Electronic Supporting information for:

Selective MonoMethyl Esterification of Linear Dicarboxylic Acids with Bifunctional Alumina Catalysts

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Contents

1. General remarks

Reagents were obtained from commercial sources and used as received.

High resolution capillary GC was performed using a fused silica capillary column SE52 (5% Phenyl, 95% Methyl Polysiloxane, 30m x 25mm).

^{1}H NMR and ^{13}C NMR spectra were recorded in $CDCl_3$ at 298 K on a Bruker 300 or 400 AVANCE spectrometer using the solvent as internal standard (7.26 ppm for ^{1}H NMR and 77.00 ppm for ^{13}C NMR). The terms m, s, d, t represent multiplet, singlet, doublet, triplet respectively.

2. Experimental procedures

Preparation of ordered mesoporous Al_2O_3 Mes

Aluminum tri-sec-butoxide (27.4 g) was added to a calculate amount of deionized water (6.2 ml) and stearic acid (10.2 g), previously dissolved in 1-propanol (200 ml) by sonication, in order to reach the following molar composition: 1 Al(sec-BuO)$_3$: 0.33 $C_{17}H_{35}COOH$: 24 C_3H_7OH: 3 H_2O.
The resulting suspension was left to settle at 100°C for 42 h, then centrifuged and washed with ethanol and deionized water. The sample was dried overnight at 80°C, then calcined in nitrogen flow at 410 °C for 6 h, and subsequently in air up to 550°C for 6 h. The alumina sample was referred to as Al_2O_3 Mes.

Preparation of ordered mesoporous Al_2O_3-ZrO_2 Mes

The preparation procedure of the mesoporous alumina-zirconia sample is exactly alike that described for pure alumina, with the only difference being the addition of zirconium(IV) n-propoxide at first and, after 20 min of sonication, the Al alkoxide. When both aluminium tri-sec-butoxide and zirconium(IV) n-propoxide were used as Al and Zr precursors, the molar ratio between the two reagents was: 1 Al(sec-BuO)$_3$: 0.11 Zr(PrO)$_4$ to reach a Al/Zr=9/1 atomic ratio. The sample was identified as Al_2O_3-ZrO_2 Mes.

Preparation of SiO_2-$(CH_2)_3$-SO_3H

Amorphous silica (8.0 g) has been refluxed in toluene (120 mL) with (3-mercaptopropyl)trimethoxysilane (MPTS) (1.15 mL; 6.1 mmol) under stirring for 24 hours. The mixture was then filtered and the resulting solid, namely supported propylmercaptane has been oxidized to propanesulfonic acid by treatment with 30% aq H_2O_2 (100 mL; 1 mol) under stirring for 24 hours at rt, adding few drops of concentrated sulfuric acid after 12 hours. The white solid was then filtered and dried in vacuum. Its acidity has been measured by titration with an aqueous NaOH solution.

Nitrogen Physisorption at -196°C. N_2 adsorption–desorption measurements were performed at -196 °C with a Micromeritics ASAP2010. The analysis procedure is fully automated and operates with the static volumetric technique. The samples (0.1 g) were outgassed at 130 °C for 12. The isotherms were used to determine the specific surface areas (S.A.), through the BET equation, and the specific pore volume (Vs) calculated at $p/p_0 = 0.98$. The Barrett-Joyner-Halenda (BJH) model was used to calculate the pore size distribution.

NH_3-TPD Temperature programmed desorption of ammonia. NH_3-TPD measurements were carried out by an AUTOCHEM 2910 automatic temperature programmed desorption apparatus (Micromeritics). About 0.1 g of sample were treated at 500°C in helium flow for 90 min. The temperature was reduced to 100°C and the sample was kept in a flow of NH_3 (1% in helium) for 30 min and then in helium flow (40 ml min^{-1}) for 60 min. The amount of desorbed NH_3 was determined by heating the sample at 25°C min^{-1} up to 600°C in helium flow (40 ml min^{-1}) and a thermal conductivity detector was used.

FT-IR spectra of adsorbed pyridine. IR spectral measurements were carried out in an evacuable Pyrex cell with CaF_2 windows. The sample was ground to a fine powder. A total of 10 mg of the sample was pressed at 4 tons, in order to get a self-supporting wafer. The wafers were mounted in the holder of the IR cell and degassed by heating at 100°C and 10^{-4}Torr. After cooling to RT pyridine vapor was adsorbed on the samples. The spectra were recorded after degassing the wafers under vacuum at 100°C and 10^{-4} Torr for 2 h.

Catalytic reactions under batch conditions. Methanol (10 ml, 50 equiv.), the dicarboxylic compound (5 mmol) and the heterogeneous catalyst (250 mg of acid Al_2O_3) were stirred in a batch reactor at room temperature for 48 hours. The solid catalyst was then recovered by filtration and the reaction mixture was analyzed by high resolution capillary GC with a fused silica capillary column SE52 (5% Phenyl, 95% Methyl Polysiloxane, 30m x 25mm) using decane as internal standard. The products were eventually identified by NMR (^1H and ^{13}C).

3. Figures and Additional Tables

Figure S1 Pore distribution curves of the tested aluminas: Al_2O_3 CE (black), Al_2O_3 SA (red), Al_2O_3 Mes (blue), Al_2O_3-ZrO_2 Mes (magenta).

