

Supplementary Information

Transition metal-free, NaO^tBu-O₂-mediated one-pot cascade oxidation of allylic alcohols to α,β -unsaturated carboxylic acids

Sun Min Kim, Young Sug Kim, Dong Wan Kim and Jung Woon Yang*

Department of Energy Science (DOES), Sungkyunkwan University

Suwon 440-746, Korea

E-mail: jwyang@skku.edu; Fax: (+82)-31-299-4279; Tel: (+82)-31-299-4276

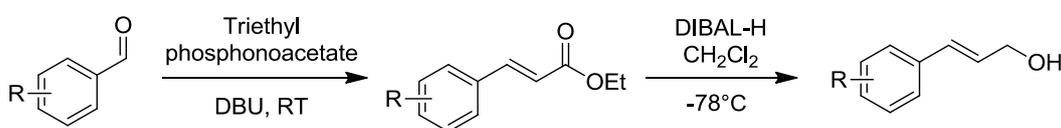
Contents

General Methods and Experimental Procedure	S2
Characterization Data for Products	S4
References	S10
¹H NMR and ¹³C NMR Spectra of Products	S11

General Methods

Unless stated otherwise, reactions were carried out under a dry argon atmosphere in vacuum-flame dried glassware. Thin-layer chromatography (TLC) was performed on Merck silica gel 60 F254. ^1H NMR spectra were recorded on a Varian at 300 MHz in CDCl_3 (δ 7.26 ppm) or $\text{DMSO}-d_6$ (δ 2.50 ppm), ^{13}C NMR spectral measurements were performed at 75 MHz using CDCl_3 (δ 77.16 ppm) or $\text{DMSO}-d_6$ (δ 39.52 ppm). The terms m, s, d, t, q, quint., and sept. represent multiplet, singlet, doublet, triplet, quadruplet, quintuplet, and septet, respectively, and the term br means a broad signal. Commercial grade reagents and solvents were used without further purification.

The preparation of cinnamyl alcohol by HWE reaction and DIBAL-H reduction



Starting material was prepared by us using the most convenient way reported in the literature.¹

General Procedure for Horner-Wadsworth-Emmons Reaction

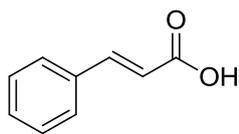
DBU (1.59 g, 10.5 mmol) was added to a flame-dried round bottom flask containing triethyl phosphonoacetate (1.57 g, 7 mmol), and the reaction mixture was maintained at room temperature for 15 min. The aldehyde (7.7 mmol) was added dropwise, and the reaction mixture was stirred overnight. After completion of the reaction, it was quenched with water and, extracted with Et_2O (30 mL \times 3). The combined organic layers were dried over MgSO_4 and concentrated under vacuum. The pure α,β -unsaturated ester was obtained by column chromatography.

General Procedure for DIBAL-H Reduction

α,β -Unsaturated ester (4 mmol) was slowly added to a flame-dried round bottom flask pre-cooled to -78°C containing a solution of 1.0 M DIBAL-H in hexane (10.8 mL, 10.8 mmol) in CH_2Cl_2 . After completion of the reaction, it was quenched with water and, extracted with CH_2Cl_2 (30 mL \times 3). The combined organic layers were dried over MgSO_4 and concentrated under vacuum. The pure *trans*-cinnamyl alcohol was obtained in almost quantitative yield.

Typical procedure for the oxidation of *trans*-cinnamyl alcohol **1a to cinnamic acid **2a****

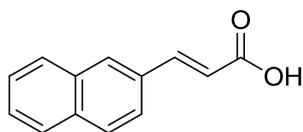
NaO^tBu (192 mg, 2 mmol) was added to a suspension of cinnamyl alcohol **1a** (132 mg, 1 mmol) in 3 mL of dry toluene at room temperature under oxygen atmosphere. The reaction was stirred until TLC analysis indicated complete consumption of the starting material, and then the reaction mixture was quenched with 5% HCl and, extracted with EtOAc (50 mL×3). The combined organic layers were dried over MgSO₄ and concentrated under vacuum. The pure *trans*-cinnamic acid **2a** (91%) was obtained by column chromatography.



2a *trans*-cinnamic acid (Table 2, Entry 1)

Physical and spectroscopic data were identical to previous literature reports for this compound.²

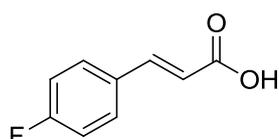
Yield: 91%; ¹H NMR (300 MHz, CDCl₃) δ: 7.82 (d, *J* = 15.9 Hz, 1H), 7.65-7.54 (m, 2H), 7.5-7.36 (m, 3H), 6.48 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.66, 144.01, 134.32, 130.26, 128.96, 128.24, 119.35 ppm.



2b *trans*-3-(naphthalen-2-yl)acrylic acid (Table 2, Entry 2)

Physical and spectroscopic data were identical to previous literature reports for this compound.²

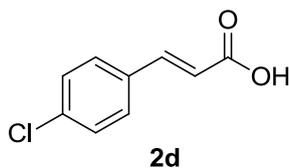
Yield: 75%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 8.13 (s, 1H), 7.95-7.84 (m, 4H), 7.8 (d, *J* = 15.9 Hz, 1H), 7.53-7.51 (m, 2H), 6.7 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.78, 144.01, 133.77, 132.98, 131.95, 129.71, 128.57, 128.51, 127.72, 127.26, 126.76, 123.96, 119.67 ppm.



2c *trans*-4-fluorocinnamic acid (Table 2, Entry 3)

Physical and spectroscopic data were identical to previous literature reports for this compound.²

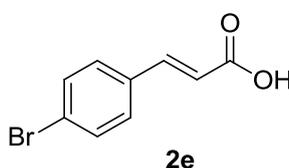
Yield: 99%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.8-7.66 (m, 2H), 7.58 (d, *J* = 16.2, 1H), 7.3-7.13 (m, 2H), 6.47 (d, *J* = 16.2 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.68, 163.28 (d, *J* = 246.98 Hz), 142.79, 131.00 (d, *J* = 3.15 Hz), 130.53 (d, *J* = 8.6 Hz), 119.24, 115.94 (d, *J* = 21.7 Hz) ppm.



***trans*-4-chlorocinnamic acid (Table 2, Entry 4)**

Physical and spectroscopic data were identical to previous literature reports for this compound.³

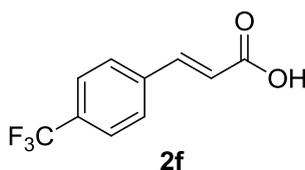
Yield: 99%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.76 (d, *J* = 8.7 Hz, 2H), 7.57 (d, *J* = 15.9 Hz, 1H), 7.47 (d, *J* = 8.7 Hz, 2H), 6.56 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.59, 142.56, 134.87, 133.3, 129.9, 128.98, 120.22 ppm.



***trans*-4-bromocinnamic acid (Table 2, Entry 5)**

Physical and spectroscopic data were identical to previous literature reports for this compound.⁵

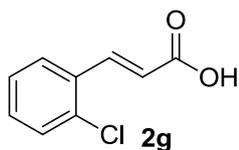
Yield: 93%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.62 (d, *J* = 15.6 Hz, 1H), 7.66-7.51 (m, 5H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.42, 142.59, 133.55, 131.85, 130.11, 123.53, 120.16 ppm.



