-3-ium-1,3-diyl)dipropane-1-sulfonate (**1**)*

Yield 82%; Mp 268.5–269.5 °C; IR (KBr) 1562 (C=C), 1180 (SO), 1045 (SO) cm^{-1}; ^1H NMR (D_2O, 400 MHz) δ 2.33 (quint, J = 7.24 Hz, 4H), 2.94 (t, J = 7.24 Hz, 4H), 4.38 (t, J = 7.24 Hz, 4H), 7.57 (d, J = 1.69 Hz, 2H), 8.88 (s, 1H); ^{13}C NMR (D_2O, 100 MHz) δ 37.6 (s), 59.8 (s), 60.4 (s), 135.1 (s), 148.3 (s); HRMS (FAB+) 335.0345 ($C_9H_{16}N_2NaO_6S_2$ requires 335.0347 (M−I)).

To sodium 3,3′-(1*H*-imidazole-3-ium-1,3-diyl)dipropane-1-sulfonate (**1**) (1.009 g, 3.018 mmol) in water (1 mL) was added trifluoromethanesulfonic acid (1.154 g, 7.689 mmol) at 0 °C, and the mixture was stirred at room temperature for 12 h and concentrated under vacuum. Precipitation of the obtained compounds with a mixture of methanol and Et_2O, filtration, and drying under vacuum at 80 °C gave 1,3-bis(3-sulfopropyl)-1*H*-imidazol-3-ium trifluoromethanesulfonate (**2**) (0.999 g, 72%).

*2.1.3. 1,3-Bis(3-sulfopropyl)-1H-imidazol-3-ium trifluoromethanesulfonate (**2**) [7]*

Yield 72%; Mp 284.0–284.3 °C; IR (KBr) 3151 (SO_3H), 3098 (SO_3H), 1562 (C=C), 1273 (SO), 1200 (SO), 1049 (SO) cm^{-1}; ^1H NMR (DMSO, 400 MHz) δ 2.08 (quint, J = 7.06 Hz, 4H), 2.40 (t, J = 7.06 Hz, 4H), 4.28 (t, J = 7.06 Hz, 4H), 7.78 (d, J = 1.45, 2H), 9.15 (s, 1H); ^{13}C NMR (D_2O, 100 MHz) δ 38.3 (s), 60.5 (s), 61.1 (s), 132.2 (q, J = 269.3 Hz), 135.8 (s), 149.0 (s); HRMS (FAB+) 313.0532 ($C_9H_{17}N_2O_9S_2$ requires 313.0528 (M−CF_3SO_3)).

*2.2. Adsorption of 1,3-bis(3-sulfopropyl)-1H-imidazol-3-ium trifluoromethanesulfonate **2** onto silica gel*

To 1,3-bis(3-sulfopropyl)-1*H*-imidazol-3-ium trifluoromethanesulfonate (**2**) (0.069 g, 0.150 mmol) in methanol (20 mL) was added silica gel (Wakogel C-200, 100–200 mesh, 75–150 μm) (30 mg), and the mixture was stirred at room temperature for 30 min. The obtained solid was dried under vacuum at room temperature for 5 h.

2.3. Typical procedure for the silica gel-adsorbed acid 2-catalyzed esterification of carboxylic acids with alcohols

A mixture of the silica gel-adsorbed acid **2** (0.033 g), 2-bromoacetic acid (**3a**) (0.137 g, 0.988 mmol), and phenylmethanol (**4a**) (0.108 g, 1.000 mmol) under argon was stirred at 80 °C for 24 h. After the reaction mixture was cooled to room temperature, the addition of diethyl ether (5 mL × 5) and decantation resulted in complete separation of the organic layer and the silica gel-adsorbed acid **2**. After the solvent was removed under reduced pressure, the product was purified by column chromatography on silica gel with hexane/EtOAc (v/v = 10/1) to give benzyl 2-bromoacetate (**5aa**) (0.189 g, 83%). The silica gel-adsorbed acid **2** was dried under vacuum at room temperature, and recovered as a white powder (0.033 g, 99%).

