Propargylation of Aldehydes Using Potassium Allenyltrifluoroborate

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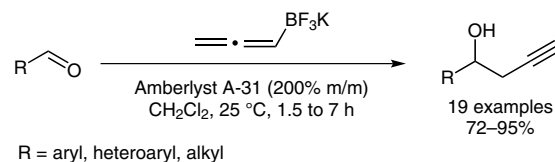
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R = aryl, heteroaryl, alkyl

Abstract The commercially available resin Amberlyst A-31 was efficiently used to promote the propargylation of aldehydes using potassium allenyltrifluoroborate. The method is simple and fast, and the products were obtained in short reaction times in high yields and purity at room temperature in a regio- and chemoselective manner.

Key words propargylation, potassium organotrifluoroborates, Amberlyst A-31

The propargylation of carbonyl compounds is an important reaction in organic synthesis.[1] Usually, it involves the use of an appropriate propargyl or allenyl organometallic compound or the direct propargylic substitution of propargyl alcohols or their derivatives with nucleophiles.[2]

The reactions involving the direct addition of an allenyl or propargyl organometallic reagent to a carbonyl compound usually proceed through an S_E2-type mechanism.[3] On the other hand, some reactions are based on the in situ formation of the propargyl or allenyl organometallic species, which can interconvert, followed by the subsequent addition to the appropriate carbonyl compound. In this case, the regioselectivity of the reaction is usually governed by the rate of isomerization, stability, and the nucleophilicity of propargyl or allenyl species involved in the reaction.[3]

The development of propargyl nucleophiles that are able to form new C–C bonds under mild conditions in a very regioselective manner is a subject of great interest and a variety of propargyl or allenyl organometallics derived from zinc,[4] titanium,[5] aluminum,[6] lithium,[7] and magnesium,[8] were developed for this purpose. In addition, different silicon,[9] tin,[10] and boron derivatives[11] were successfully employed in this reaction.

The use of less reactive compounds such as allenylsilanes and allenylstannanes requires Lewis acid as additives. Although the utility of allenylstannanes is further indicated by the commercial availability of some of them, the toxicity of these compounds makes them inappropriate for use in pharmaceutical synthesis.[12] Moreover, the removal of tributyltin residues from reaction mixtures is also a major issue.

The use of organoboranes is limited to their compatibility to functional groups and sensitivity to air and moisture. Conversely, boronic acids are known for their difficulty to purify and the uncertainty in the stoichiometry.[13] This problem can be circumvented by converting these into their corresponding boronate esters,[14] which is a more stable alternative, but lacks atom economy. In addition, this class of compounds has low hydrolytic stability, which is dependent on the kind of alcohol used for its preparation.[15]

The use of potassium organotrifluoroborates seems to be the best option due to their stability, which also allows the complete characterization of these salts by heteronuclei NMR analysis,[16] and exact mass measurements.[17] Additionally, a marked increase in atom economy,[18] stability, and the apparent low toxicity[19] of organotrifluoroborate salts make them more appealing.

Recently, we have described the use of the commercially available resin Amberlyst-15 as an efficient promoter for the allylation of aldehydes using potassium allyltrifluoroborate.[20] Herein, we describe the synthesis of homopropargylic alcohols from the reaction of potassium allenyltrifluoroborate and aldehydes containing different functional groups. To our knowledge, this is the first method for propargylation of aldehydes based on the use of potassium organotrifluoroborates.

In the course of developing an optimal set of reaction conditions, the amount of resin and the type of solvent were first examined to promote the reaction. Thus, 4-nitrobenzaldehyde (**1a**; 1 mmol) and potassium allenyltrifluo-

roborate (**2**; 1.7 mmol) were treated at room temperature using Amberlyst A-15 and the progress of the reaction was monitored by TLC. The results are presented in Table 1.