***trans*-4-(trifluoromethyl)cinnamic acid (Table 2, Entry 6)**

Physical and spectroscopic data were identical to previous literature reports for this compound.⁵

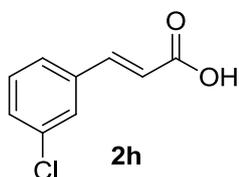
Yield: 96%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.92 (d, *J* = 8.1 Hz, 2H), 7.77 (d, *J* = 8.4 Hz, 2H), 7.66 (d, *J* = 15.9 Hz, 1H), 6.69 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.88, 142.59, 138.88, 130.64, 130.54 (q, *J* = 31.78 Hz), 139.308, 126.19 (q, *J* = 3.8 Hz), 122.81 ppm.



2g *trans*-2-chlorocinnamic acid (Table 2, Entry 7)

Physical and spectroscopic data were identical to previous literature reports for this compound.³

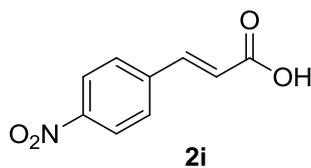
Yield: 85%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.88 (d, *J* = 16.2 Hz, 1H), 7.54-7.38 (m, 2H), 7.37-7.28 (m, 2H), 6.56 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.85, 139.40, 134.29, 132.56, 132.13, 130.51, 128.74, 128.27, 122.86 ppm.



2h *trans*-3-chlorocinnamic acid (Table 2, Entry 8)

Physical and spectroscopic data were identical to previous literature reports for this compound.⁵

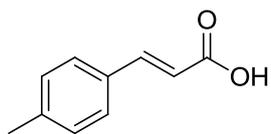
Yield: 93%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.76 (s, 1H), 7.67-7.51 (m, 1H), 7.56 (d, *J* = 15.9 Hz, 1H), 7.48-7.36 (m, 2H), 6.6 (d, *J* = 16.2 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.39, 142.32, 136.55, 133.80, 130.64, 129.81, 127.82, 126.75, 121.03 ppm.



2i *trans*-4-nitrocinnamic acid (Table 2, Entry 9)

Physical and spectroscopic data were identical to previous literature reports for this compound.²

Yield: 37%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 8.4-8.18 (m, 2H), 8.09-7.9 (m, 2H), 7.68 (d, *J* = 15.9 Hz, 1H), 6.73 (d, *J* = 16.2 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.03, 147.96, 141.34, 140.75, 129.29, 123.93, 123.61 ppm.

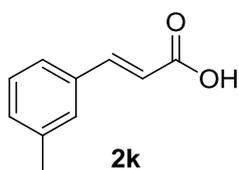


2j

***trans*-4-methylcinnamic acid (Table 2, Entry 10)**

Physical and spectroscopic data were identical to previous literature reports for this compound.²

Yield: 97%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.57 (d, *J* = 8.1 Hz, 2H), 7.55 (d, *J* = 16.2 Hz, 1H), 7.22 (d, *J* = 8.1 Hz, 2H), 6.46 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.81, 144.02, 140.20, 131.61, 129.58, 128.22, 118.18, 21.05 ppm.

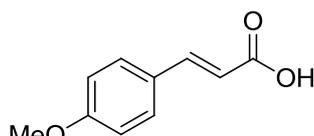


2k

***trans*-3-methylcinnamic acid (Table 2, Entry 11)**

Physical and spectroscopic data were identical to previous literature reports for this compound.³

Yield: 97%; ¹H NMR (300 MHz, CDCl₃) δ: 7.77 (d, *J* = 15.9 Hz, 1H), 7.39-7.32 (m, 4H), 6.44 (d, *J* = 15.9 Hz, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.60, 144.04, 138.15, 134.17, 130.92, 128.77, 128.64, 125.41, 119.02, 20.83 ppm.

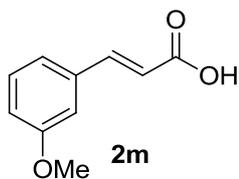


2l

***trans*-4-methoxycinnamic acid (Table 2, Entry 12)**

Physical and spectroscopic data were identical to previous literature reports for this compound.²

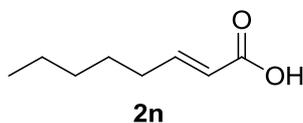
Yield: 67%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.62 (d, *J* = 8.4, 2H), 7.55 (d, *J* = 16.2, 1H), 6.96 (d, *J* = 8.4, 2H), 6.68 (d, *J* = 15.9, 1H), 3.78 (s, 3H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.88, 160.98, 143.77, 129.95, 126.88, 116.56, 114.38, 55.30 ppm.



***trans*-3-methoxycinnamic acid (Table 2, Entry 13)**

Physical and spectroscopic data were identical to previous literature reports for this compound.³

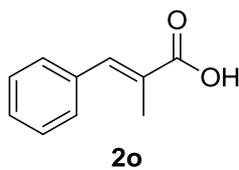
Yield: 97%; ¹H NMR (300 MHz, DMSO-*d*₆) δ: 7.56 (d, *J* = 16.2, 1H), 7.37-7.17 (m, 3H), 6.97 (d, *J* = 6.9, 1H), 6.55 (d, *J* = 15.9, 1H), 3.78 (s, 3H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 167.57, 159.61, 143.88, 135.68, 129.92, 120.75, 119.59, 116.24, 112.93, 55.22 ppm



***trans*-octenoic acid (Table 2, Entry 14)**

Physical and spectroscopic data were identical to previous literature reports for this compound.³

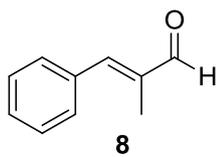
Yield: 47%; ¹H NMR (300 MHz, CDCl₃) δ: 7.17-7 (m, 1H), 5.88-5.78 (m, 1H), 2.31-2.14 (m, 2H), 1.56-1.41 (m, 2H), 1.36-1.28 (m, 4H), 0.93-0.87 (m, 3H) ppm; ¹³C NMR (75 MHz, CDCl₃) δ: 172.54, 153.14, 120.55, 32.41, 31.40, 27.62, 22.52, 14.05 ppm.



***trans*- α -methylcinnamic acid (Table 2, Entry 15)**

Physical and spectroscopic data were identical to previous literature reports for this compound.²

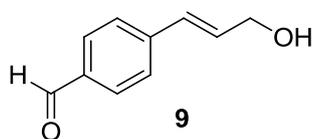
Yield: 61%; ¹H NMR (300 MHz, CDCl₃) δ: 7.84 (d, *J* = 1.2 Hz, 1H), 7.46-7.40 (m, 5H), 2.16 (d, *J* = 1.5 Hz, 3H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 169.42, 137.75, 135.66, 129.63, 128.85, 128.52 ppm.



***trans*-α-methylcinnaldehyde**

Physical and spectroscopic data were identical to previous literature reports for this compound.⁵

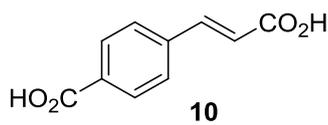
Yield: 15%; ¹H NMR (300 MHz, CDCl₃) δ: 9.58 (s, 1H), 7.55-7.42 (m, 5H), 7.27 (s, 1H), 2.08 (s, 3H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 195.81, 150.12, 138.68, 136.37, 130.28, 129.82, 128.95, 11.2 ppm.



***trans*-4-(3-hydroxyprop-1-en-1-yl)benzaldehyde**

Physical and spectroscopic data were identical to previous literature reports for this compound.⁶

¹H NMR (300 MHz, CDCl₃) δ: 9.98 (s, 1H), 7.83 (d, 2H, *J* = 8.1 Hz), 7.52 (d, 2H, *J* = 8.1 Hz), 6.70 (d, 1H, *J* = 15.9 Hz), 6.53 (dt, 1H, *J* = 15.9, 5.1 Hz), 4.39 (s, 1H), 1.81 (br, 1H) ppm; ¹³C NMR (75 MHz, DMSO-*d*₆) δ: 191.78, 142.81, 135.38, 132.39, 130.17, 129.35, 126.89, 83.29 ppm.