*2.3.1. Benzyl 2-bromoacetate (**5aa**) [8]*

Yield 82%; *Rf* 0.52 (hexane:EtOAc = 10:1); IR (KBr) 1738 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 3.85 (s, 2H), 5.19 (s, 2H), 7.24–7.37 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.7 (s), 67.8 (s), 128.3 (s), 128.46 (s), 128.52 (s), 134.9 (s), 166.6 (s); HRMS (EI) 227.9786 ($C_9H_9O_2{}^{79}Br$ requires 227.9787 (M^+)).

*2.3.2. Oxybis(methylene)dibenzene (**6aa**) [9]*

Rf 0.38 (hexane:Et_2O = 10:1); ^1H NMR ($CDCl_3$, 400 MHz) δ 4.54 (s, 4H), 7.25–7.37 (m, 10H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 71.7 (s), 127.2 (s), 127.4 (s), 128.0 (s), 137.9 (s); HRMS (EI) 198.1044 ($C_{14}H_{14}O_2$ requires 198.1045 (M^+)).

*2.3.3. Ethane-1,2-diyl bis(2-bromoacetate) (**5ab**) [6]*

Yield 68%; *Rf* 0.75 (hexane:EtOAc = 1:1); IR (KBr) 1738 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 3.81 (s, 4H), 4.35 (s, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.4 (s), 63.3 (s), 167.0 (s); HRMS (CI) 302.8868 ($C_6H_9O_4{}^{79}Br$ requires 302.8868 (M+H)).

*2.3.4. (Z)-But-2-ene-1,4-diyl bis(2-bromoacetate) (**5ac**) [10]*

Yield 76%; *Rf* 0.80 (hexane:EtOAc = 3:1); IR (KBr) 1738 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 3.80 (s, 4H), 4.74 (d, J = 4.10 Hz, 4H), 5.75 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.5 (s), 61.3 (s), 127.8 (s), 166.8 (s); HRMS (CI) 328.9032 ($C_8H_{11}O_4{}^{79}Br_2$ requires 328.9024 (M+H)).

*2.3.5. 1-Phenylethyl 2-bromoacetate (**5ad**) [11]*

Yield 37%; *Rf* 0.46 (hexane:CH_2Cl_2 = 2:1); IR (KBr) 1732 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.50 (d, J = 6.64 Hz, 3H), 3.75 (s, 2H), 5.85 (q, J = 6.64 Hz, 1H), 7.20–7.33 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 21.9 (s), 26.2 (s), 74.4 (s), 126.1 (s), 128.2 (s), 128.5 (s), 140.6 (s), 166.4 (s); HRMS (EI) 241.9943 ($C_{10}H_{11}OBr$ requires 241.9942 (M^+)).

*2.3.6. 1,1′-Oxybis(ethane-1,1-diyl)dibenzene (**6bb**) [12]*

Yield 38%; *Rf* 0.60 (hexane:CH_2Cl_2 = 1:1); ^1H NMR ($CDCl_3$, 400 MHz) δ 1.31 (d, J = 6.52 Hz, 6H), 1.39 (d, J = 6.52 Hz, 6H), 4.18 (q, J = 6.52 Hz, 2H), 4.46 (q, J = 6.52 Hz, 2H), 7.13–7.31 (m, 20H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 23.9 (s), 25.6 (s), 75.3 (s), 75.5 (s), 127.1 (s), 127.2 (s), 128.0 (s), 128.3 (s), 129.1 (s), 129.4 (s),145.0 (s), 145.1 (s); MS (EI) *m*/*z* 226 (M, 32.5%).