Table 1 Effect of Amberlyst A-15 on the Allylation of 4-Nitrobenzaldehyde by Potassium Allenyltrifluoroborate[a]
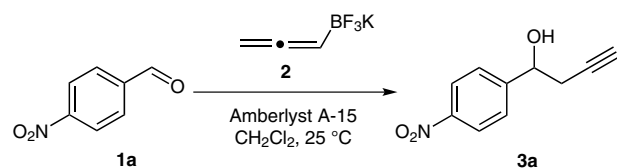
Entry	Amberlyst A-15 (% m/m)	Solvent	Time (h)	3a (%)[b]
1	100	EtOH	16.5	33
2	100	H₂O	16.5	6
3	100	CH₂Cl₂	16.5	21
4	200	EtOH	5.0	20
5	200	H₂O	5.0	5
6	200	CH₂Cl₂	3.0	90

[a] Reaction conditions: reactions were performed with **1a** (1 mmol) and **2** (1.7 mmol) in solvent (5 mL) at 25 °C for the time indicated.
[b] The conversion was determined by GC with respect to **1a**.

When a 100% m/m amount of Amberlyst A-15 was used, the corresponding low conversions were observed. When water was used as the reaction solvent, the corresponding product **3a** was obtained in low yield after 16.5 hours (Table 1, entry 2). This result can probably be explained by the low solubility of aldehyde **1a** in water. A similar behavior was observed when dichloromethane was used as the reaction solvent (Table 1, entry 3) where the formation of **3a** was observed to only 21%, probably due to the low solubility of potassium allenyltrifluoroborate **2** in dichloromethane. When ethanol was used as the reaction solvent, lower conversion to **3a** was observed together with the acid-catalyzed ketalization product of the aldehyde (Table 1, entry 1).

A dramatic effect was observed when the amount of the promoter was increased to 200% m/m. In this case, a higher conversion of the aldehyde **1a** into the product **3a** was observed when dichloromethane was used as the reaction solvent (Table 1, entry 6).

Next, we examined a variety of commercially available resins to promote the propargylation of 4-nitrobenzaldehyde (**1a**; 1.0 equiv) by potassium allenyltrifluoroborate (**2**; 1.7 equiv) using dichloromethane as the reaction solvent at room temperature (Table 2).

In the absence of a promoter, the corresponding product **3a** was obtained in low yield after 24 hours (Table 2, entry 1). When acidic resins were used, higher conversions of **1a** into the corresponding product **3a** were observed (Table 2, entries 2, 3, 6–10). The best result was obtained when Amberlyst A-31 was used as the promoter (Table 2, entry 6). In-

Table 2 Comparative Efficiency of Various Resins in the Addition of Potassium Allenyltrifluoroborate to 4-Nitrobenzaldehyde[a]
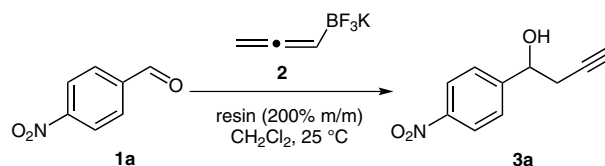
| Entry	Resin (200% m/m)	Time (h)	3a (%)[b]
1	none	24.0	19
2	Amberlyst A-15	3.0	90
3	Amberlyst A-16	3.0	99
4	Amberlyst A-21	3.0	–
5	Amberlyst A-26	3.0	–
6	Amberlyst A-31	1.5	99
7	Amberlyst A-35	3.0	99
8	Amberlyst A-36	3.0	76
9	Amberlyst A-40	3.0	93
10	Amberlyst A-41	3.0	85

[a] Reaction conditions: reactions were performed with **1a** (1 mmol) and **2** (1.7 mmol) using the appropriate resin in CH₂Cl₂ (5 mL) at 25 °C for the time indicated.
[b] The conversion was determined by GC with respect to **1a**.

terestingly, when the basic resins Amberlyst A-21 and A-26, were used, the corresponding propargylation product **3a** was not observed in either case (Table 2, entries 4 and 5).

The effect of the amount of resin to promote the reaction was also investigated. The load of Amberlyst A-31 was varied from 50 to 400% m/m (Table 3). It was observed that the reaction yield changed appreciably when the amount of the resin varied from 50 to 200% m/m (Table 3, entries 1–3) after 1.5 hours. However, higher amounts did not change the reaction yield considerably (Table 3, entry 4).