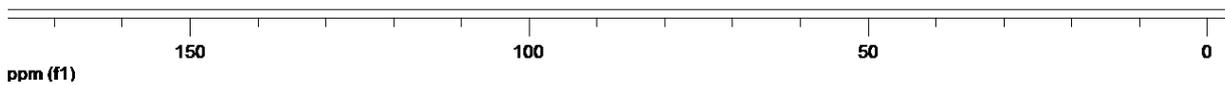
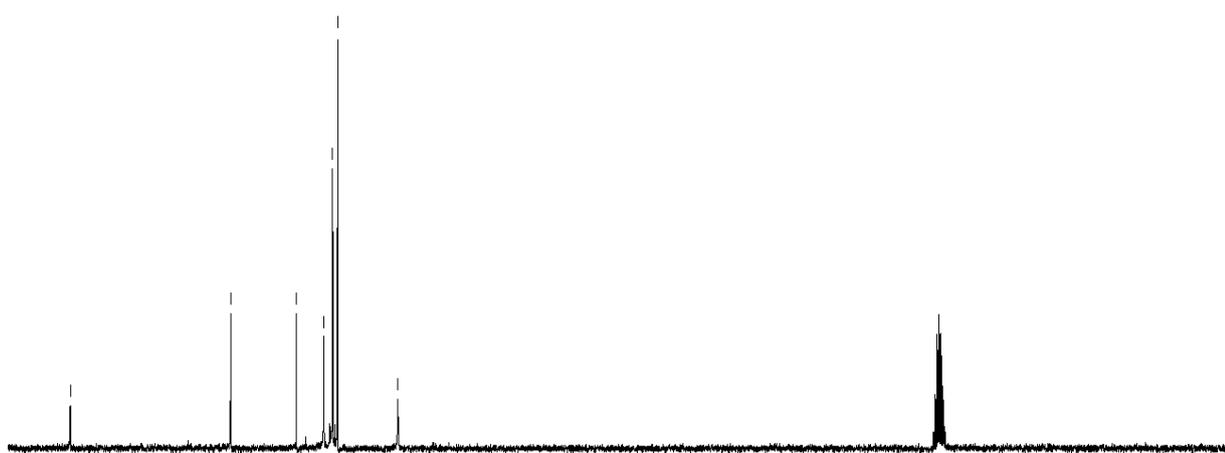
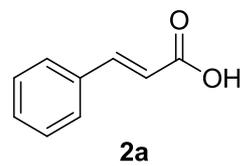
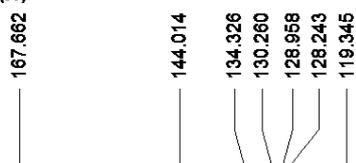
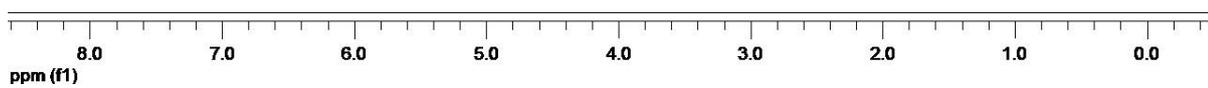
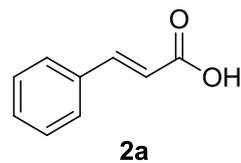
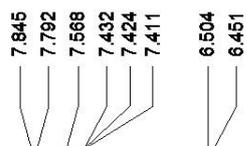
***trans*-4-(2-carboxyvinyl)benzoic acid**

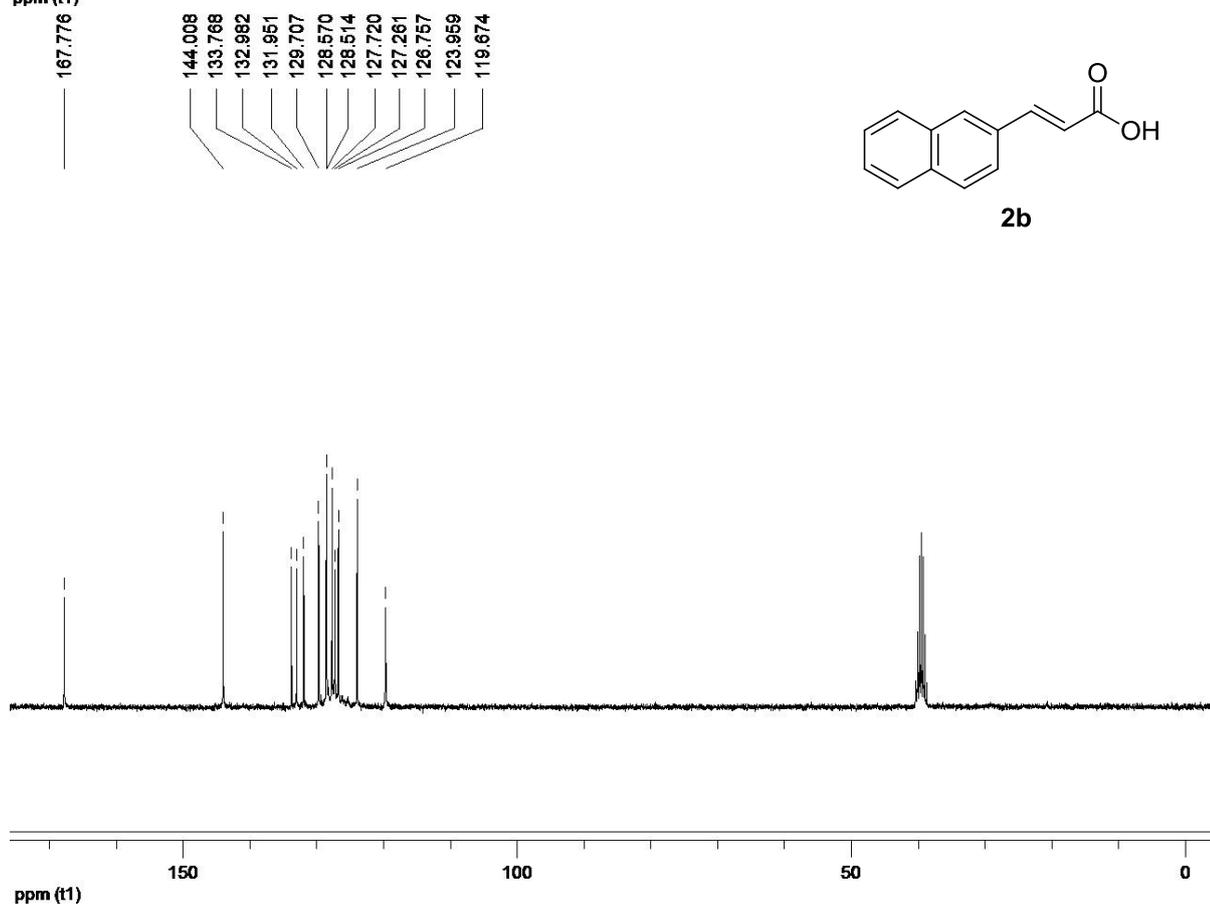
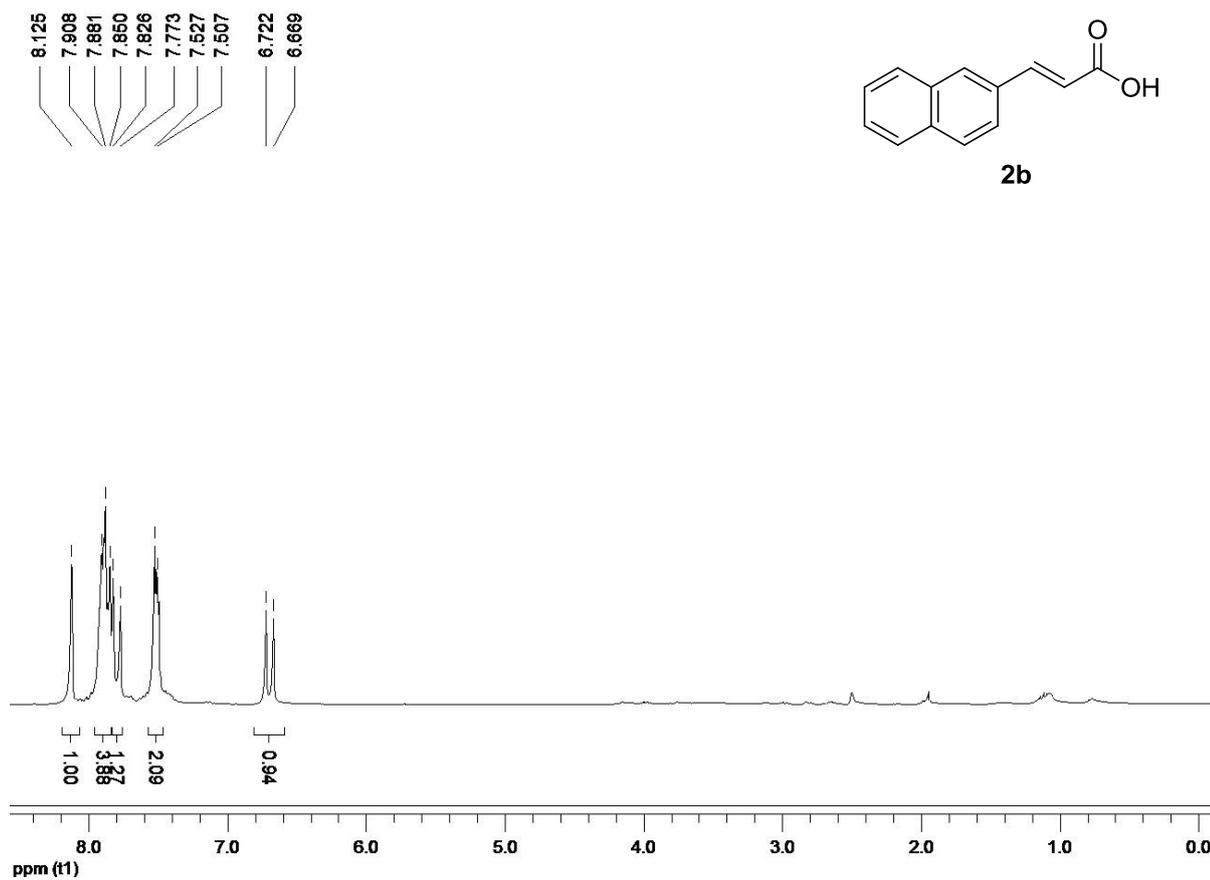
Physical and spectroscopic data were identical to previous literature reports for this compound.⁷