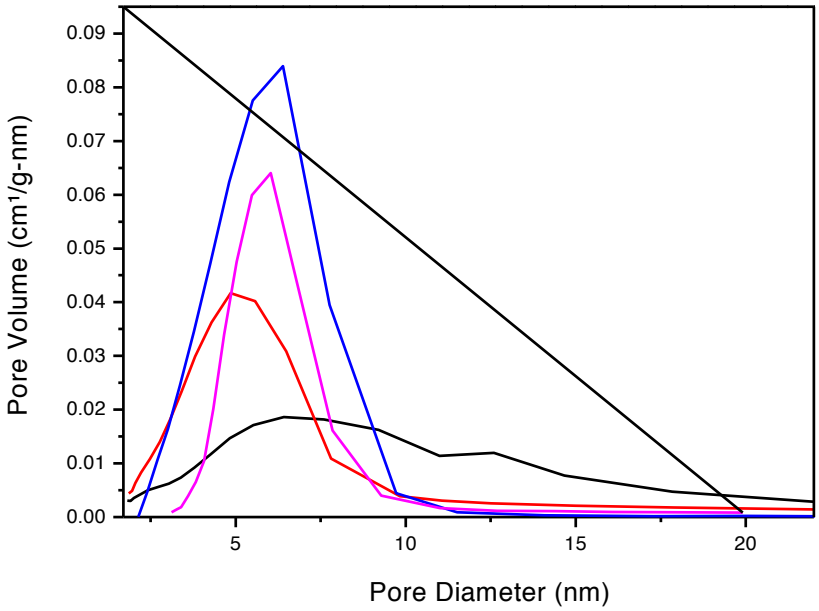


Table T1 Reactions with various alcohols

Catalytic activity of Al_2O_3 CE with various alcohols on the esterification of adipic acid (reaction conditions as Table 4 of the main manuscript, 50 mg of catalyst/mmol of 1/50 equiv. of alcohol, for 24 hours at 25 °C). Beside a tertiary alcohol, which was not reactive, low conversion and complete selectivity towards monoester 2 have been observed in all cases.

Entry	Alcohol	**1** Conv. (%)	**2** Yield (%)	**3** Yield (%)	**2** Sel. (%)
1	EtOH	9	9	-	99
2	nPrOH	5	5	-	99
3	iPrOH	4	4	-	99
4	tBuOH	-	-	-	-

Table T2 Reactions with EtOH under different conditions

Catalytic activity of Al_2O_3 CE with EtOH on the esterification of adipic acid. The low conversion could be increased with longer reaction times (entry 2), with a higher catalyst concentration (entry 3, by reducing the molar excess of the alcohol to 40-fold) and with an increase of the amount of catalyst (entry 4). The selectivity towards the desired monoester remain very high in all cases, confirming trends observed with MeOH.

Entry	Equiv. of EtOH	Time (h)	Amount of catalyst	**1** Conv. (%)	**2** Yield (%)	**3** Yield (%)	**2** Sel. (%)
1	50	24	50 mg	9	9	-	99
2	50	48	50 mg	15	15	-	99
3	40	48	50 mg	22	21	1	95
4	40	48	100 mg	30	28	2	93

Table T3 Effect of the temperature on the esterification of **1** with MeOH

Catalytic activity of Al_2O_3 CE at various temperatures (reaction conditions as Table 4 of the main manuscript). An increase in the conversion of 1 comes at the expense of the selectivity towards 2.

Entry	T (°C)	**1** Conv. (%)	**2** Yield (%)	**3** Yield (%)	**2** Sel. (%)
1	25	60	57	3	95
2	50	73	40	33	55
3	65	80	30	50	37

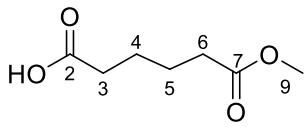
Table T4 Effect of the amount of catalyst on the esterification of **1** with MeOH

Influence of the quantity of Al_2O_3 CE on the yield and selectivity of the process. Other reaction conditions as those of Table 4 of the main article.

Entry	Amount (g)	**1** Conv. (%)	**2** Yield (%)	**3** Yield (%)	**2** Sel. (%)
1	5	30	29	1	97
2	25	40	38	2	96
3	50	60	57	3	95
4	75	61	58	3	95
5	100	64	61	3	96

4. Characterization of products

(**a**) monomethyl adipate



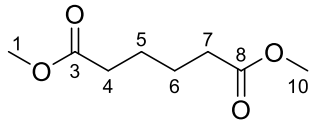
$C_7H_{12}O_4$ MW = 160.17 g/mol

According to the general procedure described above, **a** has been synthesized from adipic acid (730 mg, 5 mmol) and methanol (10 ml). Yield: 80%.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 8.48 (1H, br, H1), 3.40 (3H, s, H9), 2.10 (4H, m, H3-H6), 1.40 (4H, m, H4-H5).

^{13}C NMR (100.5 MHz, $CDCl_3$): δ = 177.6 (C2), 173.7 (C7), 51.0 (C9), 32.90 (C3), 32.87 (C6), 23.6 (C5), 23.5 (C4).

(**b**) dimethyl adipate



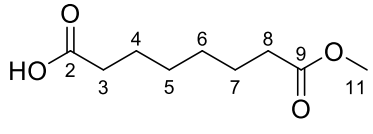
$C_8H_{14}O_4$ MW = 174.20 g/mol

According to the general procedure described above, **b** has been synthesized from adipic acid (730 mg, 5 mmol) and methanol (10 ml). Yield: 9%.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 3.56 (6H, s, H1-H10), 2.23 (4H, m, H4-H7), 1.56 (4H, m, H5-H6).

^{13}C NMR (100.5 MHz, $CDCl_3$): δ = 173.4 (C3-C8), 51.2 (C1-C10), 33.4 (C4-C7), 24.1 (C5-C6).

(**c**) 8-methoxy-8-oxooctanoic acid



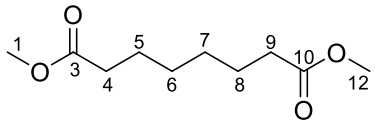
$C_9H_{16}O_4$ MW = 188.22 g/mol

According to the general procedure described above, **c** has been synthesized from octanedioic acid (870 mg, 5 mmol) and methanol (10 ml). Yield: 72%.

^{1}H NMR (300.1 MHz, $CDCl_3$): δ = 10.43 (1H, br, H1), 3.61 (3H, s, H11), 2.31(4H, m, H3-H8), 1.60 (4H, m, H4-H7), 1.33 (4H, m, H5-H6).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 179.9 (C2), 174.3 (C9), 51.5 (C11), 33.94 (C3), 33.93 (C8), 28.7, 28.6, 24.7, 24.4.