Table 3 Allylation of 4-Nitrobenzaldehyde by Potassium Allenyltrifluoroborate Using Different Amounts of Amberlyst A-31[a]
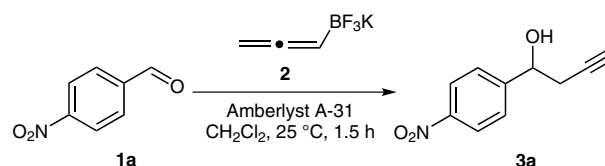
Entry	Amberlyst A-31 (% m/m)	3a (%)[b]
1	50	0
2	100	7
3	200	99
4	400	91

[a] Reaction conditions: reactions were performed with **1a** (1 mmol) and **2** (1.7 mmol) using Amberlyst A-31 (200% m/m) in CH₂Cl₂ (5 mL) at 25 °C for 1.5 h.
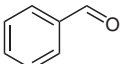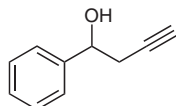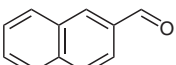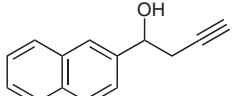[b] The conversion was determined by GC with respect to **1a**.
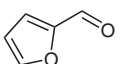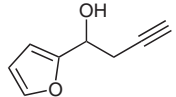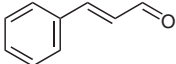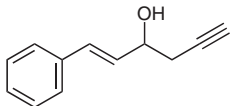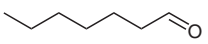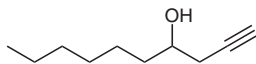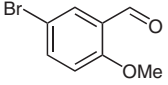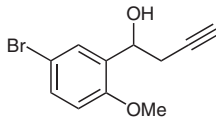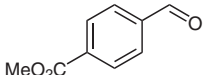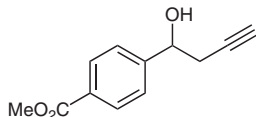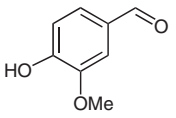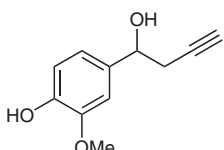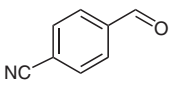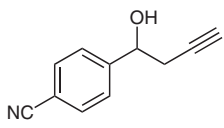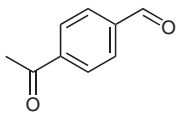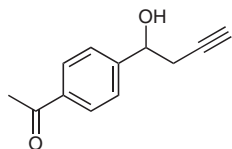
The optimized reaction conditions, namely: potassium allenyltrifluoroborate **2** (1.7 mmol), aldehyde (1 mmol) and Amberlyst A-31 (200% m/m) in dichloromethane (5 mL), were then applied in the propargylation reaction of alde-

hydes containing a wide range of functional groups. Thus, aliphatic, aromatic, α,β-unsaturated, and heterocyclic aldehydes were efficiently propargylated in high yields (Table 4).

Table 4 Propargylation of Aldehydes with Potassium Allenyltrifluoroborate[a]

Entry	Aldehyde **1**		Product **3**		Time (h)	Yield (%)[b]
1	**1a**		**3a**		1.5	95
2	**1b**		**3b**		3.0	87
3	**1c**		**3c**		2.5	95
4	**1d**		**3d**		5.0	78
5	**1e**		**3e**		5.0	87
6	**1f**		**3f**		2.5	88
7	**1g**		**3g**		3.0	79
8	**1h**		**3h**		2.0	93
9	**1i**		**3i**		2.5	94

Table 4 (continued)

Entry	Aldehyde **1**	Product **3**	Time (h)	Yield (%)[b]
10	**1j**	**3j**	7.0	72
11	**1k**	**3k**	2.5	95
12	**1l**	**3l**	3.0	73
13	**1m**	**3m**	7.0	90
14	**1n**	**3n**	3.0	80
15	**1o**	**3o**	2.5	82
16	**1p**	**3p**	2.0	85
17	**1q**	**3q**	5.0	70
18	**1r**	**3r**	2.0	92
19	**1s**	**3s**	2.0	94

[a] Reaction conditions: reactions were performed with the appropriate aldehyde **1** (1 mmol) and **2** (1.7 mmol) using Amberlyst A-31 (200% m/m) in CH_2Cl_2 (5 mL) at 25 °C for the time indicated.
[b] Isolated yields.