Yield: 89%; ¹H NMR (300 MHz, DMSO- *d*₆) δ: 7.95 (d, 2H, *J* = 8.4 Hz), 7.81 (d, 2H, *J* = 8.4 Hz), 7.64 (d, 1H, *J* = 15.9 Hz), 6.64 (d, 1H, *J* = 16.2 Hz) ppm; ¹³C NMR (75 MHz, DMSO- *d*₆) δ: 167.44, 166.97, 142.77, 138.45, 131.94, 129.87, 128.41, 121.69 ppm.

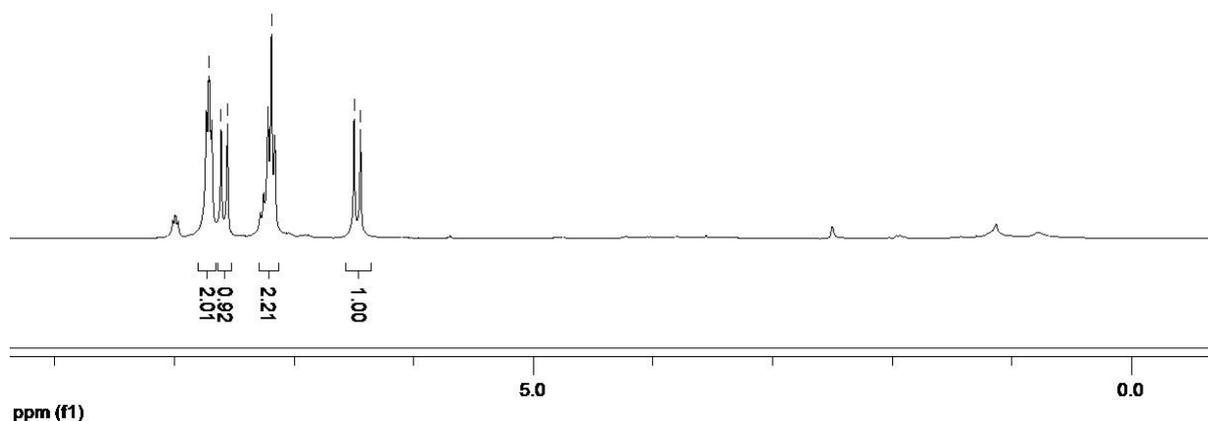
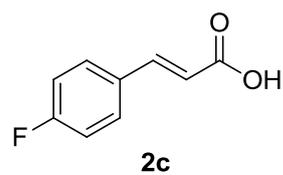
References

1. D. J. Vyas and M. Oestreich, *Chem. Commun.*, 2010, **46**, 568.
2. T. Fukuyama, M. Arai, H. Matsubara and I. Ryu, *J. Org. Chem.*, 2004, **69**, 8105.
3. S. T. Kemme, T. Šmejkal and B. Breit, *Adv. Synth. Catal.*, 2008, **350**, 989.
4. C. Pardin, J. N. Pelletier, W. D. Lubell and J. W. Keillor, *J. Org. Chem.*, 2008, **73**, 5766.
5. The corresponding product **8** was purchased from Sigma-Aldrich.
6. N. Kanbayashi and K. Onitsuka, *Angew. Chem., Int. Ed.*, 2011, **50**, 5197.
7. Z. Du, W. Zhou, F. Wang and J. X. Wang, *Synlett*, 2011, **3**, 369.