(**d**) dimethyl octanedioate



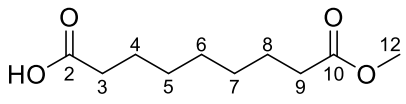
$C_{10}H_{18}O_4$ MW = 202.25 g/mol

According to the general procedure described above, **d** has been synthesized from octanedioic acid (870 mg, 5 mmol) and methanol (10 ml). Yield: 11%.

^{1}H NMR (300.1 MHz, $CDCl_3$): δ = 3.66 (6H, s, H1-H12), 2.29 (4H, m, H4-H9), 1.62 (4H, m, H5-H8), 1.32 (4H, m, H6-H7).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 174.1 (C3-C10), 51.4 (C1-C12), 33.9 (C4-C9), 28.7, 24.7.

(**e**) 9-methoxy-9-oxononanoic acid



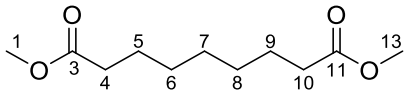
$C_{10}H_{18}O_4$ MW = 202.25 g/mol

According to the general procedure described above, **e** has been synthesized from nonanedioic acid (940 mg, 5 mmol) and methanol (10 ml). Yield: 73%.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 3.66 (3H, s, H12), 2.32 (4H, m, H3-H9), 1.61 (4H, m, H4-H8), 1.30 (6H, m, H5-H6-H7).

^{13}C NMR (100.5 MHz, $CDCl_3$): δ =179.9 (C2), 174.3 (C10), 51.5 (C12), 34.05 (C3), 33.98 (C9), 29.01, 28.99, 28.93, 24.9, 24.6.

(**f**) dimethyl nonanedioate



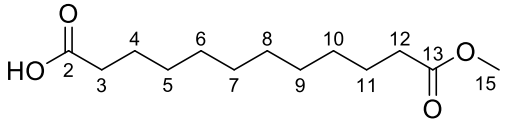
$C_{11}H_{20}O_4$ MW = 216.28 g/mol

According to the general procedure described above, **f** has been synthesized from nonanedioic acid (940 mg, 5 mmol) and methanol (10 ml). Yield: 9%.

^{1}H NMR (300.1 MHz, $CDCl_3$): δ = 3.40 (6H, s, H1-H13), 2.03 (4H, m, H4-H10), 1.35 (4H, m, H5-H9), 1.05 (6H, m, H6-H7-H8).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 174.2 (C3-C11), 51.4 (C1-C13), 34.0 (C4-C10), 28.9, 28.8, 24.8.

(**g**) 12-methoxy-12-oxododecanoic acid



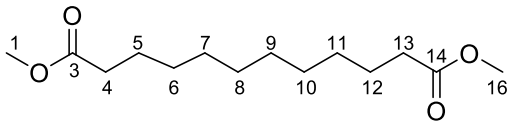
$C_{13}H_{24}O_4$ MW = 244.17 g/mol

According to the general procedure described above, **g** has been synthesized from dodecanedioic acid (1150 mg, 5 mmol) and methanol (10 ml). Yield: 40%.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 3.65 (3H, s, H15), 2.31 (4H, m, H3-H12), 1.61 (4H, m), 1.27 (12H, m).

^{13}C NMR (100.5 MHz, $CDCl_3$): δ = 179.6 (C2), 174.3 (C13), 51.3 (C15), 34.1 (C3), 34.0 (C12), 29.28, 29.27, 29.13, 29.12, 29.08, 28.99, 24.9, 24.6.

(**h**) dimethyl dodecanedioate



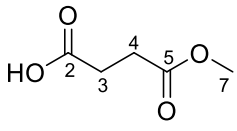
$C_{14}H_{26}O_4$ MW = 258.36 g/mol

According to the general procedure described above, **h** has been synthesized from dodecanedioic acid (1150 mg, 5 mmol) and methanol (10 ml). Yield: 6%.

^{1}H NMR (300.1 MHz, $CDCl_3$): δ = 3.66 (6H, s, H1-H16), 2.30 (4H, m, H4-H13), 1.61 (4H, m), 1.27 (12H, m).

^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 174.3 (C3-C14), 51.4 (C1-C16), 34.1 (C4-C13), 29.3, 29.2, 29.1, 24.9.

(**i**) 4-methoxy-4-oxobutanoic acid



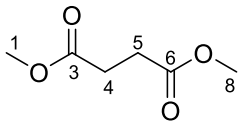
$C_5H_8O_4$ MW = 132.12 g/mol

According to the general procedure described above, **j** has been synthesized from succinic acid (590 mg, 5 mmol) and methanol (10 ml). Yield: 70%.

^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 3.70 (3H, s, H7), 2.65 (4H, m, H3-H4).

^{13}C NMR (100.5 MHz, $CDCl_3$): δ = 177.9 (C2), 172.6 (C5), 51.9 (C7), 28.8 (C3), 28.6 (C4).

(**j**) dimethyl succinate



$C_6H_{10}O_4$ MW = 146.14 g/mol

According to the general procedure described above, **k** has been synthesized from succinic acid (590 mg, 5 mmol) and methanol (10 ml). Yield: 6%.