*2.3.7. Benzyl 2-bromopropanoate (**5ba**) [13]*

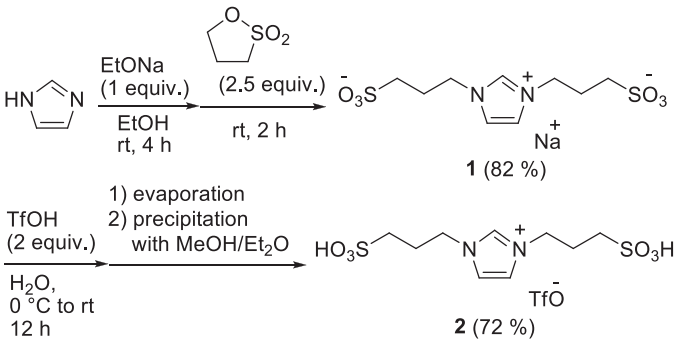
Yield 74%; *Rf* 0.60 (hexane:Et_2O = 2:1); IR (KBr) 1740 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.83 (d, J = 7.00 Hz, 3H), 4.41 (q, J = 7.00 Hz, 1H), 5.20 (s, 2H), 7.28–7.44 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 22.3 (s), 40.7 (s), 68.2 (s), 128.8 (s), 129.1 (s), 129.3 (s), 135.8 (s), 170.8 (s); HRMS (EI) 241.9949 ($C_{10}H_{11}O_2{}^{79}Br$ requires 241.9942 (M^+)). Enantiomer separation of (*R*)-**5ba**: CHIRAL GC (GL Sciences, CP-CHIRALCEL-DEX CB column, temperature: 80–180 °C (4 °C/min), muscle: 74.4 kPa, total flow: 26.0 mL/min, column flow: 0.89 mL/min, liner velocity: 25.7 cm/s, purge flow: 3.0 mL/min, sprit fraction: 24.8), t_1 (*S*) = 22.6 min, t_2 (*R*) = 22.7 min.

*2.3.8. Benzyl 2-(benzyloxycarbonylamino)acetate (**8**) [14]*

Yield 88%; Mp 69.0–69.5 °C; *Rf* 0.17 (CH_2Cl_2); IR (KBr) 1717 (C=O), 1735 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 3.99 (d, J = 5.31 Hz, 2H), 5.11 (s, 2H), 5.16 (s, 2H), 5.35 (br, 1H), 7.33–7.37 (m, 10H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 42.7 (s), 67.0 (s), 67.1 (s), 128.0 (s), 128.1 (s), 128.3 (s), 128.5 (s), 128.6 (s), 135.1 (s), 136.1 (s), 156.2 (s), 169.9 (s); HRMS (EI) 299.1156 ($C_{17}H_{17}NO_4$ requires 299.1158 (M^+)).

*2.3.9. Benzyl 2-methoxyacetate (**10**)*

Yield 65%; *Rf* 0.45 (hexane:EtOAc = 10:1); IR (KBr) 1755 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 3.42 (s, 3H), 4.04 (s, 2H),



Scheme 1. Preparation of a novel Brønsted acid catalyst **2**.

5.18 (s, 2H), 7.29–7.48 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 59.4 (s), 66.6 (s), 69.9 (s), 128.5 (s, 2C), 128.7 (s), 135.6 (s), 170.2 (s)

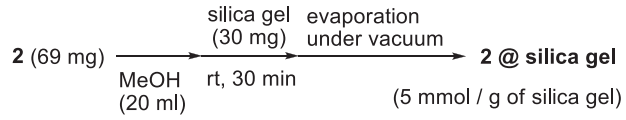
3. Results and discussion

3.1. Preparation of a novel Brønsted acid catalyst *2*

As shown in Scheme 1, a novel Brønsted acid catalyst **2** was prepared. Imidazole was successively treated with an equiv. of sodium ethoxide in ethanol at room temperature for 2 h, and with 2.5 equiv. of propanesultone at room temperature for 2 h, to give sodium 3,3′-(1*H*-imidazole-3-ium-1,3-diyl)dipropane-1-sulfonate (**1**) in 82% yield as a white powder. The obtained sodium salt **1** was reacted with 2 equiv. of trifluoromethanesulfonic acid in water at room temperature for 12 h, concentrated under vacuum, and precipitated with methanol and diethyl ether to produce 1,3-bis(3-sulfopropyl)-1*H*-imidazol-3-ium trifluoromethanesulfonate (**2**) in 72% yield as a white solid.