The effect of substituents on the aromatic ring has little influence in the yield. The propargylation of aldehydes containing electron-withdrawing groups gave the corresponding products in high yields (Table 4, entries 1–6). Electron-rich aldehydes, β-naphthaldehyde, benzaldehyde, and a heterocyclic aldehyde led to the homopropargylic alcohols also in high yields (Table 4, entries 7–12).

The reaction is regioselective while only the 1,2-addition product was observed when an α,β-unsaturated aldehyde was used (Table 4, entry 13). For aliphatic aldehydes, the propargylation method also exhibited high efficiency (Table 4, entry 14). The chemoselectivity of the method was evaluated using different functionalized aldehydes. In all cases, the corresponding products were selectively obtained in good yields (Table 4, entries 15–19).

The recoverability and recyclability of the resin were also investigated. Thus, after each run, the catalyst was separated from the reaction mixture, washed with dichloromethane, and reused. It was found that the resin could be recovered and reused in further propargylation reactions, however, the conversion of 4-nitrobenzaldehyde **1a** into the propargylation product **3a** significantly decreased after the third run (Table 5).

Table 5   Amberlyst A-31 (200% m/m) Recycling after Successive Runs[a]
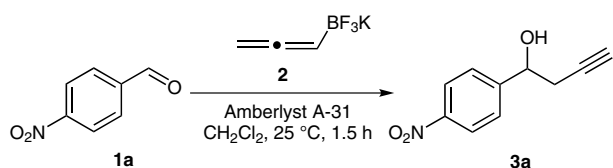
Run	Time (h)	3a (%)[b]
1	1.5	99
2	3.0	87
3	3.0	70
4	3.0	9
5	3.0	0

[a] Reaction conditions: reactions were performed with **1a** (1 mmol) and **2** (1.7 mmol) using Amberlyst A-31 (200% m/m) in CH_2Cl_2 (5 mL) at 25 °C for the time indicated.
[b] The conversion was determined by GC with respect to **1a**.

In summary, we have shown that the resin Amberlyst A-31 is an efficient promoter for the propargylation of aldehydes using potassium allenyltrifluoroborate. The method features the use of a commercially available resin, and the products were obtained in short reaction times in high yield and purity at room temperature. The method is simple, fast and efficient and could be applied for the synthesis of more complex compounds.

^{1}H NMR and ^{13}C NMR data were recorded in $CDCl_3$ or DMSO-d_6. The chemical shifts are reported as delta (δ) units in parts per million (ppm) relative to the solvent residual peak as the internal reference. ^{11}B (128 MHz) NMR spectra were recorded in D_2O and ^{19}F (376 MHz) in DMSO-d_6. Spectra were calibrated using $Et_2O\cdot BF_3$ (0.0 ppm) as external reference in the case of ^{11}B NMR and chemical shifts were referenced to external CF_3CO_2H (0.0 ppm) in the case of ^{19}F NMR spectra. Coupling constants (J) for all spectra are reported in hertz (Hz). Reactions were monitored by TLC on 0.25 mm E. Merck silica gel 60 plates (F254) using UV light, vanillin, and *p*-anisaldehyde as visualizing agents.

The preparation of potassium allenyltrifluoroborate (**2**) is described in the Supporting Information.

Propargylation of Aldehydes 1 with Potassium Allenyltrifluoroborate (2) Using Amberlyst A-31; General Procedure

To a solution of the appropriate aldehyde **1** (1.0 mmol) in CH_2Cl_2 (5 mL) was added Amberlyst A-31 (200% m/m) followed by potassium allenyltrifluoroborate (**2**; 248 mg, 1.70 mmol). The mixture was stirred for the time indicated in Table 4 and then diluted with CH_2Cl_2 (5 mL) and washed with H_2O (2 × 15 mL). The aqueous layer was extracted with CH_2Cl_2 (2 × 5 mL). The combined organic layers were dried (MgSO$_4$), filtered, and the solvent was removed under reduced pressure to yield **3** without the need for further purification.

1-(4-Nitrophenyl)but-3-yn-1-ol (3a)

Yield: 183 mg (95%); white solid; mp 116–118 °C.