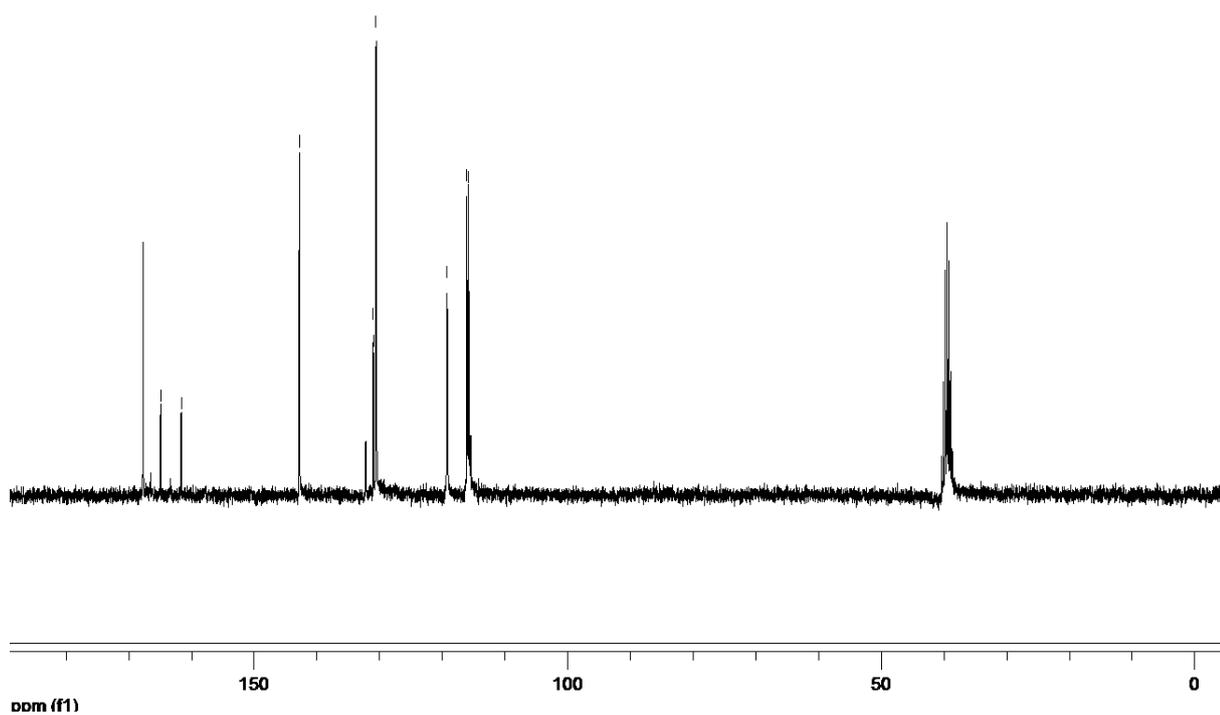
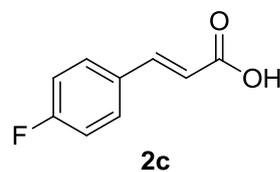


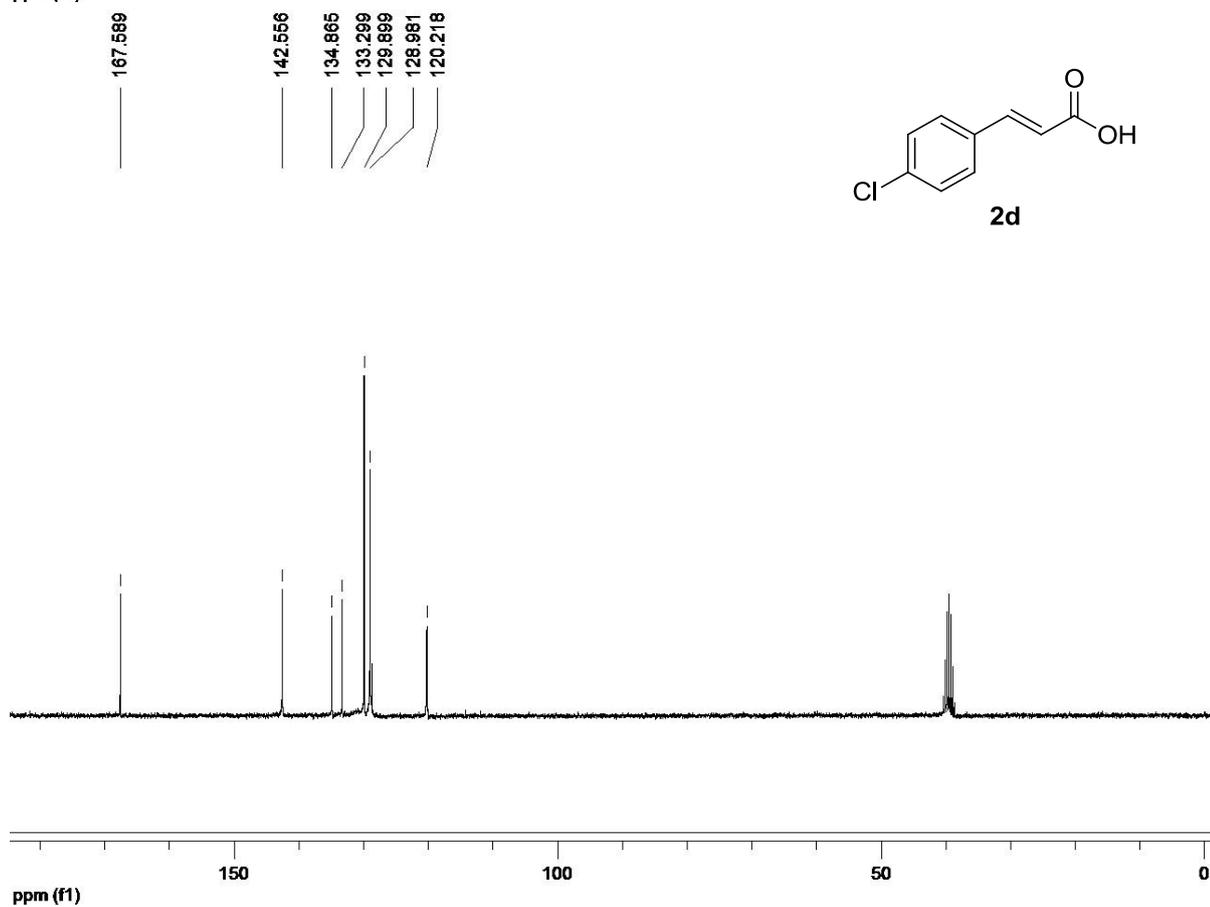
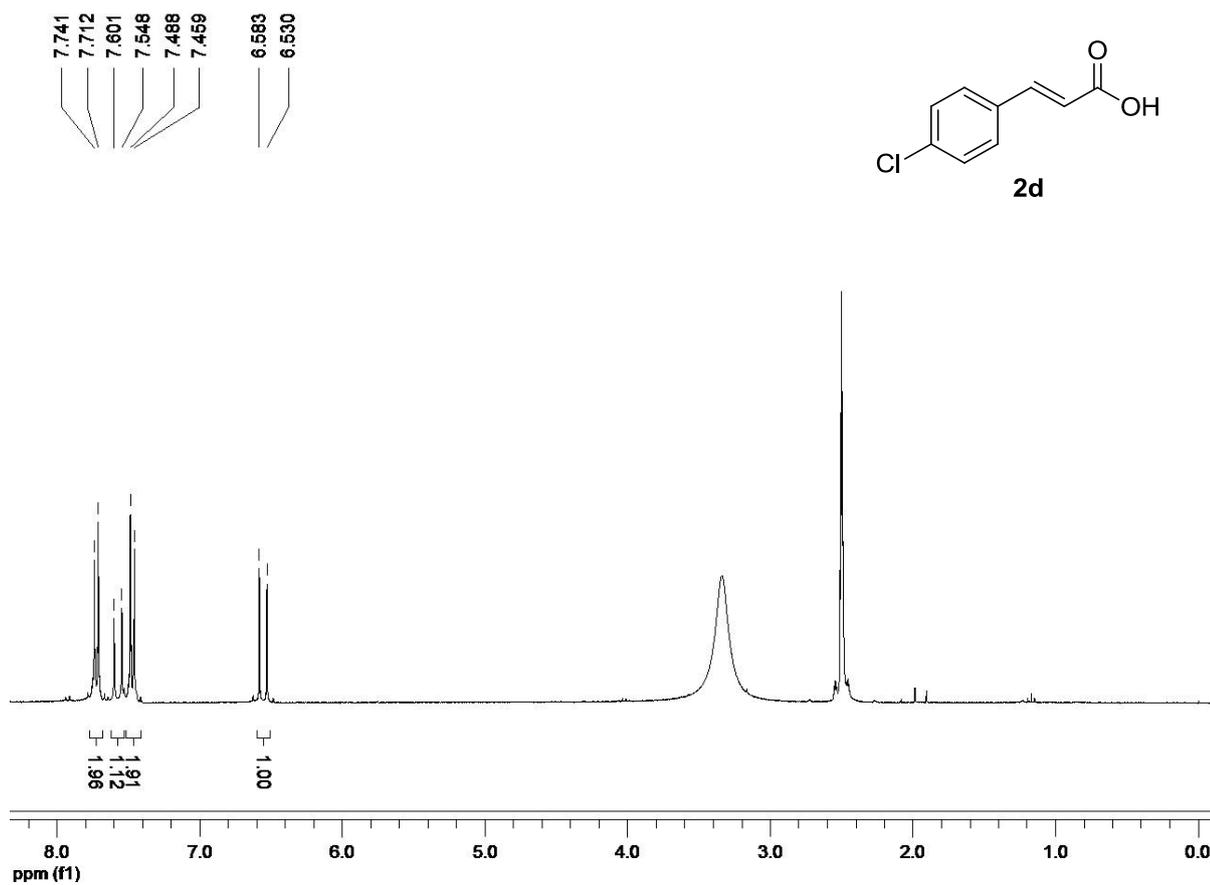