3.2. Optimization of the reaction conditions for a novel Brønsted acid 2-catalyzed esterification of bromoacetic acid (*3a*)

Table 1 summarizes the results of screening of the amount of the new catalyst **2**. The reaction of bromoacetic acid (**3a**) with an equiv. of benzyl alcohol (**4a**) in the presence of 5 mol% of solid catalyst **2** without any solvents at 80 °C for 6 h gave ester, benzyl bromoacetate (**5aa**) in 82% yield, and catalyst **2** was recovered in 90% yield, together with a trace amount of ether, oxybis(methylene)dibenzene (**6aa**) (entry 1). The ratio of the ester **5aa** to the ether **6aa** was determined to be 96:4 by gas chromatography. The use of 1 mol% of catalyst **2** resulted in a decrease in the yield of ester **5aa** from 82% to 74% (entry 2). An increase in the amount of catalyst **2** to 10 mol% gave the same yield of the product **5aa**, along with an increase in the formation of ether **6aa** (entry 3).



Scheme 2. Preparation of acid **2**-absorbed on silica gel.

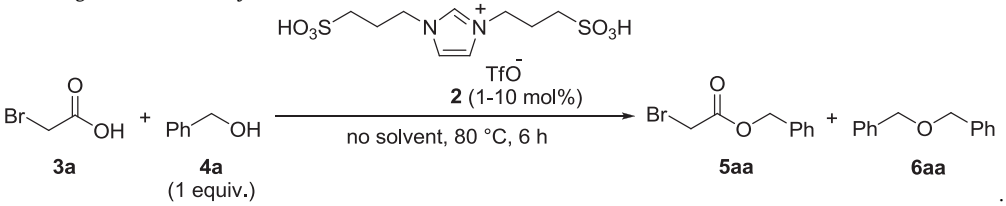
For the quantitative recovery and reuse of catalyst **2**, the acid catalyst **2** was adsorbed onto silica gel (Wakogel C-200, 100–200 mesh, particle size 75–150 μm) (Scheme 2). After silica gel was added to a methanol solution of the catalyst **2**, the resultant mixture was stirred at room temperature for 30 min and evaporated under vacuum to give acid 2-adsorbed on silica gel.

Table 2 summarizes the results of esterification with three kinds of supported catalysts, including acid **2** adsorbed on silica gel. The esterification of bromoacetic acid (**3a**) with an equiv. of benzyl alcohol (**4a**) in the presence of silica gel-adsorbed catalyst **2** (5 mol%) was carried out without any solvents at 80 °C for 6 h to give benzyl bromoacetate (**5aa**) in 72% yield (entry 1). Compared to the results using unsupported catalyst **2** in Table 1, surprisingly, the formation of ether **6aa** was not observed in the reaction mixture. An increase in the reaction time from 6 h to 24 h resulted in a sufficient yield (83%) of ester **5aa** (entry 2). Significantly, the formation of ether **6aa** was completely prevented, even with a prolonged reaction time. Furthermore, the silica gel-adsorbed acid **2** was recovered in quantitative yield in both cases. Esterification with only silica gel in the absence of catalyst **2** gave the product **5aa** in only 42% yield. Prolonged reaction time (24 and 36 h) resulted in increasing the yields (60 and 76%) of the ester **5aa** without the formation of the ether **6aa** (entries 4 and 5). In place of silica gel, ionic liquids, *N*-ethyl-*N*-methyl imidazolium trifluoromethanesulfonate (EMIOTf) and *N*-butyl-*N*-methylimidazolium tetrafluoroborate ($BMIBF_4$), were also used as supports. However, the acid catalyst **2** with these ionic liquids was not effective for the esterification of bromoacetic acid (**3a**) with benzyl alcohol (**4a**), and ester **5aa** was obtained in lower yields (49 and 63%), together with a small amount of the ether **6aa** (entries 6 and 7).