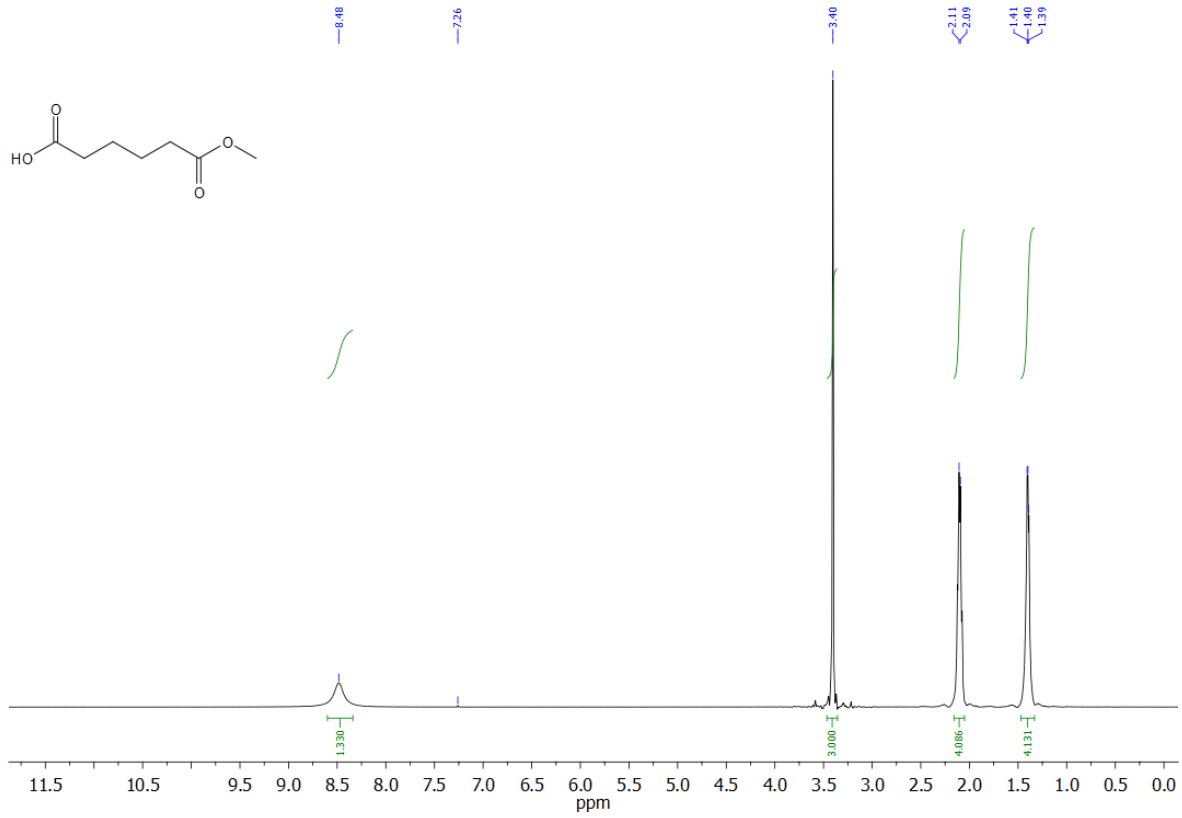
^{1}H NMR (400.1 MHz, $CDCl_3$): δ = 3.63 (6H, s, H1-H8), 2.57 (4H, m, H4-H5).

^{13}C NMR (100.5 MHz, $CDCl_3$): δ = 172.6 (C3-C6), 51.6 (C1-C8), 28.7 (C4-C5).