7.714
7.610
7.556
7.189
6.498
6.444

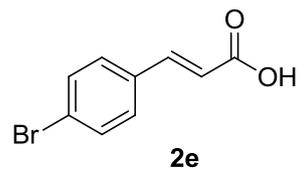


167.684
164.922
161.629
142.794
131.024
130.982
130.568
130.474
119.239
116.087
115.798



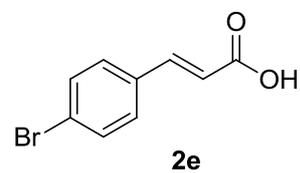


7.641
7.612
7.589
7.561
7.533
6.578
6.525



ppm (f1)

167.420
142.593
133.549
131.845
130.114
123.529
120.160



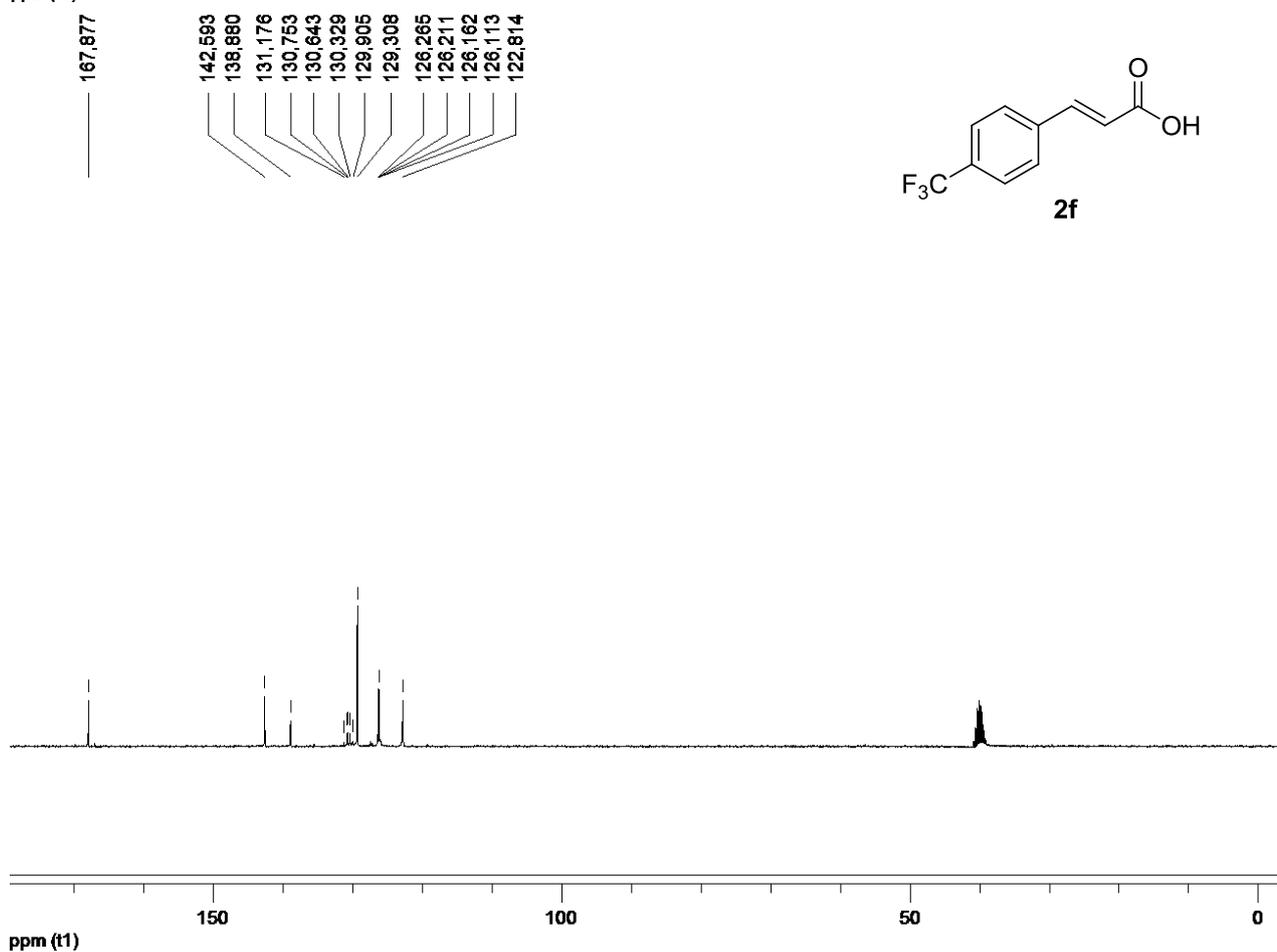
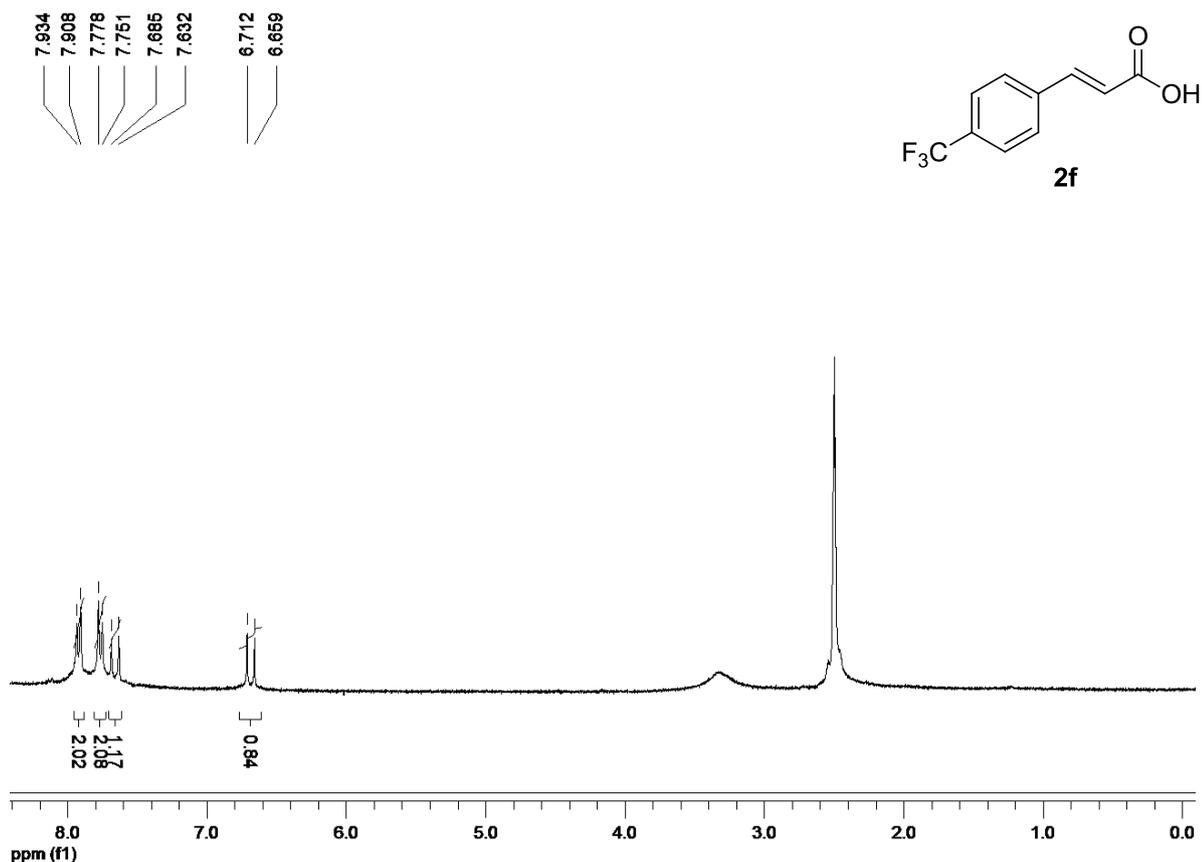
ppm (f1)