3.3. Silica gel-adsorbed Brønsted acid *2*-catalyzed esterification

As shown in Scheme 3, three other kinds of alcohols, 1,2-ethandiol (**4b**), (*Z*)-2-butene-1,4-diol (**4c**), and 1-phenylethanol (**4d**), were used for the esterification of bromoacetic acid (**3a**) under the optimized reaction conditions. Both 1,2-ethandiol (**4b**) and (*Z*)-2-buten-1,4-diol (**4c**) also participated in the esterification of

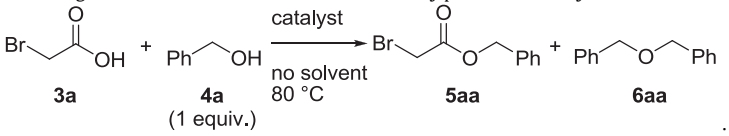
Table 1
Screening of amount of catalyst **2**.



Entry[a]	Cat	Yield of **5aa** (%)[b]	Recovery of cat. (%)	GC area ratio **5aa**:**6aa**
1	**2** (5 mol%)	82	90	96:4
2	**2** (1 mol%)	72	92	95:5
3	**2** (10 mol%)	82	Quant	90:10
4	None	48	–	>99:<1

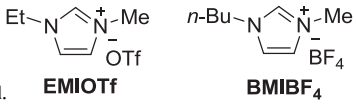
[a] All the reaction was carried out with carboxylic acid **3** (1 mmol) and alcohol **4** (1 mmol).
[b] Yields of isolated product.

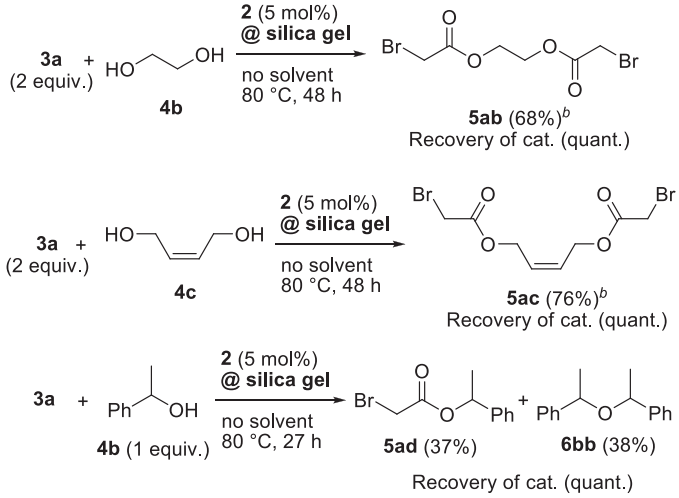
Table 2
Screening of the reaction conditions and the recovery process for catalyst **2**.



Entry[a]	Cat	Time (h)	Yield of **5aa** (%)[b]	Recovery of cat. (%)	GC area ratio **5aa**:**6aa**
1	**2** (5 mol%)@silica gel	6	72	Quant	>99:<1
2	**2** (5 mol%)@silica gel	24	83	Quant	>99:<1
3	Only silica gel	6	42	–	>99:<1
4	Only silica gel	24	60	–	>99:<1
5	Only silica gel	36	76	–	>99:<1
6[c]	**2** (5 mol%)@EMIOTf	6	63	Quant	90:10
7[c]	**2** (5 mol%)@BMIBF$_4$	6	49	Quant	98:2

[a] All the reaction was carried out with carboxylic acid **3** (1 mmol) and alcohol **4** (1 mmol).
[b] Yields of isolated product.
[c] Ionic liquids (0.5 ml) was used.