5. ^{1}H and ^{13}C spectra

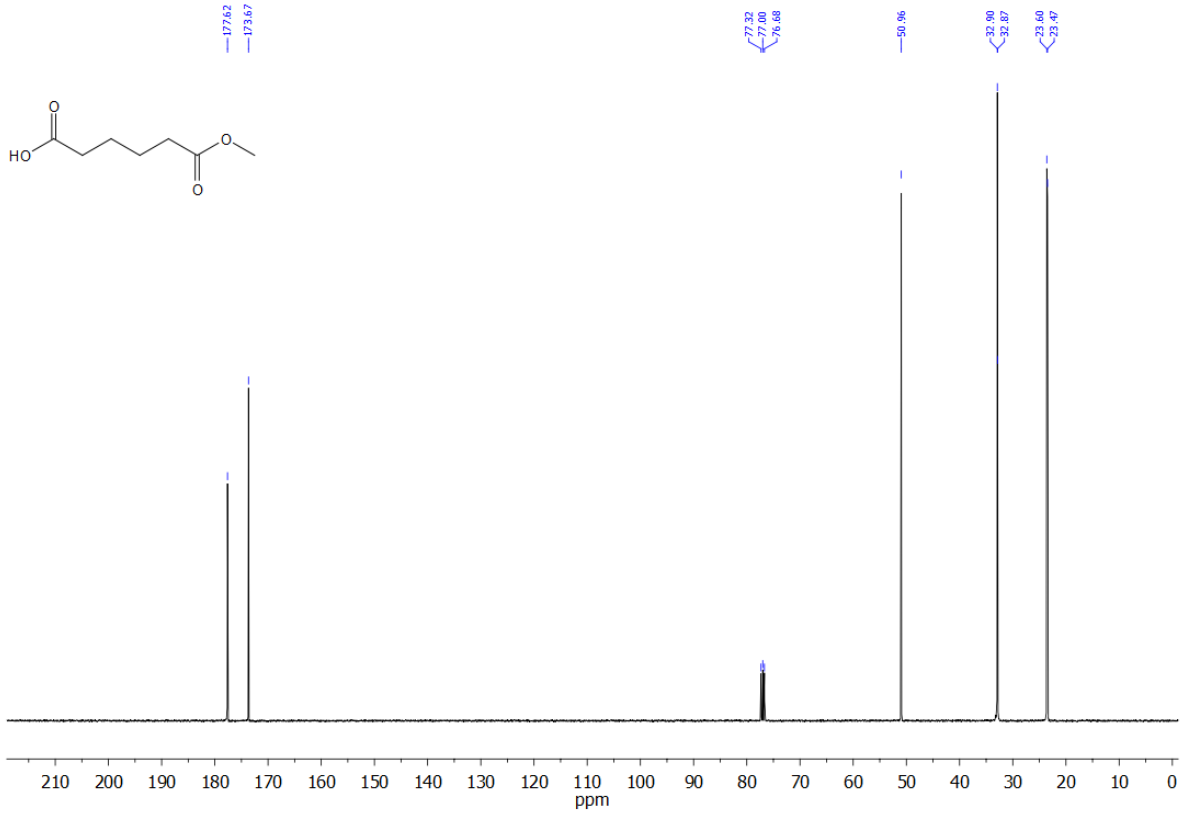
(a) monomethyl adipate

400 MHz ^{1}H NMR in $CDCl_3$



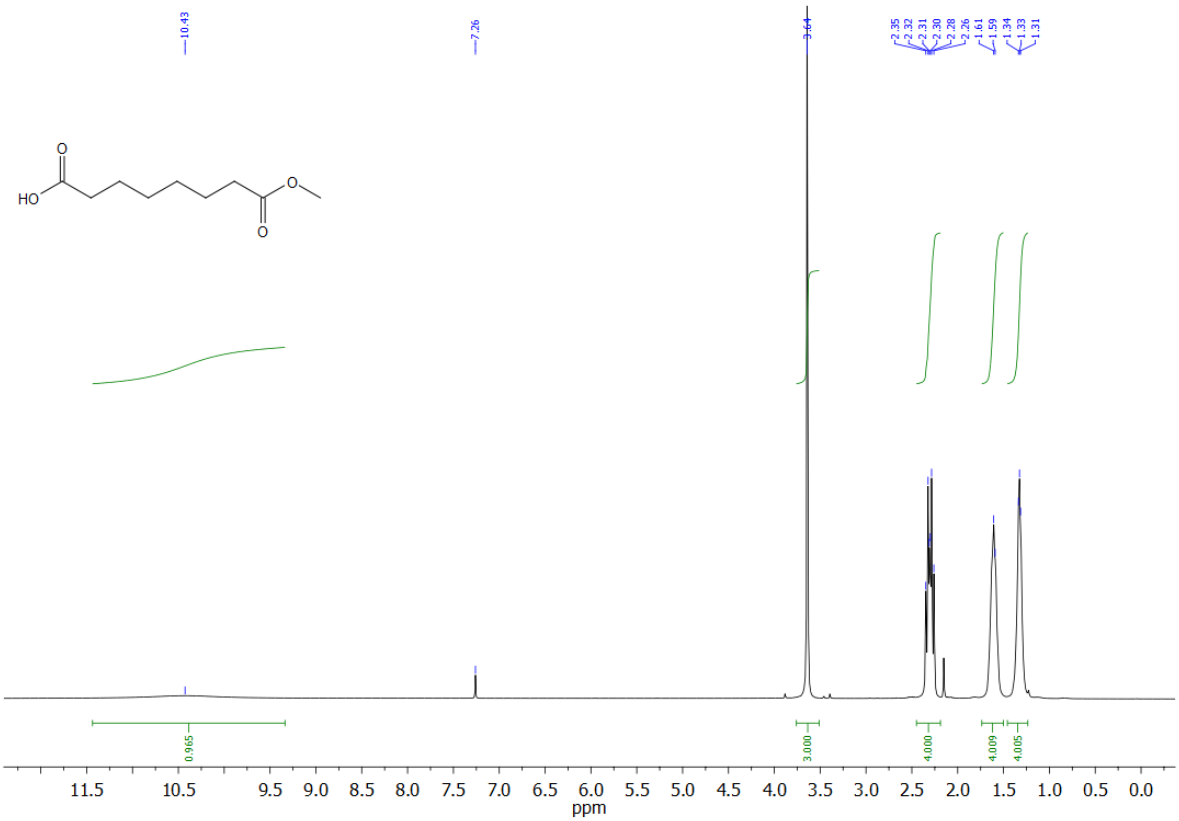
(a) monomethyl adipate

400 MHz ^{13}C NMR in $CDCl_3$



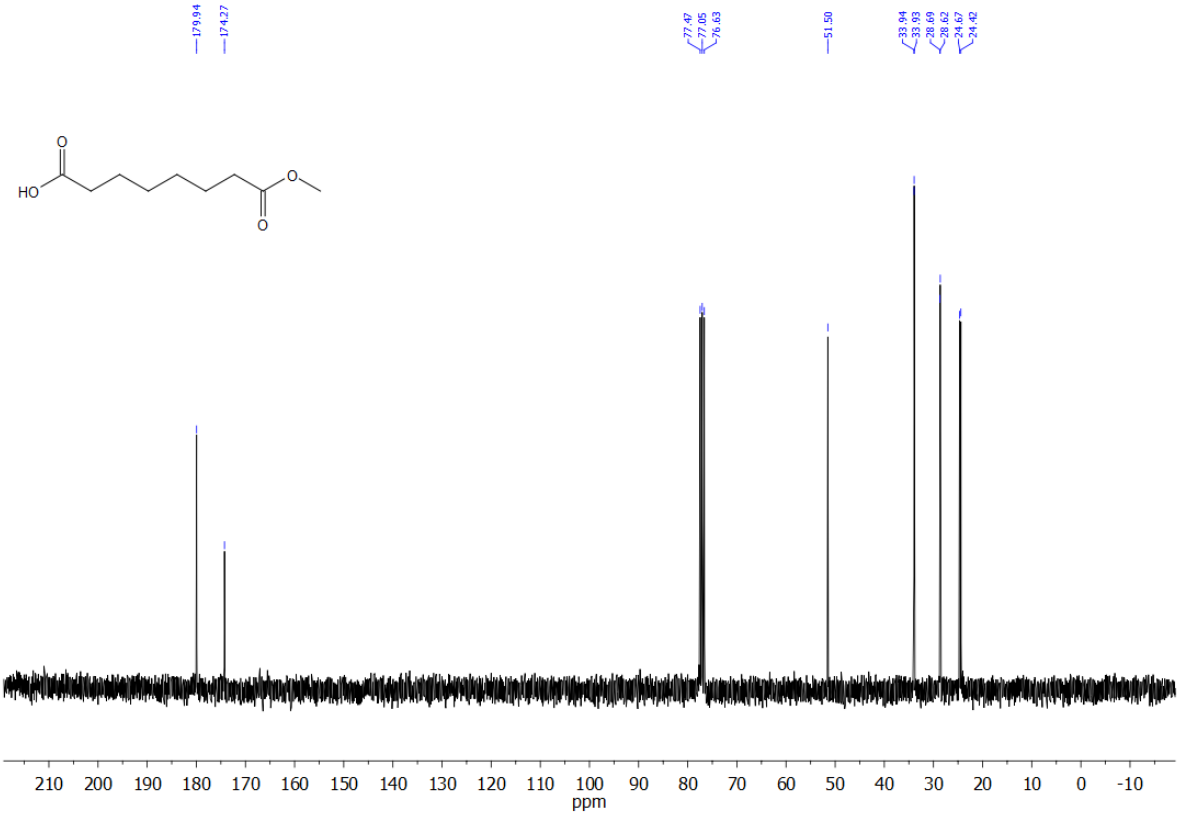