^{1}H NMR (400 Hz, $CDCl_3$): δ = 8.23 (d, J = 8.4 Hz, 2 H$_{arom}$), 7.59 (d, J = 8.4 Hz, 2 H$_{arom}$), 5.00 (dd, J = 7.2, 6.0 Hz, 1 H, OC*H*CH$_2$), 2.72 (ddd, J = 16.8, 6.0, 2.8 Hz, 1 H, OCHC*H*$_2$), 2.63 (ddd, J = 16.8, 7.2, 2.8 Hz, 1 H, OCHC*H*$_2$), 2.11 (t, J = 2.8 Hz, 1 H, C≡CH), 1.88 (br s, 1 H, OH).

^{13}C NMR (100 Hz, $CDCl_3$): δ = 149.4, 147.6, 126.6, 123.7, 79.3, 72.0, 71.3, 29.5.

The spectra were in accordance with the previously reported data.[21]

1-(3-Nitrophenyl)but-3-yn-1-ol (3b)

Yield: 168 mg (87%); yellow oil.

^{1}H NMR (400 Hz, $CDCl_3$): δ = 8.22 (t, J = 2.0, 1 H$_{arom}$), 8.09 (ddd, J = 8.0, 2.0, 0.8 Hz, 1 H$_{arom}$), 7.69–7.67 (m, 1 H$_{arom}$), 7.48 (t, J = 7.6 Hz, 1 H$_{arom}$), 4.93 (dd, J = 7.2, 5.6 Hz, 1 H, OC*H*CH$_2$), 2.64–2.60 (m, 2 H, OCHC*H*$_2$), 2.08 (br s, 1 H, OH), 2.04 (t, J = 2.8 Hz, 1 H, C≡CH).

^{13}C NMR (100 Hz, $CDCl_3$): δ = 148.3, 144.4, 131.9, 129.4, 122.9, 120.9, 79.4, 72.0, 71.2, 29.5.

The spectra were in accordance with the previously reported data.[21]

1-(2-Nitrophenyl)but-3-yn-1-ol (3c)

Yield: 183 mg (95%); yellow oil.

^{1}H NMR (400 Hz, $CDCl_3$): δ = 7.90 (dd, J = 8.0, 1.2 Hz, 1 H$_{arom}$), 7.82 (dd, J = 8.0, 1.2 Hz, 1 H$_{arom}$), 7.61 (t, J = 8.0 Hz, 1 H$_{arom}$), 7.40 (t, J = 8.0 Hz, 1 H$_{arom}$), 5.41 (dd, J = 7.6, 4.8 Hz, 1 H, OC*H*CH$_2$), 2.86 (ddd, J = 16.4, 4.8, 2.8 Hz, 1 H, OCHC*H*$_2$), 2.62 (ddd, J = 16.4, 7.6, 2.8 Hz, 1 H, OCHC*H*$_2$), 2.04 (t, J = 2.8 Hz, 1 H, C≡CH).

^{13}C NMR (100 Hz, $CDCl_3$): δ = 147.8, 137.7, 133.5, 128.6, 128.2, 124.5, 79.7, 71.8, 67.4, 28.5.

The spectra were in accordance with the previously reported data.[22]

1-(4-Fluorophenyl)but-3-yn-1-ol (3d)

Yield: 129 mg (78%); yellow oil.

^{1}H NMR (400 Hz, CDCl$_3$): δ = 7.32–7.28 (m, 2 H$_{arom}$), 7.00–6.96 (m, 2 H$_{arom}$), 4.80 (t, J = 6.4 Hz, 1 H, OC*H*CH$_2$), 2.56 (dd, J = 6.4, 2.8 Hz, 2 H, OCHC*H*$_2$), 2.01 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 Hz, CDCl$_3$): δ = 163.6, 138.1, 127.5, 115.4, 80.3, 71.7, 71.2, 29.6.

The spectra were in accordance with the previously reported data.[21]

1-(4-Chlorophenyl)but-3-yn-1-ol (3e)

Yield: 158 mg (87%); yellow oil.

^{1}H NMR (300 Hz, CDCl$_3$): δ = 7.27 (br s, 4 H$_{arom}$), 4.79 (dd, J = 7.2, 6.0 Hz, 1 H, OC*H*CH$_2$), 2.57–2.54 (m, 2 H, OCHC*H*$_2$), 2.08 (br s, 1 H, OH), 2.01 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (75 Hz, CDCl$_3$): δ = 140.8, 133.7, 128.6, 127.2, 80.1, 71.6, 71.3, 29.5.