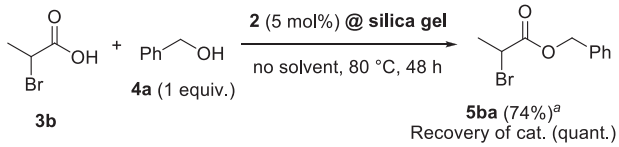




Scheme 3. Silica gel-adsorbed acid **2**-catalyzed esterification of α-bromoacetic acid (**3a**) with various alcohols **4**.

bromoacetic acid (**3a**) for 48 h to give the corresponding diesters, ethane-1,2-diyl bis(2-bromoacetate) (**5ab**) and (*Z*)-but-2-ene-1,4-diyl bis(2-bromoacetate) (**5ac**), in yields of 68–76%, together with quantitative recovery of the catalyst. Isomerization of the alkene moiety of **4c** did not occur, based on the *trans*-coupling constants of the vinyl protons by ^{1}H NMR. Unfortunately, the esterification of bromoacetic acid (**3a**) with phenylethanol (**4d**) under the same conditions gave the product **5ad** in only 37% yield, together with 1,1′-oxybis(ethane-1,1-diyl)dibenzene (**6bb**) in 38% yield.

As another bromocarboxylic acid, the esterification of 2-bromopropanoic acid (**3b**) was examined (Scheme 4). The reaction of racemic 2-bromopropanoic acid (**3b**) with benzyl alcohol (**4a**) in the presence of a catalytic amount (5 mol%) of silica gel-adsorbed **2** at 80 °C for 48 h produced the corresponding ester **5ba** in 74% yield, together with quantitative recovery of the catalyst (Scheme 4).



Scheme 4. Silica gel-adsorbed acid **2**-catalyzed esterification of α-bromopropanoic acid (**3b**) with benzyl alcohol (**4a**).

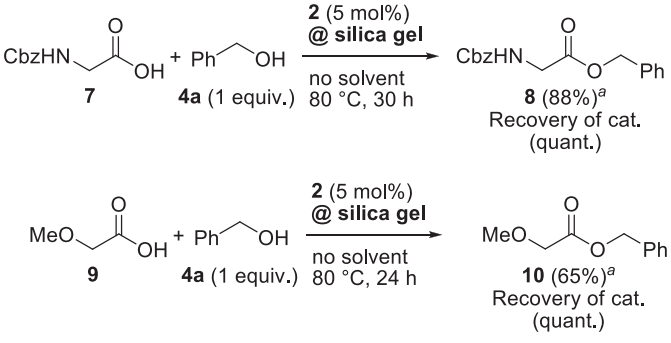
Next, the epimerization of 2-bromopropanoic acid (**3b**) was examined under silica gel-adsorbed acid **2**-catalyzed esterification with benzyl alcohol (**4a**).

As shown in Table 3, in the case of enantiopure (*R*)-2-bromopropanoic acid ((*R*)-**3b**), esterification with benzyl alcohol (**4a**) under the same conditions (no solvent, 80 °C, 48 h) gave benzyl (*R*)-2-bromopropanoate ((*R*)-**5ba**) in 74% yield. However, the ee of the ester (*R*)-**5ba** decreased from >99% ee to 88% ee. A decrease in the reaction temperature to room temperature for a prolonged reaction time gave the ester (*R*)-**5ba** in moderate yield with a sufficient ee (96% ee).

As shown in Scheme 5, in place of α-bromocarboxylic acid, *N*-(benzyloxycarbonylamino)glycine (**7**) and 2-methoxyacetic acid (**9**) as another functionalized carboxylic acids were used in silica gel-adsorbed acid **2**-catalyzed esterification with benzyl alcohol (**4a**) under the same conditions. Consequently, benzyl 2-(benzyloxycarbonylamino)acetate (**8**) and benzyl 2-methoxyacetate (**10**) were obtained in 88% and 65% yields, respectively, together with the quantitative recovery of **2**.