(c) 8-methoxy-8-oxooctanoic acid

300 MHz ^{1}H NMR in $CDCl_3$



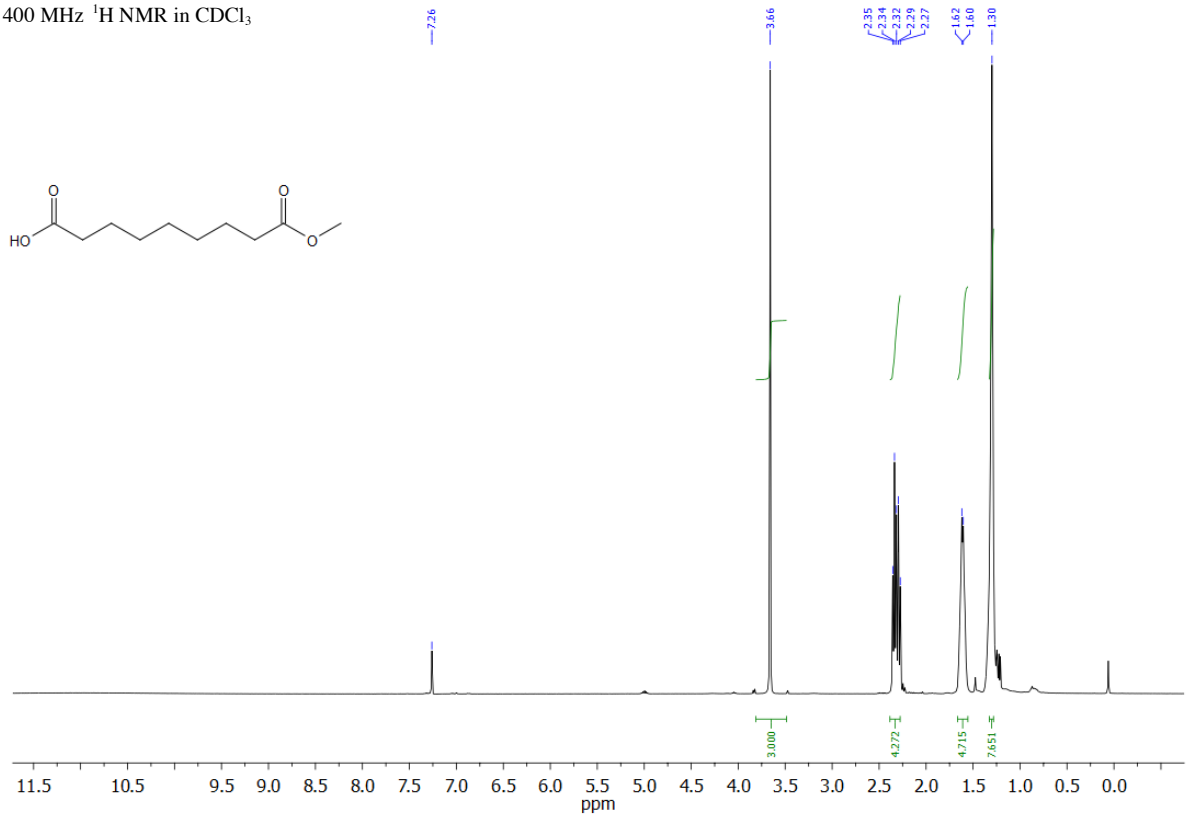
(c) 8-methoxy-8-oxooctanoic acid

300 MHz ^{13}C NMR in $CDCl_3$



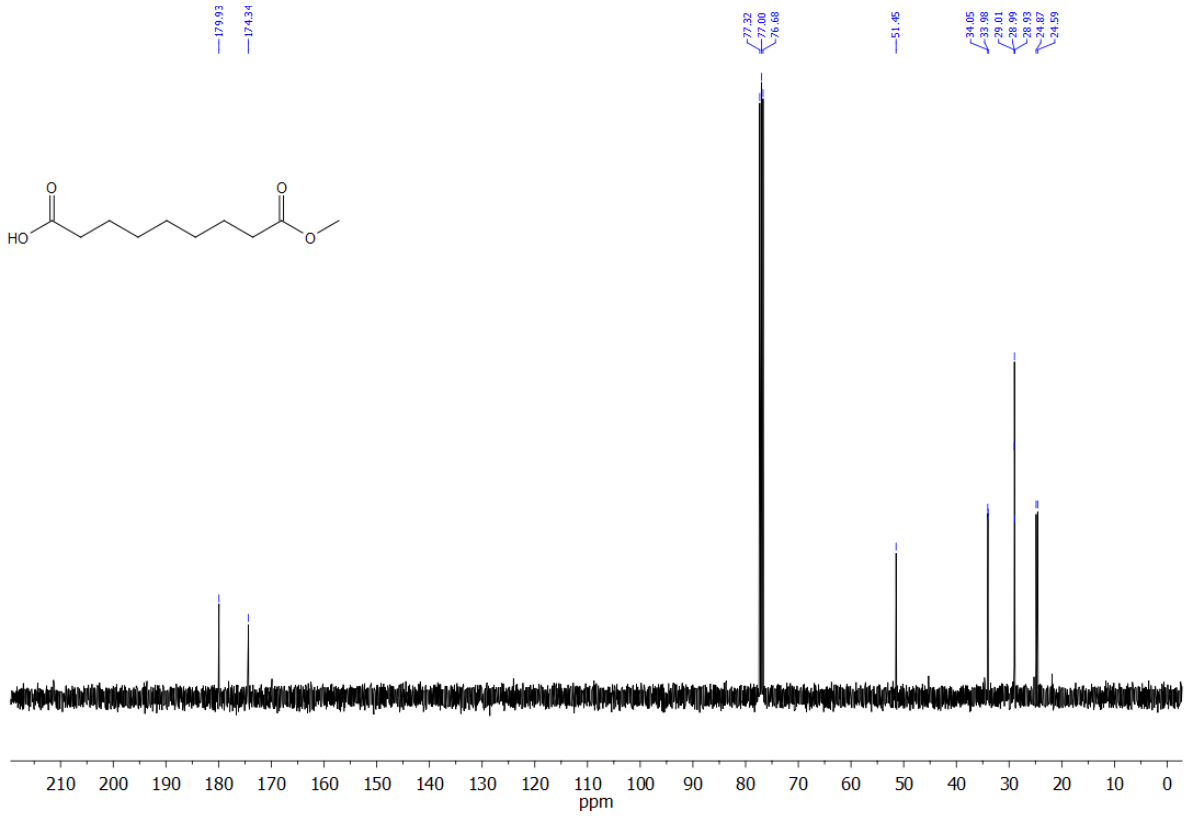
(e) 9-methoxy-9-oxononanoic acid