The spectra were in accordance with the previously reported data.[21]

1-(4-Bromophenyl)but-3-yn-1-ol (3f)

Yield: 200 mg (88%); yellow oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.42 (d, J = 8.4 Hz, 2 H$_{arom}$), 7.21 (d, J = 8.4 Hz, 2 H$_{arom}$), 4.78 (dd, J = 6.8, 5.6 Hz, 1 H, OC*H*CH$_2$), 2.56–2.53 (m, 2 H, OCHC*H*$_2$), 2.01 (t, J = 2.4 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 141.4, 131.6, 127.5, 121.8, 80.1, 71.6, 71.4, 29.4.

The spectra were in accordance with the previously reported data.[22]

1-(4-Methoxyphenyl)but-3-yn-1-ol (3g)

Yield: 140 mg (79%); yellow oil.

^{1}H NMR (400 Hz, CDCl$_3$): δ = 7.25 (d, J = 8.4 Hz, 2 H$_{arom}$), 6.91 (d, J = 8.4 Hz, 2 H$_{arom}$), 4.77 (t, J = 6.4 Hz, 1 H, OC*H*CH$_2$), 3.74 (s, 3 H, OCH$_3$), 2.58–2.55 (m, 2 H, OCHC*H*$_2$), 2.00 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 Hz, CDCl$_3$): δ = 159.3, 134.6, 127.0, 113.8, 80.8, 72.0, 70.9, 55.3, 29.4.

The spectra were in accordance with the previously reported data.[21]

1-(3-Methoxyphenyl)but-3-yn-1-ol (3h)

Yield: 165 mg (93%); yellow oil.

^{1}H NMR (400 Hz, CDCl$_3$): δ = 7.23–7.18 (m, 1 H$_{arom}$), 6.90–6.88 (m, 2 H$_{arom}$), 6.79–6.76 (m, 1 H$_{arom}$), 4.79 (t, J = 6.4 Hz, 1 H, OC*H*CH$_2$), 3.75 (s, 3 H, OCH$_3$), 2.58–2.56 (m, 2 H, OCHC*H*$_2$), 2.01 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 Hz, CDCl$_3$): δ = 160.0, 144.4, 129.8, 118.3, 113.7, 111.5, 80.9, 72.5, 71.3, 55.5, 29.7.

The spectra were in accordance with the previously reported data.[21]

1-(2-Methoxyphenyl)but-3-yn-1-ol (3i)

Yield: 167 mg (94%); colorless oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.34 (dd, J = 7.6, 1.6 Hz, 1 H$_{arom}$), 7.23–7.18 (m, 1 H$_{arom}$), 6.91 (dd, J = 8.0, 7.2 Hz, 1 H$_{arom}$), 6.82 (d, J = 8.0 Hz, 1 H$_{arom}$), 5.01 (dd, J = 7.6, 4.8 Hz, 1 H, OC*H*CH$_2$), 3.79 (s, 3 H, OCH$_3$), 2.70 (ddd, J = 16.8, 4.8, 2.8 Hz, 1 H, OCHC*H*$_2$), 2.57 (ddd, J = 16.8, 7.6, 2.8 Hz, 1 H, OCHC*H*$_2$), 1.98 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 156.5, 130.6, 129.1, 127.1, 121.0, 110.7, 81.6, 70.7, 69.3, 55.6, 27.7.

The spectra were in accordance with the previously reported data.[22]

1-Phenyl-3-butyn-1-ol (3j)

Yield: 106 mg (72%); colorless oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.34–7.24 (m, 5 H$_{arom}$), 4.82 (t, J = 6.4 Hz, 1 H, OC*H*CH$_2$), 2.60–2.57 (m, 2 H, OCHC*H*$_2$), 2.10 (br s, 1 H, OH), 2.01 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 142.5, 128.4, 127.9, 125.7, 80.7, 72.0, 70.7, 29.1.