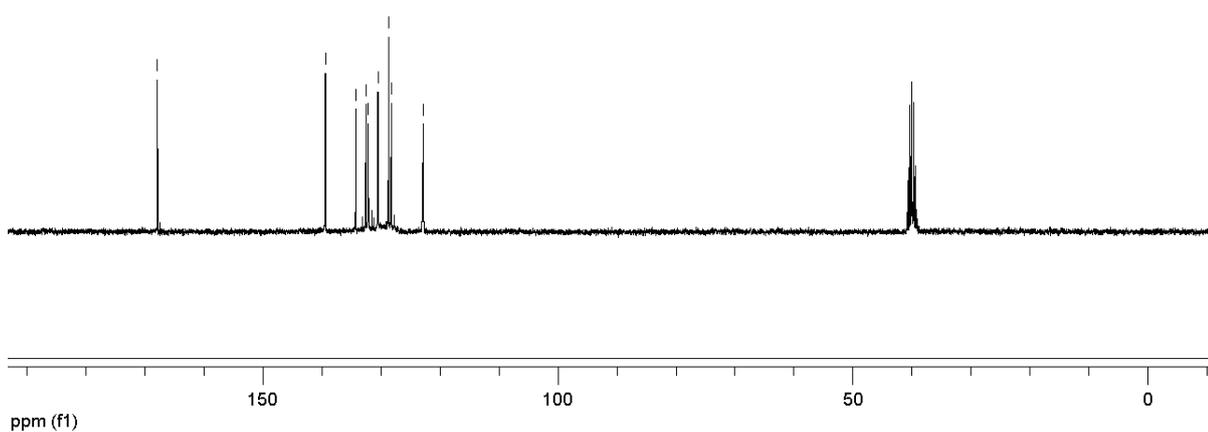
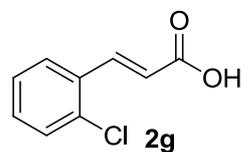
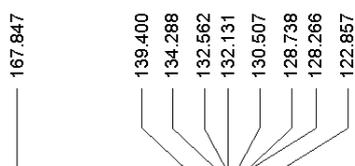
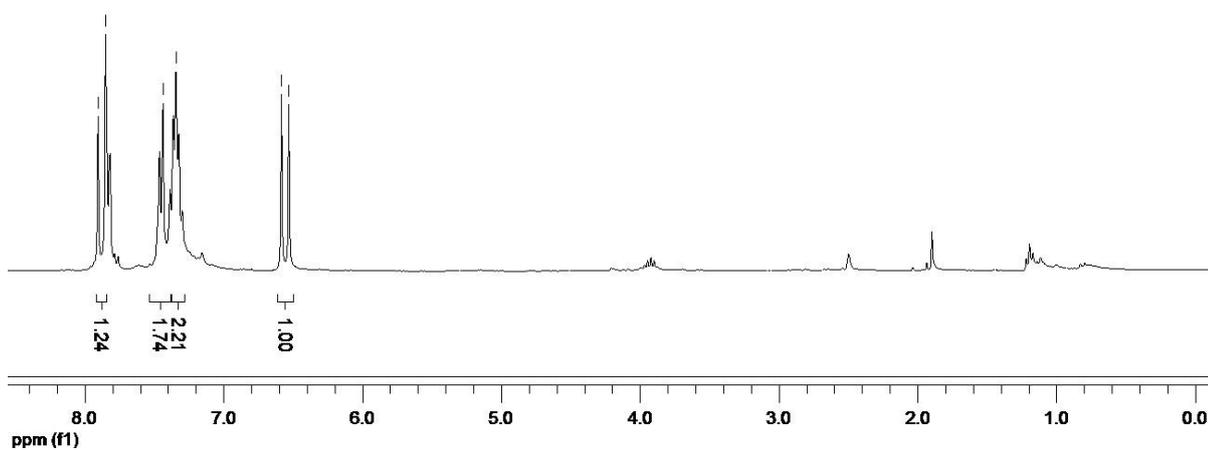
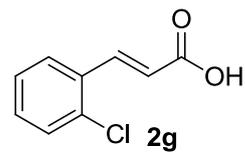
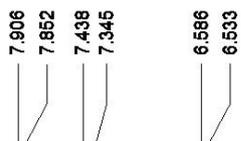
150