400 MHz ^{1}H NMR in $CDCl_3$



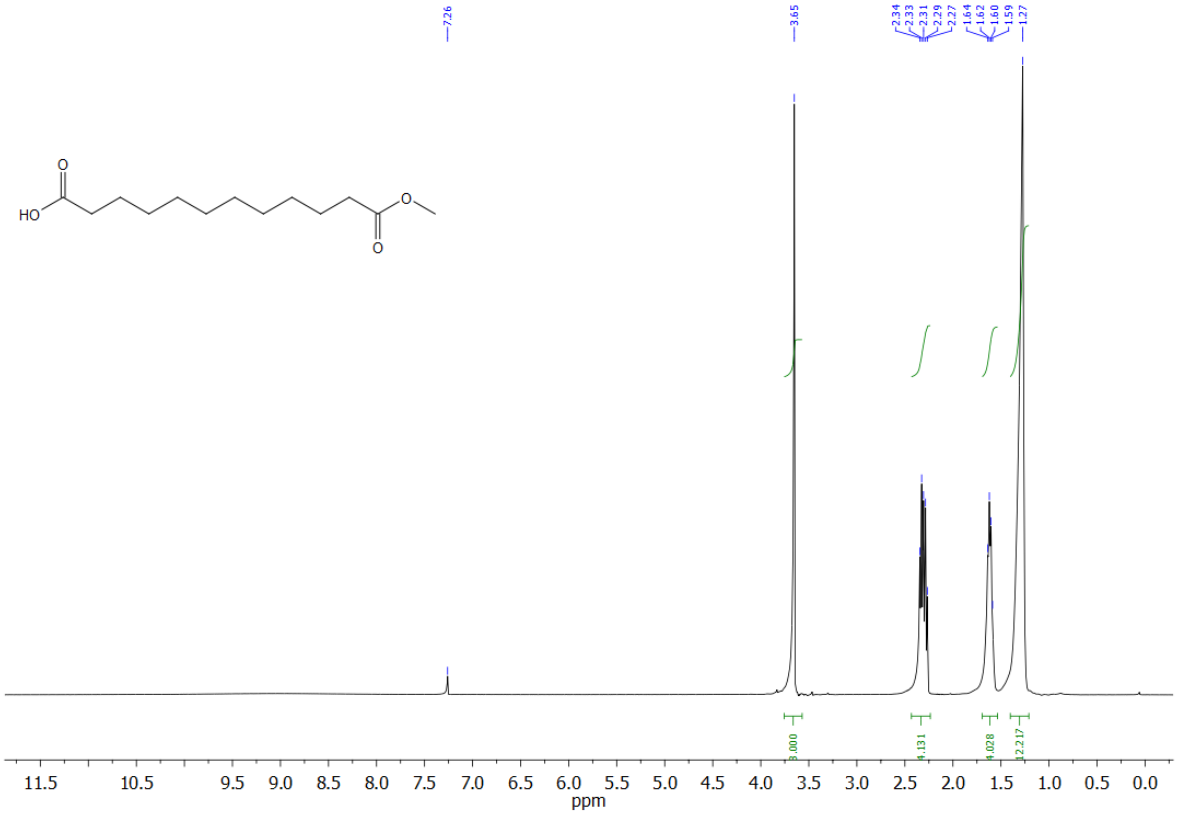
(e) 9-methoxy-9-oxononanoic acid

400 MHz ^{13}C NMR in $CDCl_3$



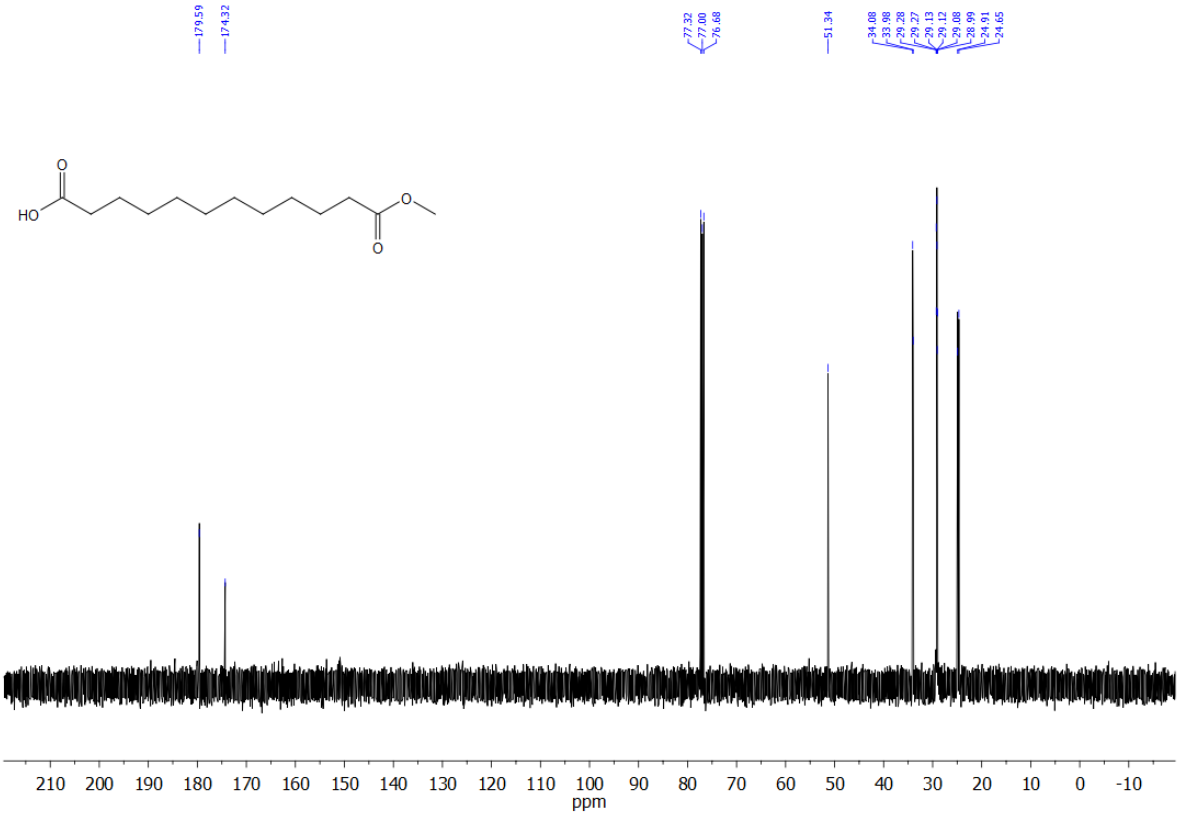
(g) 12-methoxy-12-oxododecanoic acid

400 MHz ^{1}H NMR in $CDCl_3$