The spectra were in accordance with the previously reported data.[21]

1-(Naphth-2-yl)but-3-yn-1-ol (3k)

Yield: 188 mg (95%); yellow oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.79–7.75 (m, 4 H$_{arom}$), 7.44–7.40 (m, 2 H$_{arom}$), 7.29 (s, 1 H$_{arom}$), 4.98 (t, J = 6.0 Hz, 1 H, OC*H*CH$_2$), 2.68–2.66 (m, 2 H, OCHC*H*$_2$), 2.41 (br s, 1 H, OH), 2.01 (t, J = 2.8 Hz, 1 H, C≡C*H*).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 139.8, 133.13, 133.09, 128.3, 128.0, 127.7, 126.2, 126.0, 124.6, 123.7, 80.6, 72.4, 71.1, 29.4.

The spectra were in accordance with the previously reported data.[21]

1-(2-Furyl)but-3-yn-1-ol (3l)

Yield: 101 mg (73%); yellow oil.

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.32 (t, J = 1.2 Hz, 1 H$_{het}$), 6.28 (d, J = 1.2 Hz, 2 H$_{het}$), 4.82 (t, J = 6.0 Hz, 1 H, OC*H*CH$_2$), 2.71 (dd, J = 6.0, 2.4 Hz, 2 H, OCHC*H*$_2$), 2.26 (s, 1 H, OH), 2.01 (t, J = 2.4 Hz, 1 H, C≡C*H*).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 154.6, 142.3, 110.2, 106.6, 79.8, 71.1, 66.1, 26.1.

The spectra were in accordance with the previously reported data.[21]

(*E*)-1-Phenylhex-1-en-5-yn-3-ol (3m)

Yield: 156 mg (90%); yellow oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.33 (d, J = 7.6 Hz, 2 H$_{arom}$), 7.25 (t, J = 7.6 Hz, 1 H$_{arom}$), 7.20–7.16 (m, 2 H$_{arom}$), 6.60 (d, J = 16.0 Hz, 1 H, C*H*=CH), 6.21 (dd, J = 16.0, 6.4 Hz, 1 H, CH=C*H*), 4.43–4.39 (m, 1 H, OC*H*CH$_2$), 2.61 (ddd, J = 16.8, 5.6, 2.8 Hz, 1 H, OCHC*H*$_2$), 2.55 (ddd, J = 16.8, 6.0, 2.4 Hz, 1 H, OCHC*H*$_2$), 2.02 (t, J = 2.8 Hz, 1 H, C≡C*H*), 1.89 (br s, 1 H, OH).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 136.3, 131.4, 129.9, 128.6, 127.9, 126.6, 80.2, 71.1, 70.7, 27.7.

The spectra were in accordance with the previously reported data.[21]

Dec-1-yn-4-ol (3n)

Yield: 125 mg (80%); colorless oil.

^{1}H NMR (300 MHz, CDCl$_3$): δ = 3.80–3.72 (m, 1 H, OC*H*CH$_2$), 2.43 (ddd, J = 16.4, 4.8, 3.2 Hz, 1 H, OCHC*H*$_2$C≡CH), 2.33 (ddd, J = 16.4, 6.4, 3.2 Hz, 1 H, OCHC*H*$_2$C≡CH), 2.06 (t, J = 3.2 Hz, 1 H, C≡C*H*), 1.97 (br s, 1 H, OH), 1.59–1.51 (m, 2 H, CH$_2$), 1.37–1.24 (m, 8 H, 4 × CH$_2$), 0.89 (t, J = 6.4 Hz, 3 H, CH$_3$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 80.9, 70.7, 69.9, 36.2, 31.7, 29.2, 27.3, 25.5, 22.6, 14.0.

The spectra were in accordance with the previously reported data.[23]

1-(5-Bromo-2-methoxyphenyl)but-3-yn-1-ol (3o)

Yield: 211 mg (82%); yellow oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.48 (d, J = 2.4 Hz, 2 H$_{arom}$), 7.28 (dd, J = 8.4, 2.4 Hz, 1 H$_{arom}$), 6.67 (d, J = 8.8 Hz, 1 H$_{arom}$), 4.98 (dd, J = 7.6, 4.8 Hz, 1 H, OCHCH$_2$), 3.75 (s, 3 H, CH$_3$), 2.67 (ddd, J = 16.8, 7.2, 2.8 Hz, 1 H, OCHCH_2), 2.48 (ddd, J = 16.8, 7.6, 2.4 Hz, 1 H, OCHCH_2), 2.00 (t, J = 2.8 Hz, 1 H, C≡CH).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 155.1, 132.5, 131.25, 129.6, 113.2, 112.0, 80.7, 70.9, 67.7, 55.5, 27.4.