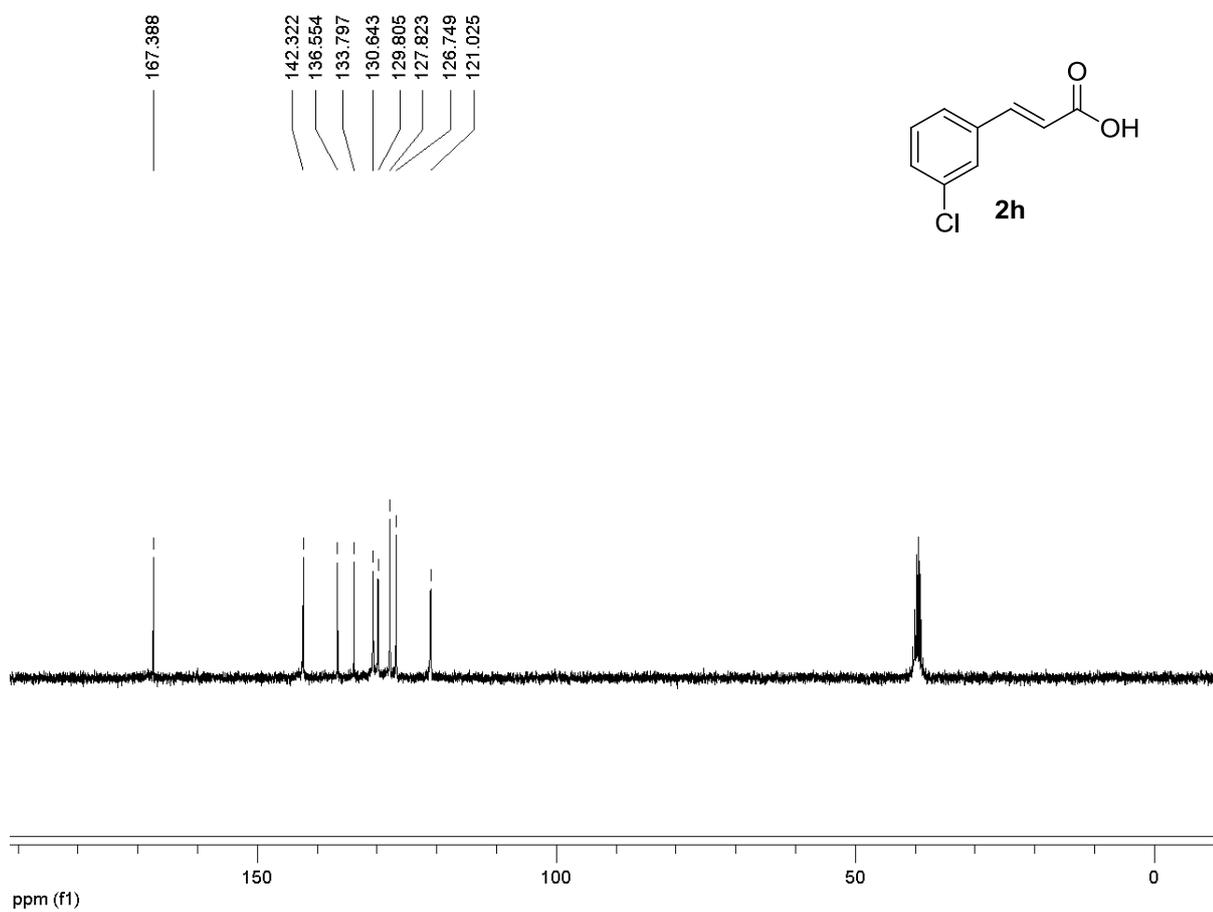
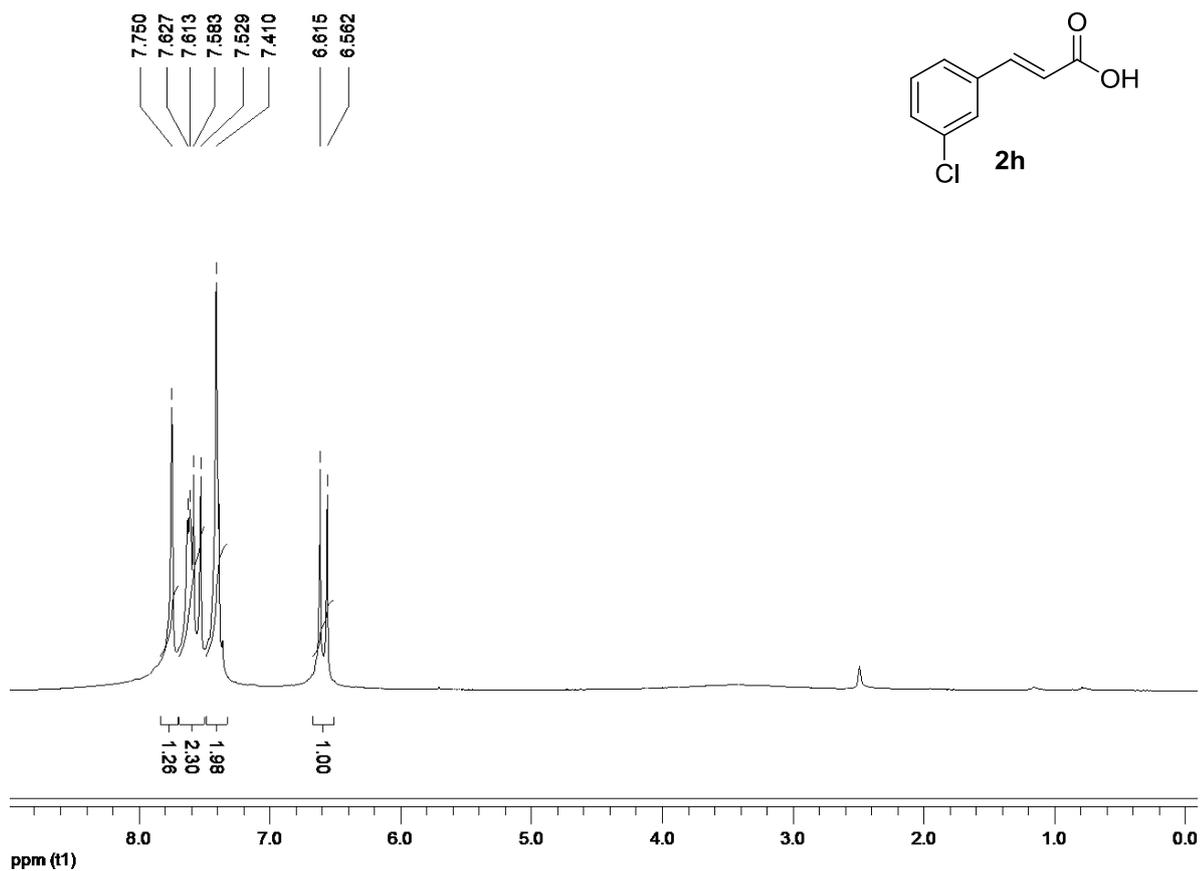
100

50

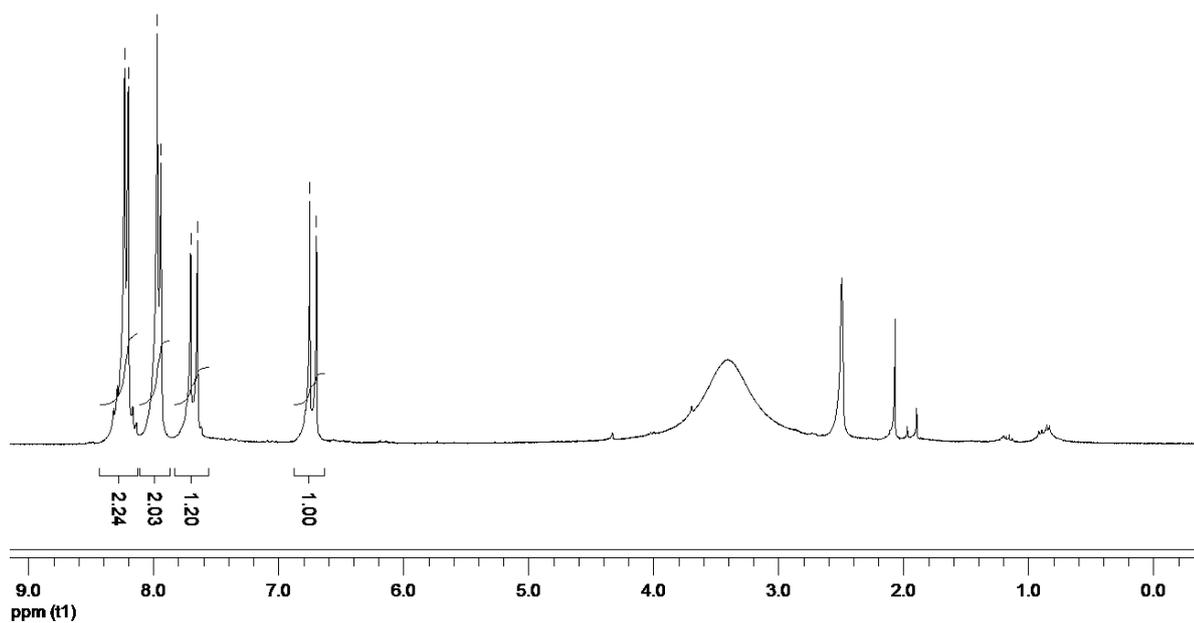
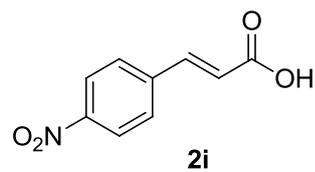
0







8.233
8.204
7.971
7.942
7.704
7.650
6.751
6.698



167.033
147.957
141.337
140.746
129.294
123.927
123.611