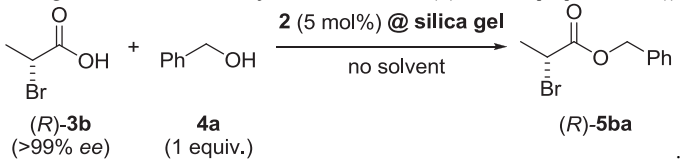
3.4. Reuse of silica gel-adsorbed acid 2

Finally, reuse of the silica gel-adsorbed Brønsted acid **2** in the esterification of bromoacetic acid (**3a**) with benzyl alcohol (**4a**) was examined (Table 4).



Scheme 5. Silica gel-adsorbed acid **2**-catalyzed esterification of *N*-(benzyloxycarbonylamino)glycine (**7**) and 2-methoxyacetic acid (**9**) with benzyl alcohol (**4a**).

Table 3
Silica gel-adsorbed acid **2**-catalyzed esterification of (*R*)-α-bromopropanoic acid ((*R*)-**3b**) with benzyl alcohol (**4a**).

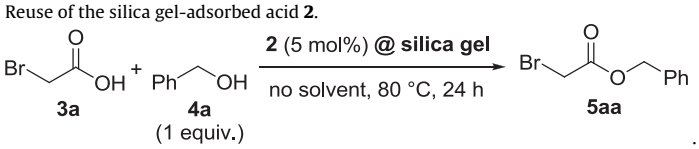


(*R*)-**3b** (>99% *ee*) **4a** (1 equiv.) (*R*)-**5ba**

Entry[a]	Conditions	Yield of (*R*)-**5ba** (%)[b]	ee of (*R*)-**5ba** (%)[c]	Recovery of cat. (%)
1	80 °C, 48 h	74	88	Quant.
2	rt, 84 h	47	96	Quant.

[a] All the reaction was carried out with carboxylic acid **3** (1 mmol) and alcohol **4** (1 mmol).
[b] Yields of isolated product.
[c] Measured by chiral GC with a CP-CHIRASIL-DEX CB

Table 4
Reuse of the silica gel-adsorbed acid **2**.



3a **4a** (1 equiv.) **5aa**

Run[a]	1	2	3	4	5	6	7	8	9	10	11
Yield of **5aa** (%)[b]	83	80	80	80	82	83	83	80	83	80	81

[a] All the reaction was carried out with carboxylic acid **3** (1 mmol) and alcohol **4** (1 mmol).
[b] Yields of isolated product.

The silica gel-adsorbed acid **2** (5 mol%)-catalyzed esterification of bromoacetic acid (**3a**) with an equiv. of benzyl alcohol (**4a**) at 80 °C for 24 h was carried out without the use of any solvents. After the reaction mixture was cooled to room temperature, the addition of diethyl ether and decantation resulted in complete separation of the organic layer and catalyst. Evaporation of the organic layer under vacuum and column chromatography by silica gel with hexane–dichloromethane (v/v = 1/4) as the eluent gave the ester **5aa** in 83% yield in the first run. The recovered catalyst was dried under vacuum at room temperature for 1 h, and used for the next run after the addition of the acid **3a** and the alcohol **4a**. As summarized in Table 4, the silica gel-adsorbed acid **2** could be reused 10 times without a loss of catalytic activity to give the corresponding ester **5aa** with similar yields (80–83% yields) in every run.

4. Conclusion

In summary, we have developed a new type of bifunctional Brønsted acid. Adsorption of this new Brønsted acid onto amorphous silica gel enabled us to suppress the formation of dibenzyl ether and gave the esters in high yield with *the use of a stoichiometric amount of benzyl alcohol even without a solvent*. The esterification of chiral acid at room temperature gave the corresponding benzyl ester *with a retention of enantioselectivity*. Finally, the catalyst could be *reused 10 times without a loss of catalytic activity* in the esterification.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.molcata.2012.11.004.

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