The spectra were in accordance with the previously reported data.[24]

Methyl 4-(1-Hydroxybut-3-ynyl)benzoate (3p)

Yield: 175 mg (85%); yellow oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.95 (d, J = 8.8 Hz, 2 H$_{arom}$), 7.39 (d, J = 8.8 Hz, 2 H$_{arom}$), 4.86 (t, J = 6.0 Hz, 1 H$_{arom}$), 3.84 (s, 3 H, CH$_3$), 2.61 (ddd, J = 16.8, 8.0, 2.8 Hz, 1 H, OCHCH_2), 2.55 (ddd, J = 16.8, 7.2, 2.8 Hz, 1 H, OCHCH_2), 2.01 (t, J = 2.8 Hz, 1 H, C≡CH).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 166.8, 147.4, 129.8, 129.7, 125.7, 80.0, 71.8, 71.4, 52.1, 29.4.

The spectra were in accordance with the previously reported data.[6a]

4-(1-Hydroxybut-3-ynyl)-2-methoxyphenol (3q)

Yield: 136 mg (70%); yellow oil.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.96 (d, J = 2.0 Hz, 1 H$_{arom}$), 6.89 (d, J = 8.0 Hz, 1 H$_{arom}$), 6.85 (dd, J = 8.4, 1.6 Hz, 1 H$_{arom}$), 4.81 (t, J = 6.4 Hz, 1 H, OCHCH$_2$), 3.90 (s, 3 H, CH$_3$), 2.64–2.62 (m, 2 H, OCHCH_2), 2.44 (br s, 1 H, PhOH), 2.08 (t, J = 2.8 Hz, 1 H, C≡CH).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 146.5, 145.3, 134.5, 118.8, 114.1, 108.23, 80.8, 72.2, 70.9, 55.9, 29.4.

The spectra were in accordance with the previously reported data.[25]

4-(1-Hydroxybut-3-yn-yl)benzonitrile (3r)

Yield: 160 mg (92%); white solid; mp 120–122 °C.

^{1}H NMR (400 MHz, CDCl$_3$): δ = 7.58 (d, J = 8.0 Hz, 2 H$_{arom}$), 7.45 (d, J = 8.4 Hz, 2 H$_{arom}$), 4.86 (t, J = 6.0 Hz, 1 H, OCHCH$_2$), 2.63–2.51 (m, 2 H, OCHCH_2), 2.11 (d, J = 2.4 Hz, 1 H, C≡CH).

^{13}C NMR (100 MHz, CDCl$_3$): δ = 147.5, 132.2, 126.5, 118.6, 111.6, 79.5, 71.8, 71.4, 29.4.

The spectra were in accordance with the previously reported data.[6a]

1-[4-(1-Hydroxybut-3-yn-1-yl)phenyl]ethanone (3s)

Yield: 179 mg (94%); yellow oil.

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.88 (d, J = 11.2 Hz, 2 H$_{arom}$), 7.43 (d, J = 11.2 Hz, 2 H$_{arom}$), 4.87 (dd, J = 8.8, 8.4 Hz, 1 H, OCHCH$_2$), 2.61–2.57 (m, 2 H, OCHCH_2), 2.53 (s, 3 H, CH$_3$), 2.47 (br s, 1 H, OH), 2.09 (t, J = 3.0 Hz, 1 H, C≡CH).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 197.8, 147.6, 136.7, 128.6, 125.9, 79.9, 71.6, 71.5, 29.4, 26.7.

HRMS (ESI, MeOH–H$_2$O): m/z calcd for C$_{12}$H$_{12}$O$_2$ [M − H]$^+$: 187.0765; found: 187.0748.

Acknowledgment

Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0034-1379163. Included are additional experimental procedures and ^{1}H, ^{13}C, ^{19}F, and ^{11}B NMR for all synthesized compounds.

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