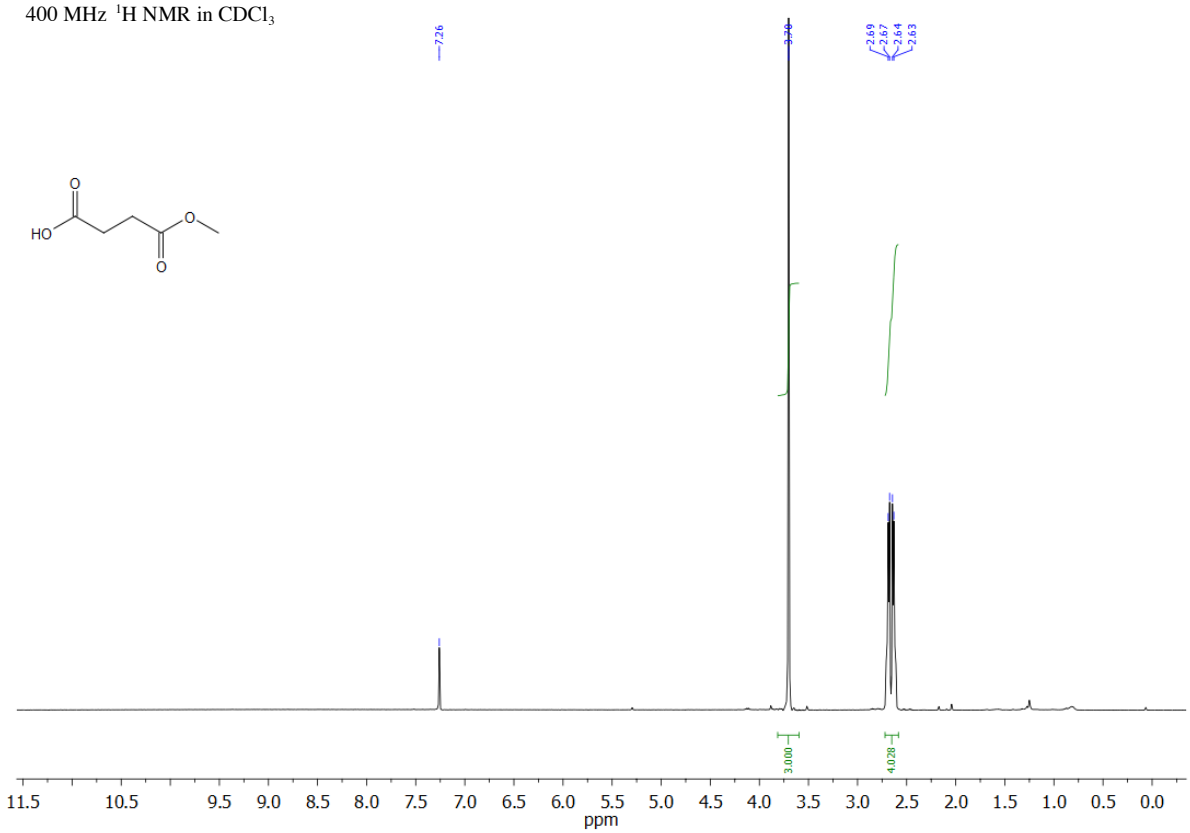
(g) 12-methoxy-12-oxododecanoic acid

400 MHz ^{13}C NMR in $CDCl_3$



(i) 4-methoxy-4-oxobutanoic acid

400 MHz ^{1}H NMR in $CDCl_3$



(i) 4-methoxy-4-oxobutanoic acid

400 MHz ^{13}C NMR in $CDCl_3$